Some Contributions to Model Based Control & Estimation for Industrial Systems

Thesis submitted

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Dedicated to My Daughters
Stuti & Oishi

ABSTRACT

This dissertation deals with Model Based Control and in particular Active Anti-Disturbance Control (AADC) for Industrial Process control Systems. As Disturbance Observers (DOB) are increasingly being suggested as a necessary component in AADC, designing nonlinear DOB occupies a major portion of this dissertation. It may be noted that, although the structure and design pragmatics of DOB's for linear systems are fairly well-known, literature about DOB for nonlinear systems is limited. In this dissertation it is demonstrated how the DOB, a deterministic disturbance estimation technique, may be fruitfully employed in control architectures to make such systems robust with respect to unknown disturbances. In the present work, we limit our attention to so-named matched disturbances.

The work shows how Internal Model Control (IMC), a form of Model Based Control may be restructured to create decoupled control and anti-disturbance control. This is in addition to the well known properties of IMC like the capability of obtaining set-point tracking, disturbance rejection and robustness. For MIMO systems, decoupling is a convenient step for an anti-disturbance architecture.

As the disturbances and uncertainties become stronger, better control for disturbance rejection becomes desirable. By combining IMC as feedback control and Disturbance Observer (DOB) as feed-forward control, a Modified Active Anti-Disturbance Control architecture has been proposed in this work. Though the work was motivated by the need to evolve improved methods of nonlinear AADC for nonlinear systems, for the sake of conceptual continuity the scope of the thesis has been broadened to include linear systems.

Some new methods for designing DOB for nonlinear systems have been proposed in this dissertation. Instead of the usual observer gain based approach, the proposed approaches employ Lie Derivative and Hirschorn Inverse.

Additionally, a number of decoupling structures have been proposed in this work, one of which is an extension of an existing method of linear MIMO decoupling IMC. Performance of the closed loop systems for set-point tracking, disturbance rejection, robustness with respect to parametric uncertainty have been analysed.

Regarding the AADC, it has been shown how employing DOB for feed-forward control, along with the usual feedback controller, improved performance may be obtained. The feed-forward scheme uses the reconstructed disturbance signal from the DOB, and thereby annuls the effects of such exogenous disturbances faster than that achievable by feedback controller alone. It has been shown that strong external disturbances and model uncertainties have been actively mitigated by using the proposed AADC architecture, indicating superior robustness compared to ordinary nonlinear IMC based control. Different set-point and disturbance conditions have been considered to characterize the algorithm.

The salient contributions of this research work are as follows:

- Two versions of a SISO DOB for nonlinear system have been proposed which is applicable to a large class of industrial control systems, namely
    - DOB using state variables of the process model.
    - DOB employing special state observers .
- The above DOB using state variables of the process model has been extended to nonlinear MIMO systems.
- An Active Anti-Disturbance Control (AADC) Architecture for Nonlinear Process Models has been proposed combining IMC and DOB for nonlinear system.
- Architecture for AADC applicable to linear MIMO time delay systems has been proposed using multivariable decoupling IMC and MIMO DOB and their performance evaluated.
- AADC for linear SISO time delay system has been proposed using IMC and Modified Noise Reduction Disturbance Observer (MNR-DOB) which can attenuate high frequency measurement noise along with other disturbances. Performance of such controllers has been evaluated.
- Some methods of Decoupling Internal Model Controller have been proposed for linear MIMO system with multiple time delays and such methods have been implemented and evaluated. Such schemes include:
    - A controller structure obtained by extending an existing decoupling IMC.
    - A decoupling IMC controller structure obtained for systems with V-structure.
    - Inverted decoupling controllers obtained using IMC.

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PART-A:
Introduction and Background

Chapter 1: Introduction

1.1 About this Chapter

This chapter contains introduction of the dissertation on Model Based Control and Estimation for Industrial Systems. This particular chapter summarizes the motivation, background, objective and organization of the thesis. It also enumerates salient contributions of this dissertation as well as peer reviewed publications arising out of this work.

1.2 Motivation and Objective

1.2.1 Motivation

Advantages of feedback control for Industrial processes are well known. However as many industrial systems are nonlinear, care and skill are required to design controllers for such plants. Industrial controllers need to be robust with respect to parameter variations and at the same time should ensure stability and routine performance measures like accuracy and speed of response.

Designing controller for nonlinear systems is a non-trivial task. This is because of several difficulties e.g. unmodeled dynamics, parametric variations, presence of external disturbance, stability issues etc. A number of techniques and architectures have been proposed to ensure the above properties. Out of them two interesting approaches require special attention. The first approach is to use a nominal model of the plant within the controller structure; this approach ensures that under nominal condition the duty of the feedback controller is minimal. So, the controller's main function would be to ensure stability and performance under off-nominal conditions. The second architectural approach involves estimation of external disturbance inputs and compensating the effects of such disturbances by appropriate feed-forward method. The above background is further elaborated in subsequent sections.

From a literature survey described subsequently, the following gaps in knowledge may be identified. Further, paucity of literature in a few areas indicated that more investigation in these areas are required. On the basis of the above, the following areas, inter alia, have been identified for contribution in the present work and the corresponding findings are incorporated in the dissertation.

- Though the structure and design pragmatics of DOBs for linear systems are well known, very few publications deal with DOB for nonlinear systems.
  - DOB structures for nonlinear systems proposed in previous literature are found to be based on conventional observer gain based approach [Li2014]. Further most of these previous publications assume the availability of state variables. The above provides an impetus to find alternative structures and approach (avoiding use of state variables if possible) to DOB for nonlinear systems.
  - The available DOB's applicable for nonlinear systems have been developed assuming specific disturbance waveform like sine wave and polynomial functions. Therefore, a possible research area would be to avoid such assumptions.
- No existing research work on nonlinear Active Anti-Disturbance Control (AADC) involving DOB and IMC has been found in literature.

Moreover, these gaps have been the motivations of the current work presented in this dissertation.

1.2.2 Objectives of the Research

This dissertation deals with Model Based Control and in particular Active Anti-Disturbance Control (AADC) for Industrial Process control Systems. As Disturbance Observers (DOB) are increasingly being suggested as a necessary component in AADC, designing nonlinear DOB occupies a major portion of this dissertation. It may be noted that, although the structure and design pragmatics of DOBs for linear systems are fairly well-known, literature about DOB for nonlinear systems is limited.

Specific objective of the research are as follows:

- To characterize Internal Model Control for industrial systems and to explore the possibility of evolving improved structure for the same.
- To evolve DOB architecture and algorithm for nonlinear system and to apply them in process control applications.

- To explore the possibility and evaluate the efficiency of AADC (using Internal Model Control and Disturbance Observer) for both linear and nonlinear systems.

1.3 Elaboration of the Background

Background of the present research work has been provided in a summarized form in the motivation section. In order to have a better appreciation of the present work, some of the background areas are elaborated in the present section.

In this dissertation, earlier works have been explained in pedagogical manner. A substantial part of this dissertation is concerned with Active Anti-Disturbance Control employing Internal Model Control and Disturbance Observer as would be discussed and demonstrated shortly. Other major concern of the present work is to design DOB applicable for nonlinear systems and design of IMC applicable for MIMO time delay systems. Backgrounds on these relevant fields of research are provided below:

1.3.1 Background on Disturbance Observer

Literature review on the Disturbance Observer (DOB) is a significant part of this research work as the DOB is the central theme of this research. Disturbance Observer (DOB), a popular disturbance estimation technique, is centrepiece of Active Anti-Disturbance Control (AADC). Literature indicate that not only external disturbance, but unmodeled dynamics and uncertainties can also be estimated using appropriate forms of DOB [Li2014] and may be employed in so named Disturbance Observer Based Control (DOBC). Moreover, as the Disturbance Observer (DOB) has simplicity in design, it has been employed in many industrial applications. There are literature available where DOB and DOBC or similar methods have been documented for linear SISO and MIMO systems including time delay or non-minimum phase part. DOB's for nonlinear SISO and MIMO systems are found to be important research areas.

Existing literature indicate that Disturbance Observers are designed by two ways: (i) Frequency domain and (ii) Time domain [Li2014]. Under first category of frequency domain design which is mainly applicable for linear systems, is sub-categorized as design for Minimum-Phase case and Non-minimum Phase case respectively. In frequency domain design category of DOB design (linear systems), some literature [Zhou2012, Zhou2014] have used the fact that DOB can estimate measurement disturbance also. Under second category, time domain DOB design is mainly applicable for nonlinear systems, where process is in state space form. Recently, DOB's are also used in AADC where high frequency measurement noise rejection is required. There are also some applications are present where DOB has been designed for discrete systems.

For most of the DOB's for nonlinear systems reported in literature, the algorithms had been derived assuming restricted disturbance waveform e.g. constant disturbance estimation in [Chen2000a], harmonic disturbance estimation in [Chen2003], time varying disturbance (generated by specified exogenous system) estimation in [Chen2004] and higher order disturbance estimation in [Kim2010]. However, it can be empirically demonstrated that a majority of such observers can also accommodate other disturbance waveforms with varying degrees of accuracy.

1.3.2 Background on Internal Model Control

This review has helped the present worker to appreciate the recent advancement in the domain of Internal Model Control (IMC) techniques, which is termed as a Passive Anti-Disturbance Control (PADC). Internal Model Control is one of the well known Model Based Controls, where model is explicitly used in designing the controller [Morari1989]. It has been found in literature that the objective of IMC is set-point tracking, disturbance rejection and robustness. Internal Model Controller design mechanisms for 1-DOF, 2-DOF and 3-DOF control have been demonstrated in literature. There are references available in IMC applicable for linear systems (stable, unstable, LPV, time delay, integrating process). Works on Decoupling IMC for MIMO linear system as well as IMC for nonlinear systems are found to be other important research areas.

1.3.3 Background on Active Anti Disturbance Control

There have been reported several Anti-Disturbance Control strategies for single disturbance as well as multiple disturbance cases. Different types of DOB based control methods have been documented in literature. It has been noted that different types of control methodologies such as

H_∞, PID, MPC, adaptive control and variable structure control have been individually combined with Disturbance Observer Based Control (DOBC).

1.4 Salient Contributions

This section will specifically state the contribution of the present work in the background of earlier work.

The contribution made by the present worker may be broadly categorized as follows:

(i) Fairly extensive and up to date literature survey has been performed on Disturbance Rejection Control methods specifically Active Anti-Disturbance Control, decoupling control methods, DOB and IMC. This review has helped the present worker to appreciate the extent of work already done and to identify gap in the existing knowledge.

(ii) Two versions of nonlinear SISO DOB have been proposed which is applicable to a large class of industrial control systems, namely

(a) DOB using state variables of the process model.

(b) DOB employing special state observers.

(iii) The above DOB using state variables of the process model has been extended to nonlinear MIMO systems.

(iv) An Active Anti-Disturbance Control (AADC) Architecture for Nonlinear Process Models has been proposed combining IMC and DOB for nonlinear systems.

(v) Architecture for AADC applicable to linear MIMO time delay systems has been proposed using multivariable decoupling IMC and MIMO DOB and their performance evaluated.

(a) Sensitivity analysis has been done for AADC and IMC in the presence of process-model mismatch.

(vi) AADC for linear SISO time delay system has been proposed using IMC and Modified Noise Reduction Disturbance Observer (MNR-DOB) which can attenuate high frequency measurement noise along with other disturbances. Performance of such controllers has been evaluated.

(vii) Some methods of Decoupling Internal Model Controller have been proposed for linear multivariable system with multiple time delay and such methods have been implemented and evaluated. Such schemes include:

(a) A controller structure obtained by extending an existing decoupling IMC [Qibing2009].

(b) A decoupling IMC controller structure obtained for systems with V-structure.

(c) An IMC based version of Inverted decoupling controllers.

1.5 Publications

The following publications in peer reviewed international journal, national and international conferences have been generated out of the present work.

International Journal Paper

1. Sudeshna Dasgupta, Smita Sadhu, T.K. Ghoshal, Designing Disturbance Observer for Nonlinear Systems- A Hirschorn Inverse Approach, IET Science Measurement & Technology Vol. 11, Issue 2, pp. 164-170, 2017.

Conference Papers

2. Sudeshna Dasgupta, Smita Sadhu, T.K Ghoshal, Disturbance Observer Structure Based Internal Model Control For Time Delay Systems, Information Sciences and Systems (CISS), 2015 49th Annual Conference on ; Baltimore, MD, USA, March 2015.

3. Sudeshna Dasgupta, Smita Sadhu, T.K Ghoshal, Internal Model Based V-Norm Decoupling Control for Four Tank System, International Conference on Control, Instrumentation, Energy and Communication, Dept. of Applied Physics, University of Calcutta, 2014, Pages: 31 – 35.

4. Sudeshna Dasgupta, Smita Sadhu, T.K Ghoshal, Performance Comparison And Robustness Studies of Robust Bode and IMC Based Controllers For Plants With Large Time Delay, International Conference on Control, Instrumentation, Energy and Communication, Dept. of Applied Physics, University of Calcutta, 2014, pp. 703 – 707.

5. Sudeshna Dasgupta, Smita Sadhu, T.K. Ghoshal, Internal Model Control Based Controller Design for a Stirred Water Tank, 2010 Annual IEEE India Conference (INDICON), pp.1 – 4, Dec 2010.

6. Sudeshna Dasgupta, Smita Sadhu, T.K Ghoshal, Decoupling Internal Model Controller Design of Distillation Column System, Michael Faraday IET India Summit-2013 (MFIIS 13).

1.6 Organization of the Dissertation

This dissertation is organized in five separate parts. 'Part A' is the introductory section consisting of two chapters. Apart from this introduction chapter (Chapter 1), it contains Chapter 2 where literature review has been performed for Disturbance Rejection Control, Decoupling control, Active Anti-Disturbance Control (AADC), Internal Model Control (IMC) and Disturbance Observer (DOB).

'Part B' consisting of Chapter 3 and Chapter 4, is devoted for Active Anti-Disturbance Control applicable for linear SISO systems. Perspectives of AADC for linear SISO systems (without time delay) has been outlined in Chapter 3 and Modified Active Anti-Disturbance Control for linear SISO time delay systems has been presented in Chapter 4.

In 'Part C', the AADC applicable for linear MIMO systems has been outlined. This part consists of two chapters; Chapter 5 presents decoupling IMC for linear systems with time delay and Chapter 6 presents the modified AADC for linear MIMO systems with multiple time delay.

'Part D' is devoted for the AADC applicable for nonlinear systems by utilizing the newly formulated nonlinear DOB. This section consists of four chapters. In Chapters 7 and 8, two types of new nonlinear DOB have been proposed: (i) DOB using Hirschorn Inverse with direct utilization of state variables of the process model (ii) DOB using Hirschorn Inverse employing special state observers where state variables of the process model are not directly accessible. This is followed by AADC for nonlinear systems in Chapter 9 where a novel method for designing Modified Active Anti-Disturbance Control (MAADC) architecture using the IMC and DOB for nonlinear systems has been proposed. Using DOB (as proposed in Chapter 8), MAADC architecture has been proposed in this chapter. In Chapter 10, the proposed design of MIMO DOB applicable for nonlinear systems has been documented.

'Part E' is the concluding section of the dissertation which consists of discussions, conclusions, suggestions for future works and Bibliography. In Chapter 11, Discussions and Conclusions comprising of salient contributions and several major findings are provided. All the literature cited in this dissertation are enlisted in the Bibliography section at the end.

Chapter 2: Literature Survey

2.1 Introduction to Literature Survey

In this dissertation, research on Model based control and estimation has been conducted for Industrial systems. Here, Active Anti-Disturbance control (AADC) has been modified by conjugative use of Internal Model Control (IMC) and Disturbance Observer (DOB) applicable for nonlinear systems. As the centrepiece of AADC is DOB itself, innovative methods for DOB design for nonlinear systems also have been proposed in this work. AADC consists of two parts: namely, feedback control part and a feed-forward part based on Disturbance Observer (DOB). Based on this context, the sub sections of this literature survey chapter address existing works on Disturbance Rejection Control, Decoupling Control, DOB, IMC and AADC combining DOB with controller (e.g. PID, Model Predictive Control, H_∞, Adaptive control, Sliding Mode Control or IMC).

In this chapter, literature survey has been conducted till date; gap on this area has been identified and scope of contribution has been highlighted. Though the period of literature survey is 1970-2017, emphasis has been given to most recent literature (1995-2017).

2.2 Disturbance Rejection Control

Since disturbances and uncertainties are usually present in Industrial systems, often they have adverse effect on system performance and stability. Thus, disturbance rejection for Industrial systems is now becoming a popular area of research. In the paper [Chen2016], a survey on Disturbance Observer Based Control (DOBC) and its related methods have been summarized. In DOBC, disturbance attenuation and disturbance rejection have been obtained by using two degree of freedom control. It has been found that AADC is one of the important methods were DOBC framework has been used.

There are some disturbance attenuation methods available e.g. Adaptive Control, Robust Control, Sliding Mode Control, Internal Model Control (IMC) etc [Li2014]. These control approaches are recognized as Passive Anti-Disturbance Control (PADC), where feedback control has been used only. Though IMC can reject disturbances to a considerable extent, their performance sometimes is inadequate in the presence of strong disturbances [Li2014, Chen2011a]. To overcome the limitations of such PADC methods in disturbance handling, Active Anti-Disturbance Control (AADC) approach has been used [Li2014]. In theoretical and application point of view, nonlinear control system is an emerging field [Iqbal2017]. Survey of AADC has been investigated in Section 2.6.

Some Disturbance Rejection Control Techniques other than AADC are available, which have been illustrated below:

2.2.1 Active Disturbance Rejection Control (ADRC)

Active Disturbance Rejection Control (ADRC) has been shown as a paradigm shift in feedback control system design in [Gao2006]. The main idea of ADRC (Combination of feedback control and feed-forward control based on Extended State Observer) has been summarised in [Han2009]. The detailed survey about Extended State Observer (ESO) and related ADRC method has been given in [Huang2014]. After that, ADRC has been used in several literature [Zhao2015, Guo2015, Guo2015a, Ma2016, Pan2016, Tan2016]. In [Zhao2015], a modified nonlinear Extended State Observer (ESO) has been proposed with a time-varying gain in ADRC to deal with a class of nonlinear systems which are essentially normal forms of general affine nonlinear systems. In [Guo2015], this ADRC has been applied to stabilisation for a cascade ODE (Ordinary Differential Equation)– PDE (Partial Differential Equations) system; both disturbance estimators with constant high gain and time-varying gain have been designed. In the paper [Guo2015a], an ADRC approach has been proposed to boundary state feedback stabilization for a multi-dimensional wave equation. An ADRC and predictive control strategy has been presented in [Ma2016] to solve the trajectory tracking problem for an unmanned quadrotor helicopter with disturbances. In [Pan2016], the principle of ADRC from the internal model principle point of view has been presented. In [Tan2016], linear ADRC method has been investigated. It has been shown that a linear ADRC is a two-degree-of-freedom control and can be changed into an IMC structure, thus analysis of linear ADRC can be done via the well known IMC framework.

2.2.2 Composite Hierarchical Anti-Disturbance Control (CHADC)

The Composite Hierarchical Anti-Disturbance Control (CHADC) method has been reported in [Guo2014, Guo2014a]. The CHADC has been known as refined anti-disturbance control. Though it has similar type of block diagram as used in DOBC, due to multiple disturbances present in the system, multiple loops have been used. For example, some application is subjected to stochastic noises and deterministic disturbances, then it can be said that the system is subjected to multiple disturbances. The basic idea of CHADC has been first introduced by Guo et. al. in [Guo2005] where external disturbance and model uncertainty were treated as multiple disturbances. In [Wei2010], H_∞ and variable structure control have been integrated with DOBC. Here, DOBC has been used to reject modeled disturbance and robust H_∞ control or variable structure control has been used to attenuate norm bounded disturbance or unmodeled disturbance. In [Lu2017], a constrained anti-disturbance control scheme has been proposed which can be applied to differentially flat systems. Here, the optimal states and inputs have been obtained by solving Model Predictive Control (MPC) online and used as the constrained reference for the inner-loop controller. To achieve the robustness against multiple disturbances, the CHADC method has been employed to design an inner-loop controller, which includes DOBC and H_∞ control to improve the disturbance rejection and attenuation abilities.

2.3 Decoupling Control

Most process control systems can be mathematically represented as Multiple Input Multiple Output (MIMO) models [Hangos2004]. Adopted major approaches for controlling these processes are as follows:

(i) Multiple single-input single-output (SISO) controllers to constitute a multi-loop control system [Luyben1986, Yu1986, Shen1994, Bao2000, Bao2002, Huang2003].

(ii) Multivariable controllers to form a multivariable control (MVC) system [Niederlinski1971, Rosenbrock1974, MacFarlane1977, Horowitz1979, Goodwin1980, Doyle1981, Sinha1984, Arulalan1986, Jerome1986, Stein1987, Agamennoni1989, Maciejowski1989, Figueroa1991, Skogestad1996].

As interactions among loops in multi-loop systems are important issue, performance of the controller experiences many limitations. Multivariable controllers have been used widely to overcome the above shortcoming.

A multivariable system may be simplified into a number of single variable systems if it has no cross-coupling between variables and is called decoupled. Broadly, there are two types of decoupling exist in linear multivariable control: one is static decoupling and another is dynamic decoupling [Brosilow2002]. Dynamic decoupling is more demanding than static decoupling. A signal applied to input u_i controls the output y_i and it has no effect on the other outputs. To get dynamic decoupling, sometimes, a complex control law becomes necessary. A system is called statically decoupled if it is stable and its static gain matrix *G(0)* is diagonal and non-singular.

The study of multivariable systems with coupling is an area that has received the attention of researchers for years [Wang2003]. For effective control of MIMO systems with multiple time delays, decoupling is a major concern [Wang2002]. In [Wang2002], an approach to the decoupling Internal Model Control (IMC) analysis and design based on model reduction procedure has been proposed for multivariable stable processes with multiple time delays. In [Gilberta2003] and [Garcia2005], decoupling compensators using PI and PID control have been designed. In [Huang2006], a 2-DOF decoupling multivariable control system and method of design have been proposed, which is capable of dealing with both servo tracking and disturbance rejection.

To study the degree of decoupling, Gershgorin bands have been used in some literature [Maciejowski1989, Skogestad1996]. In [Chen2001, Chen2002, Garcia2005, Ho2000], Gershgorin circles have been presented, based on which controller design have been obtained for multivariable systems. Additionally, Relative Gain Array (RGA) method has been used as a quantitative measure of interaction. In this method of RGA, input-output pairing is possible which provides more effective control [Chen2009].

Ideal, simplified and inverted decoupling are some of the other decoupling methods which are widely used in industrial process control [Gagnon1998]. Many researchers have worked on Inverted Decoupling due to its simple general expression of controller elements e.g. [Garrido2010, Garrido2011, Garrido2012, Garrido2014, Garrido2014a, Chen2007a]. Its various advantages over the other decoupling methods have been reported in [Chen2007a, Gagnon 1998].

Internal Model Control (IMC) is a well known model based control since [Garcia1982]. In [Wang2002], an approach to the decoupling Internal Model Control (IMC) analysis and design based on model reduction procedure has been proposed for multivariable stable processes with multiple time delays. Another method based on linear matrix inequality (LMI) for designing multivariable internal model control has been proposed in [Yang2005]. In [Liu2006], a decoupling IMC scheme has been proposed for a 2X2 process with time delay. Chen et. al. has been proposed an analytical design and tuning method for the multivariable controller in [Chen2007b] for stable, linear, MIMO process with multiple time delay and non-minimum phase zero. In [Chen2011], a method using Internal Model Control has been proposed to design Smith delay compensation decoupling controller for multivariable non-square systems with transfer function elements consisting of time delay. In [Qibing2009], a decoupling IMC has been presented for MIMO system with multiple time delay.

In [Garrido2015], a multivariable smith predictor has been proposed for time delay system based on centralized inverted decoupling structure. In [Garrido2014], an Internal Model Controller has been designed for a multivariable time delay system based on the structure of centralized inverted decoupling and a tuning methodology has been proposed in designing that controller.

A 2-DOF model matching control scheme has been proposed in [Beevi2017] that introduces a two degree of freedom (2-DOF) controller for tracking the desired trajectory of a multi-input multi-output (MIMO) system.

2.4 Disturbance Observer (DOB)

Disturbance Observer (DOB), a popular disturbance estimation technique, is centrepiece of Active Anti-Disturbance Control (AADC). Not only external disturbance, but unmodeled dynamics and uncertainties can also be estimated using appropriate forms of DOB [Li2014] and may be employed in so named Disturbance Observer Based Control (DOBC). Moreover, as the Disturbance Observer (DOB) has simplicity in design, it has been employed in many industrial applications.

In [Ohishi1987], possibly the concept of DOB has been introduced first. There has been equivalence of DOB structure for linear systems; which has been presented in [Gorez1991, Schrizver2000]. In [Radke2006], the state and disturbance observers have been reviewed for the benefits of the practitioners. In [Shim2016a], tutorial review of DOB has been presented. In [Ali2015], current and future trend of recent observers were analyzed for chemical process systems. It has been found that DOB is of current interest. Disturbance Observer Based Control (DOBC) and related methods have been reviewed in a recent survey paper [Chen2016]. [Chen2016] is a systematic and comprehensive tutorial and summary on the existing disturbance/uncertainty estimation and attenuation techniques, most notably, DOBC, active disturbance rejection control (ADRC), and composite hierarchical anti disturbance control (CHADC) have been explained;. as a part of those design techniques, Disturbance Observer or other types of observers also have been reviewed and summarized.

There are literature available where DOB and DOBC or similar methods have been documented for linear SISO and MIMO systems (including time delay or non-minimum phase part), nonlinear SISO and MIMO systems. The end result is disturbance (and/or uncertainties) attenuation or sometimes rejection. Broadly, Disturbance Observers have been designed in two ways: (i) Frequency domain and (ii) Time domain [Li2014]. Under first category of frequency domain design which is mainly applicable for linear systems, can be sub-categorized as design for Minimum-Phase case and Non-minimum Phase case respectively. In frequency domain design category of DOB design (linear systems), some literature [Zhou2012, Zhou2014] have used the fact that DOB can estimate measurement disturbance also. Time domain DOB design is mainly applicable for nonlinear system, where process is in state space form. Recently, DOBs are also used for high frequency measurement noise estimation. There are also some applications present using discrete DOB [Chen2013, Chen2011b]. All the cases have been mentioned in the subsequent paragraphs.

2.4.1 DOB for linear SISO system

As DOB design using frequency domain for linear time delay system suffers problem due to inversion of process model, some references [Zhu2005, Chen2009, Yang2011] have been documented for modified designing method of DOB applicable for linear time delay systems. A Modified DOB (MDOB) has been proposed in [Zhu2005] for time delay system with inverse response. In [Chen2009], though a MIMO 2X2 system with multiple time delay has been considered, a feasible variable pairing u1-y1 and u2 -y2 have been done according to Relative Gain Array (RGA) analysis. Then MDOB has been designed for diagonal elements of transfer function matrix (G_{11} and G_{22}). However, this design was based on [Zhu2005]. In [Yang2011], MDOB has been designed for time delay system according to [Chen2009] and MDOB and MPC compositely used to control SISO First Order Plus Delay Time (FOPDT) process and disturbance rejection has been achieved. New DOB configurations have also been proposed for linear non-minimum phase system in [Shim2008, Jo2010].

Integral processes with dead time have been controlled by Disturbance Observer Based 2DOF control in [Zhong2001, Zhong2002].

For Fractional Order Linear Time Invariant (FO-LTI) systems, DOB design has been investigated in [Cheng2016] with two types of disturbances: time series expansion and sinusoidal.

In [Joo2016], a DOB structure has been proposed with embedded internal model of disturbance for achieving asymptotic disturbance rejection. The speciality of the designing of this Q-filter is that the numerator of the Q-filter is designed for embedding the internal model; the denominator and the bandwidth are for ensuring robust stability. In [Wang2016a], a novel disturbance observer (DOB)-based switching control strategy has been proposed to achieve fast, smooth, and accurate control performance in the presence of both external disturbances and internal uncertainties. Here, two DOBs have been designed with different frequency responses, and the switching mechanism has been designed to schedule different DOB's. A sensor-less control method for the Permanent Magnet Synchronous Machine (PMSM) drive that is robust against load torque variations has been proposed in [Xiaoquan2016]. The proposed method was based on the DOBC, and involves the use of a back electromotive force observer to estimate rotor position and a torque observer to compensate for load torque disturbance.

2.4.2 DOB for linear MIMO system

In [Shahruz2008], MIMO (without delay) DOB structure has been shown in the form of IMC. But, without using system inversion, design has been done using two techniques: (i) Technique based on minimization of a H_∞ norm and (ii) Technique based on parametric optimization. In [Chen2009], a ball mill grinding circuit (a MIMO time delay system) has been considered. Using RGA analysis, MDOB has been designed for diagonal elements of process model transfer function matrix G_{11} and G_{22} (based on [Zhu2005]) i.e. MDOB design has been followed as SISO system. A decoupling-type MIMO disturbance observer architecture has been formulated in [G¨uvenc2010] for square systems. A multi-objective parameter space disturbance observer design procedure satisfying certain D-stability, mixed sensitivity, and desired phase margin objectives have been presented. In [Zhou2012], an Improved DOB (IDOB) has been proposed for MIMO non-minimum phase time delay system. Then disturbance rejection performance of MPC has been improved by using a compound control scheme (IDOB-MPC) In [Li2013], Bank-to-Turn (BTT) Missiles dynamics have been divided into three subsystems and DOB has been introduced for each subsystem to estimate both the nonlinear couplings and the external disturbances. Another Modified DOB (MDOB) has been proposed in [Zhou2014] for a Grinding circuit (a MIMO system with multiple time delay and non-minimum phase zero). Here, according to H_2 optimal performance specification of IMC theory, MDOB has been designed. In [Zhang2016], a MDOB for both stable and unstable MIMO system with multiple time delay has been proposed.

2.4.3 DOB for nonlinear system

A Nonlinear Disturbance Observer with sliding mode structure has been proposed in [Chen2000] for minimum phase dynamical systems with arbitrary relative degrees. Only constant disturbances can be handled using the approach presented in [Chen2000a]. In [Chen2004], for a well defined relative degree from the disturbance to the output, disturbance observer has been designed; the nonlinear observer gain has been represented using Lie derivative and constant disturbance has been considered. For most of the DOBs for nonlinear systems reported in literature, the algorithm had been derived assuming restricted disturbance waveform e.g. constant disturbance estimation in [Chen2000a], harmonic disturbance estimation in [Chen2003], time varying disturbance (generated by specified exogenous system) estimation in [Chen2004] and higher order disturbance estimation in [Kim2010]. However, it can be empirically demonstrated that a majority of such observers can also accommodate other disturbance waveforms with varying degrees of accuracy.

Nonlinear DOB design approaches available in literature have been used in applications like robotic manipulators [Chen2000a, Chen2004, Mohammadi2013, Mohammadi2011, Gupta2011, Mohammadi2012, Lichiardopol2010], missile systems [Yang2011a], magnetic bearing systems [Chen2004a], permanent magnet synchronous motors [Yang2012], flight control systems [Guo2005], small scale helicopters [Liu2012], Reusable Launch Vehicles (RLV) [Wang2016], etc. In [Shim2016], quasi-Disturbance-to-Error Stability (qDES) Observer has been proposed; frameworks have been developed for both full-order and reduced-order qDES observers based on Lyapunov functions. In [Su2016], a generic analysis of the relationship between time-domain and frequency-domain DOBs have been presented. As the traditional frequency-domain DOBs using a low-pass filter with unity gain can only handle disturbances satisfying matching condition and the traditional time-domain DOBs always generate an observer with a high-order; a Functional DOB has been proposed in this paper to improve the time domain DOB. A new nonlinear DOB (NDOB), namely High-Order Nonlinear Disturbance Observer (HONDO), for a nonlinear system with an unknown fast time-varying disturbance (i.e. $\dot{d}(t) = 0$) has been proposed in [Yang2016]. The HONDO not only inherits all the advantages of the usual NDO, but also guaranteed the convergence of the estimated error for a nonlinear system with a fast time-varying disturbance. In [Zhang2018], the stochastic DOB based on pole placement and LMI has been constructed to estimate disturbance which is generated by an exogenous system.

[Chen2014] has been discussed DOB for linear system in the context of optimal robust observer design. [Rubio2014] describes a scheme where both states and disturbances are observed and thereby a disturbance rejection controller has been constructed. Here again, the plant model is linear. [Wei2009a] describes an active disturbance rejection control scheme involving a DOB and sliding mode controller for MIMO nonlinear systems. However, it restricts the disturbance types to be norm bounded and having harmonic components which is essentially an improvement and extension to [Chen2004]. [Yang2012] applied a MIMO DOB for cancelling disturbances in a nonlinear control problem. The DOB employed is derived from [Chen1999] and [Chen2000].

2.4.4 DOB for high frequency measurement noise estimation

In recent papers [Jo2013, Jo2016, Kim2015, Xie2010, Zhang2015a] DOBs have been used for high frequency measurement noise estimation. In [Jo2013], a Modified DOB has been proposed for a SISO system without time delay; presented a necessary and sufficient condition for robust stability of the actual closed-loop system. This MDOB can attenuate high frequency measurement noise. In a recent paper [Jo2016], Noise- Suppression DOB has been used in order to achieve disturbance suppression as well as noise reduction. A discrete-time nonlinear damping back-stepping controller with an extended state observer have been used in [Kim2015] to track the desired output and to compensate low-frequency broad-band disturbances; also a narrowband DOB has been constructed for rejecting narrowband high-frequency disturbances. Thus, both broad-band disturbances at low frequencies and narrow-band disturbances at high frequencies have been compensated simultaneously in [Kim2015]. In [Zhang2015], a Double Disturbance Observer (DDOB) structure has been proposed to handle time delay, external disturbance, and measurement noise simultaneously. In the presence of external disturbance and sensor noise exist in discrete time systems, disturbance observers (DOBs) and baseline controller designs have been explained.

2.5 Internal Model Control (IMC)

Internal Model Control is one of the well known Model Based Controls [Agachi2006, Ansari2000, Berber1995, Berber1998, Van den Hof2009], where model is explicitly used in designing the controller. Possibly, IMC has been first introduced in [Garcia1982]. [Morari1989] is a compendium on IMC. IMC has the capability of both process disturbance [Zhang2016] and measurement disturbance [Morari1989] rejection. In [Brosilow2002], controller design mechanisms for 1-DOF, 2-DOF IMC controller have been demonstrated. Moreover, Internal Model controller design for time delay systems also has been presented in [Brosilow2002]. In [Datta1998], adaptive Internal Model Control has been depicted. A note on stability analysis of discrete-time IMC which is subject to saturation and a bounded uncertainty has been explained in [Choo2017]. A survey of internal model control has been reported in [Saxena2012]. But IMC methods for unstable, integrating with dead time, MIMO or nonlinear systems were not covered extensively; so, further investigation is required in this area. A detailed review on IMC has been done on the following subsections.

2.5.1 IMC for linear SISO system

Murad et. al. has introduced an internal model control (IMC) design procedure for synthesizing two degrees-of-freedom (2-DOF) IMC controllers in an H_∞ optimization framework in [Murad1996]. To improve the robustness and disturbance rejection performance of control system, a 3DOF control design algorithm that extended from IMC, has been proposed in [Wang2006]; the used controller for disturbance rejection has been designed according to sensitivity function of the 3DOF control system. The process of tuning the parameters of the technique [Wang2006] is straight forward.

A modified IMC structure has been proposed for unstable processes with small time delays in [Tan2003]. Here, a method has been proposed to tune the modified IMC structure with an emphasis on the robustness of the structure. An advantage of this structure is that setpoint tracking and disturbance rejection can be designed separately. Again, an improved internal model control based on optimal control has been reported for stable as well as unstable system with dead time in [Ogawa2013].

Internal Model control has been applied for Linear Parameter Varying (LPV) systems in [Kulcs´ar2014, Peng2013]. A novel impulse response parameter based solution for IMC within the linear parameter varying framework has been reported in [Kulcs´ar2014]. Based on a discrete-time state-space representation, a finite horizon vector autoregressive model with exogenous disturbance (VARX) has been obtained to describe the I/O relationship of an affine LPV plant. In [Peng2013], a novel internal model based robust inversion feed-forward and feedback 2DOF control approach has been proposed for LPV system with disturbance. Initially an optimal internal model based disturbance compensator for LPV system has been designed with external disturbance by H synthesis; then robust inversion based feed-forward control and feedback controller combined with internal model based compensation loop have been designed. Robust stability synthesis of a class of uncertain parameter-varying first-order time-delay systems has been presented in [Dezfuli2016]. Here, internal model principle has been used to design a robust control using H_∞ small-gain theorem.

IMC-PID control has been presented in [Bettayeb2014, Maâmar2014, Xiaochen2014]. Based on the IMC paradigm, a new approach has been developed in [Bettayeb2014], to design simple fractional-order controllers to handle fractional order processes. In [Maâmar2014], a simple analytical PID-fractional-filter-controller design method has been presented based on the IMC paradigm for integer order processes. The proposed PID-fractional-filter has been composed of an integer order PID cascaded with a fractional filter. In [Xiaochen2014], a transfer function matrix for an air-conditioned room temperature and relative humidity control system has been modelled as a 2X2 system with multiple time delay and IMC-PID controller has been designed.

[Nguyen2014] extended a data-based controller tuning method by utilizing Fictitious Reference Iterative Tuning (FRIT) in the IMC framework. With the combination of the Laguerre expansion, it has been shown its validity for the case of non-minimum phase systems without any information of the number of unstable zeros and or time delay.

To overcome the difficulty of applying IMC for integrating process, an alternative IMC implementation has been proposed in [Chia2010], where the integrator in the model was approximated by a first-order lag with a very large time constant; zero steady-state error for setpoint changes and process disturbance inputs have been assured.

2.5.2 IMC for linear MIMO system

IMC has been extended to MIMO systems in [Economou1986, Garcia1985]. Internal Model

Control for linear MIMO systems has been documented in some literature [Chen2011, Garrido2014, Jin2014]. In [Chen2011], a method using IMC has been proposed to design Smith delay compensation decoupling controller for multivariable non-square systems consisting of first order plus time delay elements. Based on Centralized Inverted Decoupling Controller, a tuning methodology has been proposed in [Garrido2014] for a square multivariable process with multiple time delays using IMC strategy. Additionally, a diagonal filter has been added to get better disturbance rejection. For square and non square systems with multiple time delays, a MIMO IMC method based on Double-Decomposition (which includes Full Rank Decomposition and Singular Value Decomposition) has been proposed in [Jin2014]. In [Wang2002], an approach to the decoupling Internal Model Control (IMC) analysis and design based on model reduction procedure has been proposed for multivariable stable processes with multiple time delays. Another method based on Linear Matrix Inequality (LMI) for designing multivariable internal model control has been proposed in [Yang2005].

In [Liu2006], a decoupling IMC scheme has been proposed for a 2X2 process with time delay. [Chen2007] proposed an analytical design and tuning method for the multivariable controller for stable, linear, MIMO process with multiple time delay and non-minimum phase zero.

2.5.3 IMC for nonlinear system

IMC has been extended for nonlinear system in [Economou1986, Henson1991]. Here, Hirschorn inverse of the system has been used while designing the controller. In [Fang2011], a new control strategy by combining an inverse system method and internal model control has been proposed. The compensation filters and the 2-DOF IMC were designed for the linearized plant of highly nonlinear, multivariable and strongly coupled Single-Gimbal Magnetically Suspended Control Moment Gyro (SGMSCMG) system. Similar kind of work as in [Fang2011] has been presented in [Fang2012]. A robust Nonlinear IMC (NIMC) of stable Wiener System (a stable linear system followed by a static nonlinearity) has been reported in [Kim2012]. Here, a NIMC has been proposed using LMI feasibility or optimization problems. In [Qiu2014], nonlinear IMC of wastegate control of a turbocharged gasoline engine has been reported and extended the inverse-based IMC design for LTI systems to nonlinear systems. A new approach for nonlinear inverse, referred to as the structured quasi-LPV model inverse, has been developed. In [Karnik2012], nonlinear IMC of wastegate control of a turbocharged gasoline engine has been reported. Here, an approximate data driven first order model has been constructed to ease inversion process. In [Zhou2014], the inverse system method combined with the 2DOF IMC has been proposed to deal with the nonlinearity and coupling of the two-axis Inertially Stabilized Platform (ISP). After designing the inverse system, a pseudo-linear system has been constructed. The coupled nonlinear MIMO system has been converted to two linear decoupled SISO subsystems. In [Shi2010], based on Inverse control method, an IMC has been used to control highly nonlinear ship motion simulation bench with strong disturbance. The internal model controller has been designed by transforming the nonlinear system to a pseudo-linear system, based on the nonlinear inverse system method.

2.5.4 IMC for Anti-windup cases

IMC has been documented in Anti-windup cases in [Adegbege2011, Wu2011, Morales2011, Heath2011, Adegbege2011a, Adegbege2011b]. The thesis [Adegbege2011] was concerned with the development of control strategies for multivariable systems which systematically account for actuator constraints while guaranteeing closed loop stability as well as graceful degradation of non-linear performance. A novel anti-windup structure has been proposed which combines the efficiency of conventional anti-windup schemes with the optimality of MPC algorithms. The paper by [Wu2011], considered the synthesis of an antiwindup compensator which comprised of an IMC antiwindup compensator and a linear antiwindup compensator, for stable linear plants subject to input saturation.

Two conditions for robustness preserving anti-windup against LTI and norm-bounded uncertainty have been presented in [Morales2011]. This has been characterised a set of robustness-preserving anti-windup controllers expressed in terms of the Zames-Falb conditions.

In [Heath2011], some examples have been given where anti-windup structures other than the IMC anti-windup structure preserve robustness. A multivariable case has been considered where the IMC anti-windup structure does not guarantee robustness preservation against output multiplicative uncertainty. The effectiveness of the two-stage IMC anti-windup in dealing with the performance degradation associated with control windup and process directionality in input-constrained multivariable systems has been demonstrated in [Adegbege2011a]. The paper [Adegbege2011b] presented a multivariable optimizing anti-windup design which guarantees closed-loop stability while compensating for both windup and directionality change in the control input vector.

Some recent publications on application based IMC are [Bazaei2016, Kere2016, Qiu2016, Sun2016, Zhu2016]. In [Bazaei2016], application of IMC has been documented for accurate tracking of spiral scan trajectories. The plant is a 2-D micro electromechanical system nanopositioner equipped with in situ differential electro-thermal sensors and electrostatic actuators. An adaptive internal model controller for a Hydrogen-based Generator (HG) has been designed in [Kere2016]. Composite Adaptive IMC (CAIMC), which is an IMC structure with simultaneous identifications of the forward and the inverse models, has been analyzed in [Qiu2016]. In [Sun2016], a decoupling control scheme consisting of inverse system method and the internal model control has been proposed in order to improve the control properties of high-precision, fast-response, and strong-robustness for the bearing-less permanent magnet synchronous motor (BPMSM) system. A method of two-degree-of-freedom (2DOF) IMC strategy of induction motors using the Immune Algorithm (IA), has been proposed in [Zhu2016].

2.6 Active Anti-Disturbance Control (AADC) (Using DOB)

Existing literatures on AADC has been documented in this section. In this area, [Guo2014a] and [Li2014] are important resources. In the papers of [Guo2014] and [Guo2014a], there have been reported several Anti-Disturbance Control strategies for multiple disturbance cases. In [Li2014], different types of DOB based control methods have been documented. It has been noted that different types of control methodologies such as H_∞, PID, MPC, adaptive control and variable structure control have been individually combined with Disturbance Observer Based Control (DOBC) and reported in [Li2014, Guo2014, Guo2014a] but combined use of IMC and DOB have not been mentioned in those resources. As feedback control part several controllers have been used with feed-forward DOB part, the possible combinations are given below in subsequent sections.

2.6.1 PID control approach

In [Chen2009], PID and DOB have been integrated and used in a linear Ball Mill Grinding Circuit which is a multivariable system with multiple time delay. In nonlinear cases, combined use of PID and DOB has been documented in [Wen2010] and [Liu2012a]. In [Wen2010], a hierarchical anti-disturbance strategy has been designed using DOB and PID controller for a class of robotic nonlinear systems. In [Liu2012a], a composite controller has been designed with a hierarchical architecture by combining DOBC and PD control for attitude control of flexible spacecrafts in the presence of model uncertainty, elastic vibration and external disturbances. For all the above cases, the end result is successful disturbance rejection.

2.6.2 Internal Model Control approach

Only a handful of publications deal with IMC and DOB while designing AADC for linear systems. In [Chen2011a, Qibing2015, Zhang2016], IMC and DOB have been combined for linear systems. In [Chen2011a], measurement disturbance attenuation has been obtained for SISO time delay system. In [Qibing2015], external disturbance and internal disturbance caused by process-model mismatch have been attenuated for SISO time delay system. In [Zhang2016], process disturbance has been attenuated for MIMO with multiple time delay system (stable as well as unstable cases). For nonlinear AADC design, IMC and DOB have not been combined yet.

2.6.3 Sliding Mode Control approach

A control scheme combining the DOBC with Terminal Sliding Mode (TSM) control has been proposed for a class of multiple-input–multiple-output (MIMO) continuous non-linear systems subject to disturbances in [Wei2009]. In [Chen2010], a disturbance observer based adaptive sliding mode controller has been proposed for a class of uncertain nonlinear systems. In [Jihong2012], a sliding mode control via backstepping scheme and nonlinear DOB has been used.

In [Xu2016], by applying DOB as the feed-forward compensator and the Non-singular Terminal Sliding Mode Control (NTSMC) as the feedback controller, a new composite NTSMC scheme has been proposed for the speed control of Permanent Magnet Synchronous Motor (PMSM) under disturbances and uncertainties with small chattering since smaller switching gain are required by the proposed scheme. A Disturbance Observer Based Integral Sliding-Mode Control approach for continuous-time linear systems with mismatched disturbances or uncertainties has been proposed in [Zhang2016a].

2.6.4 H_∞ Control Approach

In [Wei2010], DOBC and H_∞ control have been compositely used for a class of nonlinear continuous systems and disturbances have been attenuated. The disturbances have been divided into two parts: a norm-bounded vector and another one described by an exogenous system with perturbations. Again, a composite methodology using DOBC control plus H_∞ control has been proposed for Markovian jump systems with nonlinearity and multiple disturbances in [Yao2013]. In [Zhang2018], DOBC and H_∞ control have been used together and an elegant anti-disturbance control has been proposed for a class of stochastic systems with nonlinear dynamics and multiple disturbances.

2.6.5 Model Predictive Control (MPC) Approach

In [Yang2011], disturbance rejection (both external and lumped disturbance) has been shown for a SISO time delay system using MPC and DOB. In [Yang2010], MPC and DOB have been used to achieve disturbance rejection of Ball Mill Grinding system (TITO system with multiple time delay). In [Zhou2012], again MPC and DOB have been combined for MIMO systems with time delay and non-minimum phase part (Grinding circuit). It has been shown that both input and output disturbance rejection have been superior than using MPC alone.

2.6.6 Back-stepping Control Approach

A control scheme combining the disturbance-observer-based control (DOBC) with terminal sliding mode (TSM) control was proposed for a class of multiple-input–multiple-output (MIMO) continuous non-linear systems subject to disturbances in [Wei2009]. In [Chen2010], a disturbance observer based adaptive sliding mode controller has been proposed for a class of uncertain nonlinear systems. In [Jihong2012], a sliding mode control via back-stepping scheme and nonlinear DOB have been used. In [Yang2016a], using the adaptive internal model principle and observer backstepping technique, a new composite output feedback controller has been developed for multiple disturbance estimation and compensation. The output feedback control design problem of a class of non-linear systems subject to multiple sources of disturbances/uncertainties including model uncertainties, constant and harmonic external disturbances have been investigated in this paper.

For nonlinear system subjected to disturbance (generated by an unknown exogenous system) [Han2016] designed observers to estimate the system state and disturbance simultaneously. Using the estimation information, an observer-based dynamic output feedback controller has been designed.

2.7 Findings from the Survey

This literature survey about Disturbance Observer Based Control (DOBC) and related methods enabled the present worker to short list the techniques which could be used for the task of DOBC, specifically Active Anti-Disturbance Control (AADC). Disturbance Observers (DOBs) are increasingly being suggested as a necessary component in AADC. This survey also helped to identify the areas of feedback and feed-forward part which would be useful for AADC. Literature in Internal Model Control (a Model Based Control) and Disturbance Observer have also been reviewed in separate sections. Hence, a Modified Active Anti Disturbance Control could be designed.

This review has helped the present worker to appreciate the extent of work already done by various individuals and groups. Availability of some text books and survey papers helped to appreciate the evolution of the subject and the degree of maturity attained.

2.7.1 Analysis of knowledge Gaps and identification of the areas of research

From the literature survey as above, a number of gaps in knowledge have been identified. Further paucity of literature in a few areas indicated that further investigation in these areas are required. On the basis of this, the following areas have been identified for contribution in the present work and the findings are incorporated in the dissertation.

- Though the structure and design pragmatics of DOBs for linear systems are well known, very few publications deal with DOB for nonlinear systems.
    - DOB structures for nonlinear systems proposed in previous literature are found to be based on conventional observer gain based approach [Li2014]. Further most of these previous publications assume the availability of state variables. The above provides an impetus to find alternative structures and approach (avoiding use of state variables if possible) to DOB for nonlinear systems.

   - The available DOB's applicable for nonlinear systems have been developed assuming specific disturbance waveform like sine wave and polynomial functions. Therefore, a possible research area would be to avoid such assumptions.

- No existing research work on nonlinear Active Anti-Disturbance Control (AADC) involving DOB and IMC has been found in literature.

Moreover, these gaps have been the motivations of the current work presented in this dissertation.

From the comprehensive thematic reviews of the existing literature survey chapter, the above conclusive remarks can be made. Moreover, these findings have been the motivations of the current work presented in this dissertation.

PART-B:

Active Anti-Disturbance Control Applied for Linear SISO Systems

Chapter 3: Perspectives of Active Anti-Disturbance Control for linear SISO system

3.1 Chapter Introduction

Perspectives of Active Anti-Disturbance Control (AADC) for linear SISO system have been presented in this chapter. As rest of the discussion and the methodologies developed are dependent on this chapter, case studies are introduced so that readers may be initiated with the central idea of the proposed methodology in subsequent sections. In this chapter, case study for AADC has been done for linear system presented in transfer function form. Additionally, AADC has been done for a linear system (in state space form) using Hirschorn Inverse and comparison with IMC has been obtained for both the cases. The contribution of this chapter is that an alternative formulation of AADC has been proposed by designing DOB and IMC using Hirschorn Inverse for linear SISO system which is in state space form.

3.2 Methodology using IMC and DOB

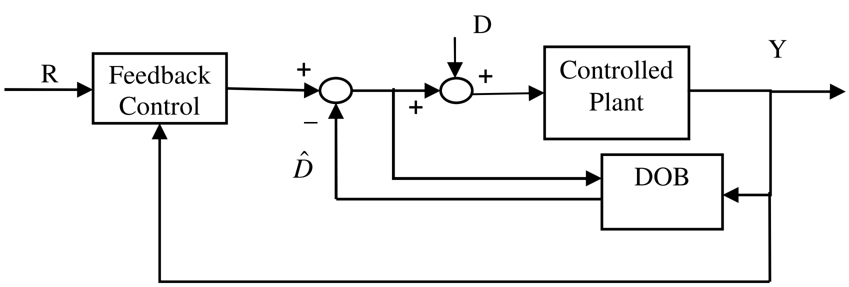
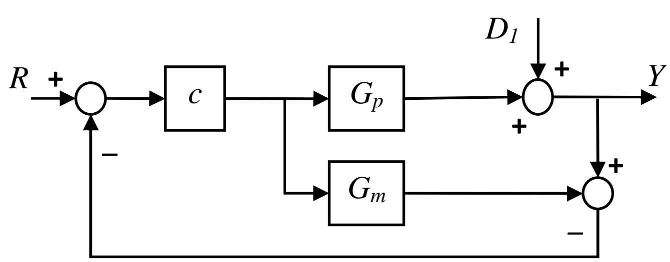


FIG.-3.2. 1: BASIC FRAMEWORK OF AADC

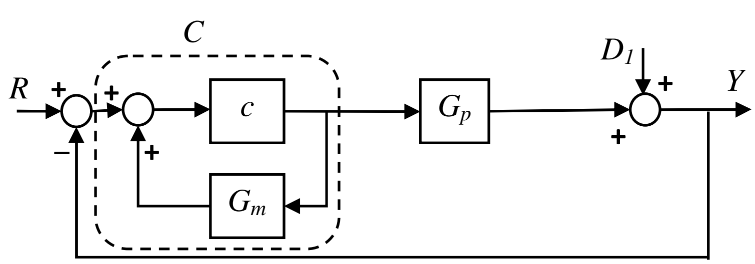
Basic framework of AADC is shown in Figure- 3.2.1, which is a two degree of freedom control structure: controller as feedback control and DOB as feed-forward control. In this work, Internal Model Control has been used as feedback control which has been compositely used with DOB.

3.2.1 General Comments about IMC Controller Design for linear SISO without time delay systems

IMC is a method of implementing controllers in which the process model is explicitly an internal part of the controller. The generic structure of IMC [Morari1989] is shown in Figure-3.2.2(A), where G_p, G_m, c denote Process, Model and Internal Model Controller respectively. Controller, $c = G_m^{-1}Q_1$ where Q_1 represent low pass filter. Here, Q_1 can be designed with suitable order such that realization problem can be avoided. Additionally, filter time constant can be tuned to get robustness of the system. Signals *R*, D_1, *Y* represent set-point, measurement disturbance and output respectively. In some literature, IMC has been used to attenuate process disturbance [Zhang2016] also.



(A)



(B)

FIG.-3.2. 2: LOCK DIAGRAM OF IMC STRUCTURE (A) SCHEMATIC DIAGRAM (B) IN UNITY FEEDBACK FORM

In both the forms, inversion of the model is required whereas for linear plants the (approximate) inversion process is well-known [Morari1989, Brosilow2002].

IMC structure can be converted into unity feedback control loop as in Figure-3.2.2B, where, $C\ (s)=\dfrac{c(s)}{(1-c(s)G_m(s))}$.

From Figure-3.2.2(A), the relation between input, output and measurement disturbance is given by:

$$Y(s)=\frac{G_p(s)c(s)}{[1+c(s)(G_p(s)-G_m(s))]}R(s)+\frac{1-c(s)G_m(s)}{[1+c(s)(G_p(s)-G_m(s))]}D_1(s) \tag{3.2.1}$$

When the model is exact representation of process i.e. $G_m(s)=G_p(s)$,

(3.2.1) Simplifies to, $Y(s)=G_p(s)c(s)R(s)+[1-G_p(s)c(s)]D_1(s)$ (3.2.2)

Now, to improve robustness, the effects of process model mismatch should be minimized. Since, discrepancies between the process and model behaviour usually occur at the high frequency end of the system's frequency response, a low-pass filter $Q(s)$ is usually added with the controller part say, $G_c(s)$ to attenuate the effects of process model mismatch. Here, $G_c(s)=G_m^{-1}(s)$.

i.e. $c(s)=G_c(s).Q_1(s)$. Thus, the internal model controller (c) is usually designed [Brosilow2002] as the inverse of the process model in series with a low-pass filter. The order of the filter is chosen such that $G_c(s).Q_1(s)$ is proper.

3.2.2 General Comments about DOB Design for linear SISO without time delay systems

Disturbance Observer design for linear system without time delay has been found in (a) frequency domain [Chen2009] and (b) time domain (e.g., fig 2.6 in [Li2014]). DOB in frequency domain has been depicted in [Chen2009, Li2014]. It may be noted in [Chen2009] that both external and internal disturbance (due to process model mismatch) can be estimated. In [Zhou2012, Zhou2014], the structure for DOB has been shown where the process disturbance and measurement disturbance have been rejected by DOB designed for linear MIMO time delay systems.

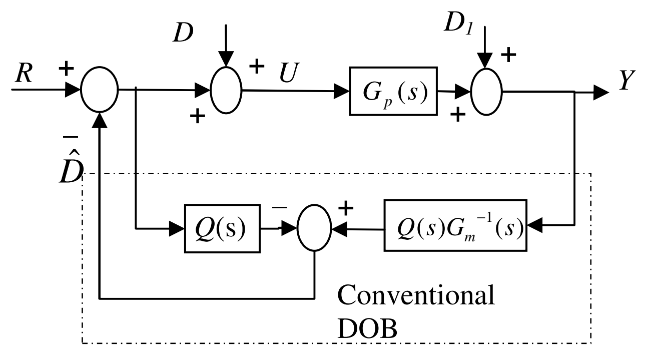


FIG.-3.2. 3: DISTURBANCE REJECTION USING LINEAR DISTURBANCE OBSERVER IN FREQUENCY DOMAIN

In frequency domain, the structure of DOB has been represented as a part of Figure-3.2.3 [Zhou2012]. Here, $G_p(s)$, $G_m(s)$, $Q(s)$ denote process, nominal model and low-pass filter respectively. Also, signals R, U, D, D_1, $\hat{D}$, Y represent command of the controller (but controller has not been shown in the figure), manipulated variable, process disturbance, measurement disturbance, estimated disturbance and output respectively.

From Figure-3.2.3, the relationship between output Y, command of the controller R, process disturbance D and measurement disturbance D_1 can be written as

$$Y(s) = G_{YR}(s)R(s) + G_{YD}(s)D(s) + G_{YD_1}(s)D_1(s) \qquad (3.2.3),$$

Where, $G_{YR}(s) = \dfrac{G_p(s)G_m(s)}{G_m(s) + (G_p(s) - G_m(s))Q(s)}$; $G_{YD}(s) = \dfrac{G_p(s)G_m(s)(1-Q(s))}{G_m(s) + (G_p(s) - G_m(s))Q(s)}$;

$$G_{YD_1}(s) = \frac{G_m(s)(1-Q(s))}{G_m(s) + (G_p(s) - G_m(s))Q(s)}$$

Usually, $Q(s)$ is designed as a low-pass filter with steady state gain 1. In low frequency domain $Q(s)$ approaches to 1. So, $G_{YR}(s) = G_m(s)$; $G_{YD}(s) = 0$; $G_{YD_1}(s) = 0$. Thus, it can be said that both process and measurement disturbance can be attenuated by selecting proper $Q(s)$.

3.2.3 General Comments about Noise Reduction DOB (NR-DOB) Design for linear SISO without time delay systems

In this section, AADC has been considered for linear SISO system without time delay in Figure-3.2.4 where high frequency measurement noise (n) attenuation has been done along with process disturbance. For that purpose, Noise Reduction DOB (NR-DOB) has been formulated [Jo2013]. In Figure-3.2.4, set-point is *R*, process disturbance is *D*, and high frequency measurement noise is *n* and *C* is the usual feedback controller. It can be shown that measurement disturbance can also be attenuated using this structure; a case study has been introduced on that aspect.

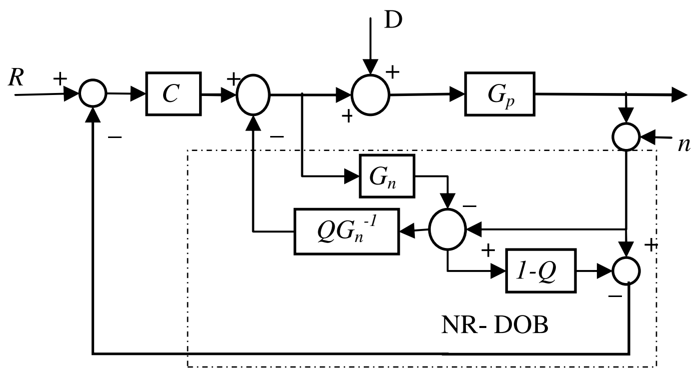


FIG.-3.2. 4: BLOCK DIAGRAM OF AADC FOR SYSTEMS WITH NR-DOB WITHOUT TIME DELAY

3.2.4 Proposed AADC for linear system without time delay and in state space form

In this Section, AADC has been proposed using IMC and DOB for linear system (without delay) which is in state space form. As inverse of model is required for both the cases of designing IMC and DOB, Hirschorn Inverse for linear system in state space form [Henson1997] has been computed.

3.2.4.1 Hirschorn Inverse for linear System

A linear SISO system is represented as

$$\begin{aligned} \dot{\mathbf{x}} &= A\mathbf{x} + bv \\ y &= c\mathbf{x} \end{aligned} \qquad (3.2.4),$$

where $\mathbf{x}$ is an n dimensional state vector, y is a scalar controlled output and $v = u + D$ is a scalar manipulated input. The equivalent disturbance at the input of the plant is denoted by *D*. The duty of the disturbance observer is to estimate the disturbance ($\hat{D}$) as closely as possible. The DOB is shown in Figure-3.2.5.

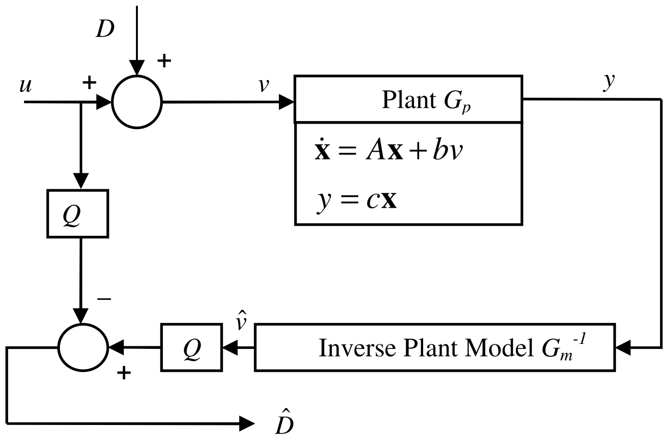


FIG.-3.2. 5: BLOCK DIAGRAM OF DISTURBANCE OBSERVER FOR LINEAR SYSTEMS IN STATE SPACE FORM

From (3.2.4),

$$\dot{y} = \frac{\partial h}{\partial \mathbf{x}}[A\mathbf{x} + bv] \tag{3.2.5}$$

If the right hand side of equation (3.2.5) contains a term involving the input v, by definition, the relative degree is 1. In case the right hand side does not contain any term involving the input v, i.e., $\dot{y} = cA\mathbf{x}$, successive differentiation is to be carried out till the term $cA^{r-1}b$ becomes non-zero. When this is obtained, by definition, the relative degree is r.

At such a step, equation of $y^{(r)}$ with non zero coefficient of v becomes

$$\frac{d^r y}{dt^r} = cA^r\mathbf{x} + cA^{r-1}bv \qquad (3.2.6),$$

where, r is relative degree.

The relative degree of the system is the integer r for which $cA^{r-1}b \neq 0$.

Here, $v = \dfrac{\dfrac{d^r y}{dt^r} - cA^r\mathbf{x}}{cA^{r-1}b}$.

Inverse for linear system in state space form has been represented as [Henson1997],

$$\dot{\mathbf{z}} = \left(A - \frac{bcA^r}{cA^{r-1}b}\right)\mathbf{z} + \frac{b}{cA^{r-1}b}\frac{d^r y}{dt^r}$$

where, $\hat{v} = -\dfrac{cA^r}{cA^{r-1}b}\mathbf{z} + \dfrac{1}{cA^{r-1}b}\dfrac{d^r y}{dt^r}$

After getting inverse, suitable low pass filter has been added to design both Internal Model Control as shown in Figure-3.2.2 and DOB as proposed in Figure-3.2.5. By combining IMC and DOB, AADC has been designed as shown in Figure-3.2.6.

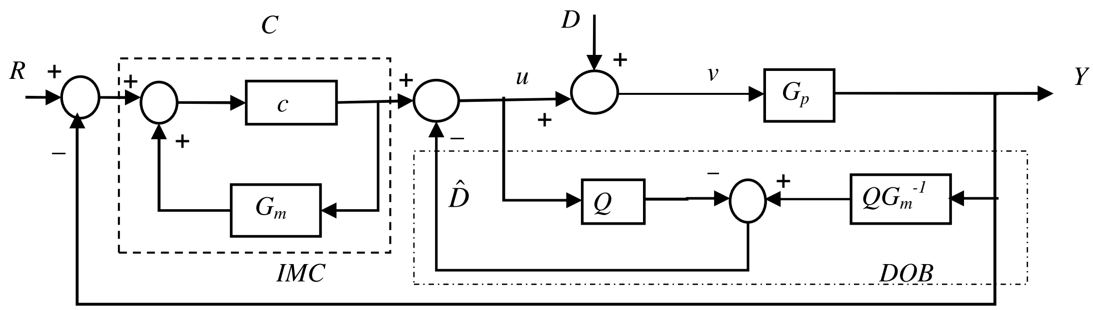


FIG.-3.2. 6: ***AADC (USING IMC AND DOB) WITH PROCESS DISTURBANCE***

3.3 Case Study 1 -- Test Problem-A

An Active Anti-Disturbance Control (AADC) has been designed for a Test Problem-A. Firstly, adverse effect of external disturbance has been prevented. For that purpose, an Internal Model controller has been integrated with a Disturbance Observer (DOB). Secondly, an IMC has been used with Noise Reduction DOB (NR-DOB) which can suppress high frequency measurement noise effect as well as measurement disturbance. Different set-point tracking and disturbance rejection (including high frequency measurement noise) have been considered to show the effectiveness of the AADC method over ordinary IMC based systems. Additionally, comparison has been done between AADC using conventional DOB and AADC using NR-DOB.

3.3.1 Plant model and Controller Design

Generic block diagram of the Test Problem-A has been represented in Figure-3.3.1.

Here, λ: Set-point, D_1: External measurement disturbance, y_1: Output.

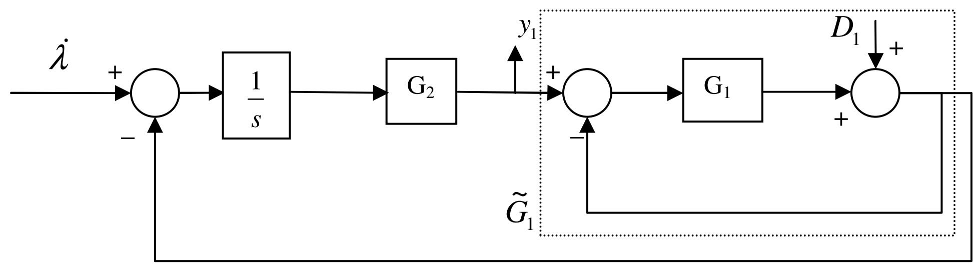


FIG.-3.3.1: BLOCK DIAGRAM OF TEST PROBLEM-A

In Figure-3.3.1, the relevant transfer functions are $G_1 = \dfrac{w_c}{s\left(1+\dfrac{s}{w_c}\right)}$; $G_2 = \dfrac{K_T}{(1+sT_s)}\cdot\dfrac{(s+w_L)}{(s+0.1w_L)}$

where $K_T = \dfrac{w_c}{\gamma}$.

Let, the closed loop transfer function of the dotted loop in Figure-3.3.1,

$$\tilde{G}_1 = \frac{G_1}{(1+G_1)} = \frac{w_c}{s\left(1+\dfrac{s}{w_c}\right)+w_c}$$

Overall closed-loop transfer function

$$\breve{G}_2 \equiv \frac{(\tilde{G}_1 G_2 / s)}{(1+\tilde{G}_1 G_2 / s)} = \frac{w_c K_T (s+w_L)}{[s(1+s/w_c)+w_c](1+sT_s)(s+0.1w_L)s + w_c K_T (s+w_L)}$$

Now, From Figure-3.3.1, $\dfrac{y_1}{\dot{\lambda}} = \dfrac{G_2/s}{1+\tilde{G}_1 G_2/s} = \dfrac{\breve{G}_2}{\tilde{G}_1}$ and $\dfrac{y_1}{D_1} = -\dfrac{\tilde{G}_1 G_2/s}{1+\tilde{G}_1 G_2/s}\cdot\dfrac{1}{G_1} = -\dfrac{\breve{G}_2}{G_1}$ which has been represented in Figure-3.3.2.

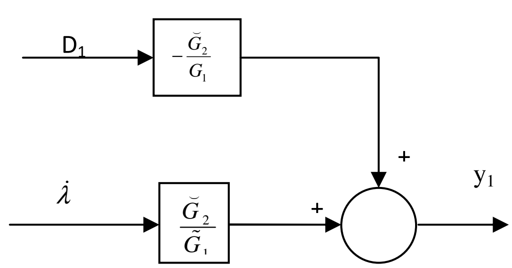


FIG.-3.3.2: EQUIVALENT PLANT OF TEST PROBLEM-A

Now, $\dfrac{y_1}{\dot{\lambda}} = \dfrac{K_T(s+w_L)(s^2+w_c s+w_c^2)}{s(s^2+w_c s+w_c^2)(s+0.1w_L)(sT_s+1)+K_T(s+w_L)w_c^2}$

and $\dfrac{y_1}{D_1} = -\dfrac{K_T(s+w_L)(s^2+w_c s)}{s(s^2+w_c s+w_c^2)(s+0.1w_L)(sT_s+1)+K_T(s+w_L)w_c^2}$

The parameters have been taken as w_c=150 rad/s; $w_L = w_c/20$; γ=5; $K_T = w_c/\gamma = 30$; $T_s = 1/30$ s.

$G_1(s) = \dfrac{150}{\frac{1}{150}s^2 + s}$; $G_2(s) = \dfrac{30s+225}{(0.03331s+1)(s+0.75)}$.

In Figure-3.3.3, response of the test problem has been shown. The input signal (a square wave of 0.2 rad/sec amplitude with 0.4 Hz frequency) has been superimposed on the same figure.

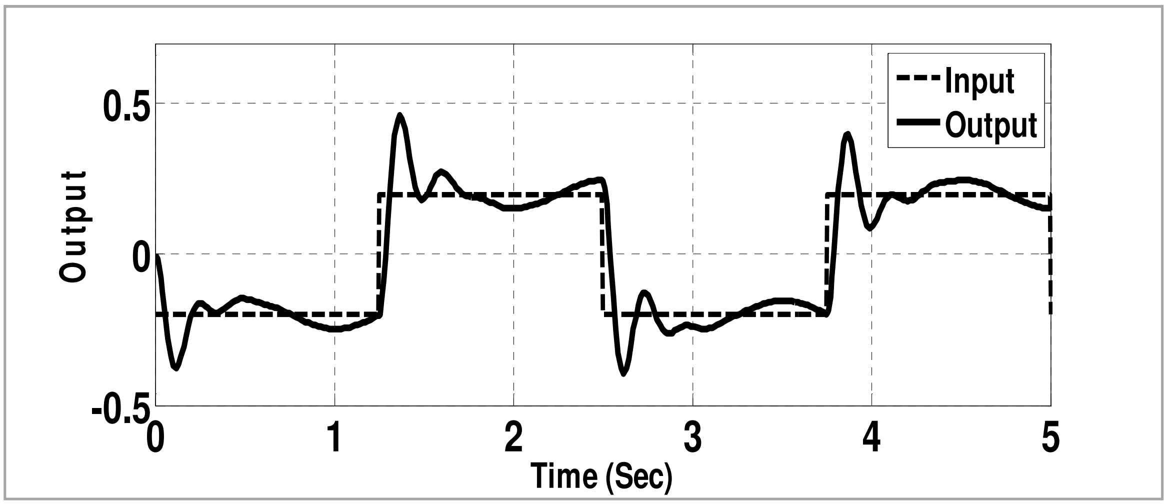


FIG.-3.3.3: RESPONSE OF THE TEST PROBLEM-A

From the Block Diagram, (Figure-3.3.2), $y_1 = \left(\dfrac{\breve{G}_2}{\tilde{G}_1}\right)\dot{\lambda} - \left(\dfrac{\breve{G}_2}{G_1}\right)D_1$.

Where from Figure-3.3.2, $G_D = \dfrac{y_1}{D_1} = -\dfrac{\breve{G}_2}{G_1}$ and $G_p = \dfrac{y_1}{\dot{\lambda}} = \dfrac{\breve{G}_2}{\tilde{G}_1}$

Disturbance transfer function matrix G_D has been considered in designing AADC.

According to the parameters mentioned above,

$$G_p(s) = \frac{30(s+7.5)(s^2+150s+22500)}{s(s^2+150s+22500)(s+0.75)(\frac{1}{30}s+1)+30(s+7.5).22500}.$$

Internal Model Controller $c = G_m^{-1}Q$

Where Q is low pass filter. To get the realizable controller, $Q(s)$ has been chosen as $\frac{1}{(\lambda s+1)^2}$,

where λ is a tuning parameter.

Here the filter time constant has been taken as 0.02. (Standard single loop design tool "sisotool" in Matlab control system Toolbox has been used to get the value.)

Here, we have assumed that the model G_m is an exact representation of the process G_p.

Active Anti-Disturbance Control using IMC and DOB has been shown in Figure-3.3.4.

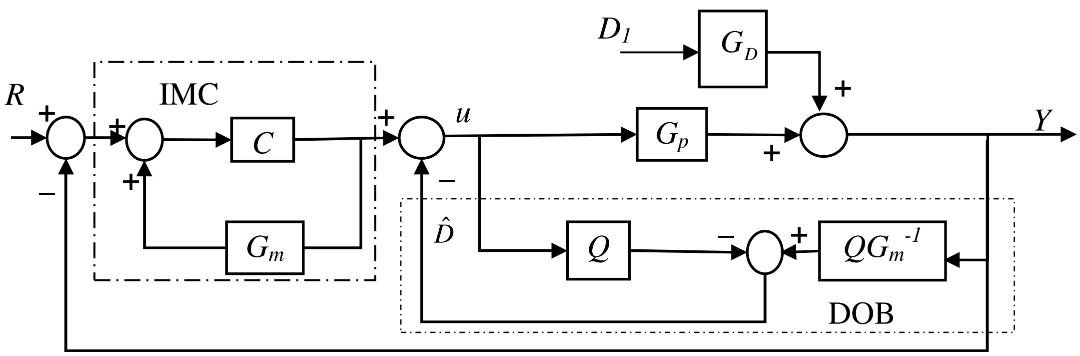


FIG.-3.3.4: AADC OF TEST PROBLEM WITH MEASUREMENT DISTURBANCE

3.3.2 Performance comparison between IMC Plus DOB approach over IMC approach

3.3.2.1 Disturbance Rejection and Set-point Tracking

Here, set-point ($\dot{\lambda}$) has been taken as a square wave of 0.2 rad/sec amplitude with 0.4 Hz frequency and external disturbance (D_1) as a sine wave of 1 rad/sec amplitude with 1 Hz frequency.

In Figure-3.3.5, performance comparison with and without using IMC has been done. In Figure-3.3.6, output y_1 of Test problem-A has been shown for both of the AADC and IMC cases. This has been shown that superior disturbance rejection has been obtained in case of AADC over IMC.

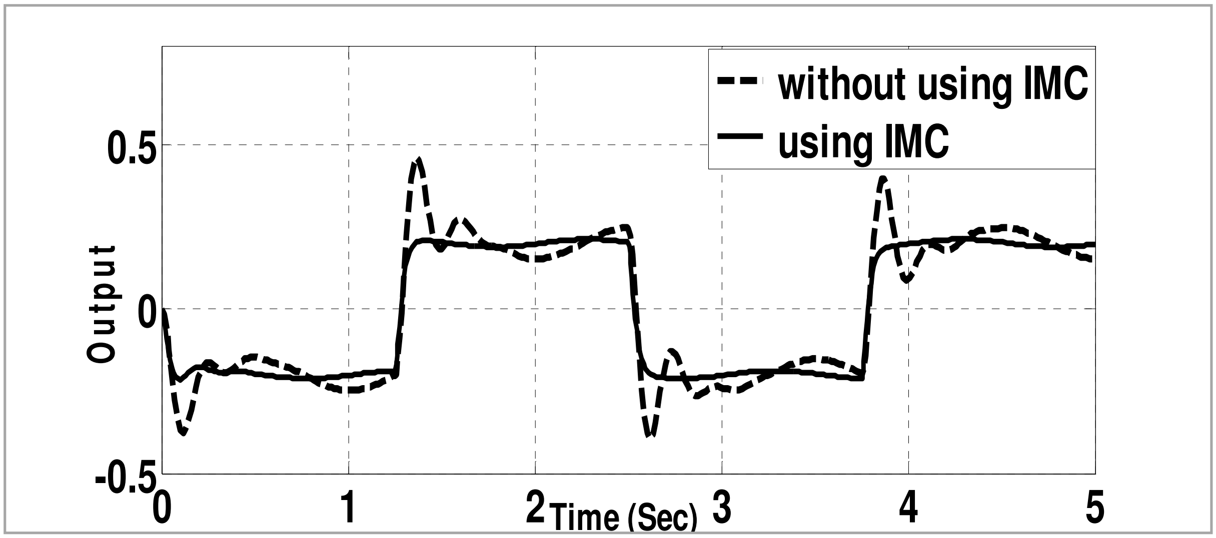


FIG.-3.3.5: PERFORMANCE COMPARISON WITH SQUARE REFERENCE INPUT AND SINUSOIDAL DISTURBANCE

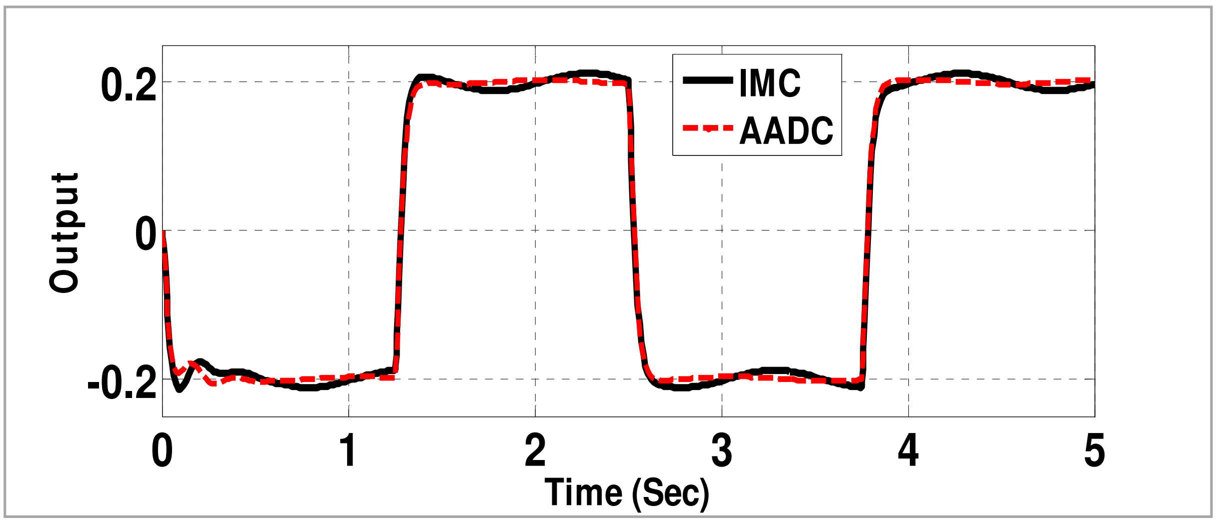


FIG.-3.3.6: PERFORMANCE COMPARISON BETWEEN AADC AND IMC

Additionally, as in Figure-3.3.4, an AADC has been designed by integrating IMC and conventional DOB with an extra measurement noise *n(t)*. Here, measurement noise has been considered as $n(t) = 10\sin(200\pi t)$. Set-point $\dot{\lambda}$ as a square wave of 0.2 rad/sec amplitude with 0.4 Hz frequency and measurement disturbance (D_1) as a sine wave of 1 rad/sec amplitude with 1 Hz frequency have been applied.

In Figure-3.3.7, poor noise suppression ability of the AADC using conventional DOB has been shown. The NR-DOB [Jo2013] has been presented in Figure-3.2.4.

First, it has been considered that $Q(s)=\dfrac{1}{(\lambda s+1)^2}$ where $\lambda = 0.02$

In the NR-DOB design, *Q(s)* has been redesigned as $Q(s)=\dfrac{1}{(\lambda s+1)^6}$ where $\lambda = 0.02$.

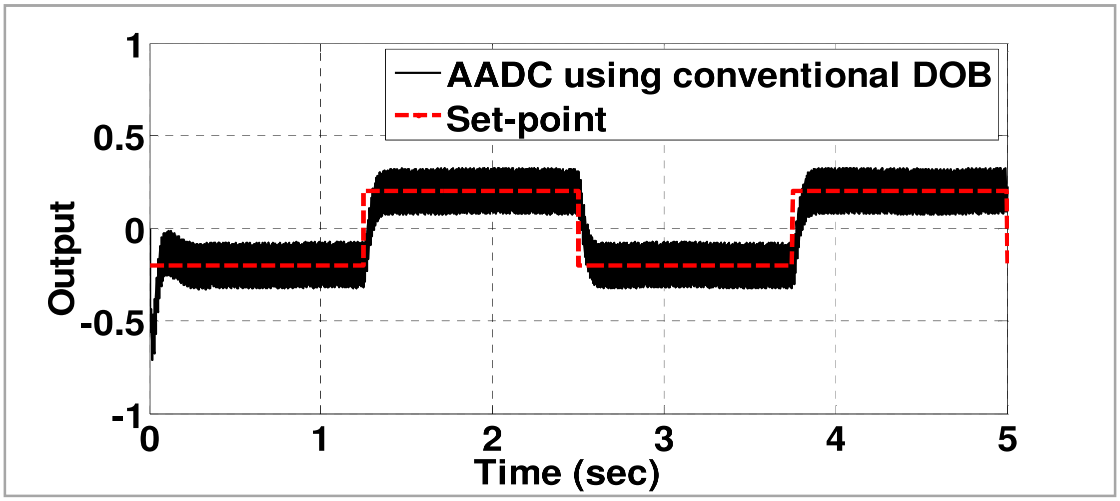


FIG.-3.3.7: NOMINAL PLANT RESPONSE FOR THE AADC USING CONVENTIONAL DOB IN THE PRESENCE OF DISTURBANCE AND MEASUREMENT NOISE $n(t)=10\sin(200\pi t)$

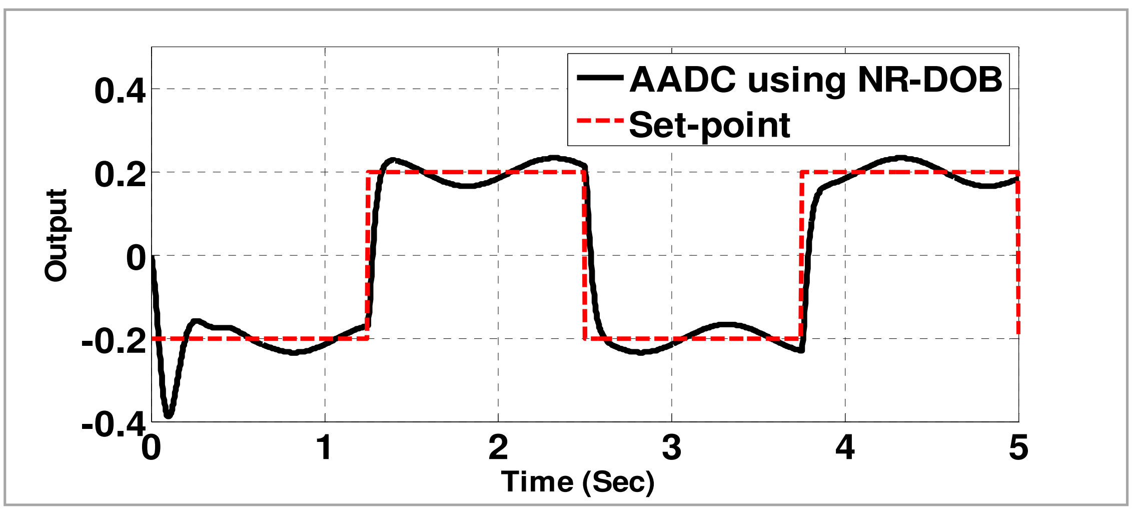


FIG.-3.3.8: NOMINAL PLANT RESPONSE FOR AADC USING NR-DOB IN THE PRESENCE OF DISTURBANCE AND MEASUREMENT NOISE

In Figure-3.3.8, it has been shown that high frequency measurement noise has been suppressed completely for AADC using NR-DOB. Also measurement disturbance has been attenuated successfully.

3.4 Case Study 2 -- Damped mass spring system

A second order Damped mass spring system has been used in state space model where process disturbance has been attenuated using AADC method. Performance comparison has been obtained with AADC and IMC.

3.4.1 Plant model and Controller Design

A damped mass spring system has been considered in this section. Where *u(t)* is an externally applied force, *v(t)* is the speed of the mass with respect to the wall inertial system and *q(t)* is the displacement from the wall. The governing differential equation is:

$$m\frac{d^2\mathbf{x}}{dt^2} + f\frac{d\mathbf{x}}{dt} + k\mathbf{x} = u$$

where $\mathbf{x} = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}$ represents position and speed of the body connected to the spring, m is the mass of the body, k is the spring constant, f is the damping coefficient, u represents the control force exerted on the mass.

The state space model is represented as:

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{f}{m} \end{bmatrix}\mathbf{x} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}u$$
$$y = \begin{bmatrix} 0 & 1 \end{bmatrix}\mathbf{x}$$

Where, $A = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix}; b = \begin{bmatrix} 0 \\ 1 \end{bmatrix}; c = \begin{bmatrix} 0 & 1 \end{bmatrix}$

For simplicity, the parameters have been taken as m=1 kg, k=1 kg/s^2, f=1 kg/s.

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -x_1 - x_2 + 1u$$
$$y = x_2$$

Clearly, relative degree of the above system is r=1.

The Hirschorn inverse system is

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \hat{v}$$

Where $\hat{v} = -\dfrac{cA^r}{cA^{r-1}b} z + \dfrac{1}{cA^{r-1}b} . \dfrac{d^r y}{dt^r}$

$$\hat{d} = \frac{dy}{dt} + z_1 + z_2 - u$$

Using Hirschorn inverse, both Internal Model Controller and DOB have been designed. Here, process disturbance has been considered.

For IMC, a low-pass filter with transfer function $\dfrac{1}{(3s+1)}$ and for DOB, low-pass filter transfer function $\dfrac{1}{(0.02s+1)}$ has been used.

3.4.2 Simulation Results

3.4.2.1 Performance comparison between AADC approach over IMC approach

A sinusoidal disturbance waveform with amplitude 0.5 and frequency 1/20 Hz has been considered as process disturbance. Reference signal has been considered as

$r(t) = -1; 0 \le t \le 40$

$= 1; 40 \le t \le 80$

$= -1; t \ge 80$

In Figure-3.4.1, output using IMC, output using AADC and set-point have been superimposed on a same figure. From Figure-3.4.1, it has been ensured that superior performance has been obtained for AADC over IMC.

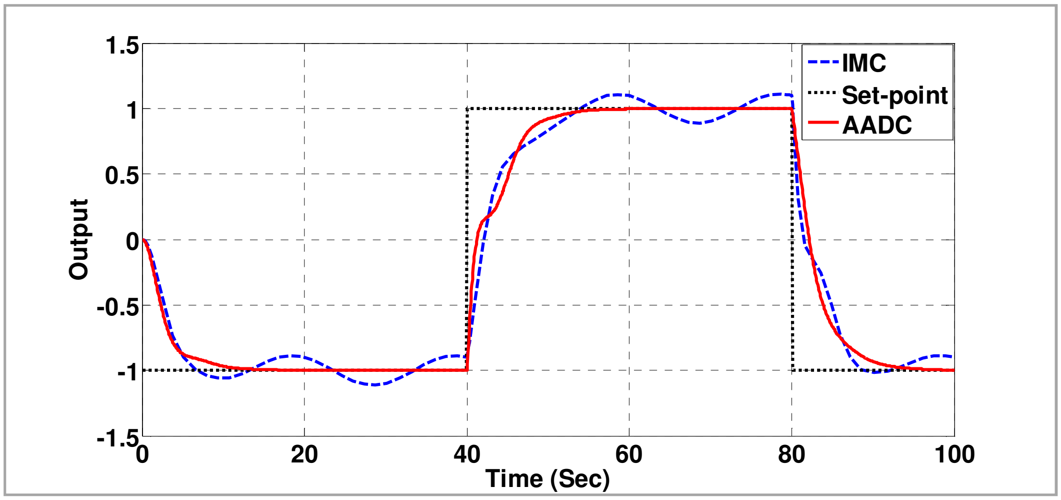


FIG.-3.4.1: PLANT RESPONSE WITH SINUSOIDAL PROCESS DISTURBANCE AND SQUARE REFERENCE SIGNAL

Additionally, Integral Absolute Error (IAE) has been computed for IMC and AADC. In case of AADC, IAE value has been found as 2.994, whereas for IMC, IAE value has been found as 3.156. Hence, by measurement of control system performance, this can be inferred that AADC (using IMC and DOB) has superior disturbance rejection capability than using IMC alone for linear system without time delay.

3.5 Chapter Conclusion

Analysing several case studies in this chapter, it can be concluded that superior disturbance rejection has been obtained in AADC using IMC and DOB over IMC for linear system without time delay. Process disturbance, measurement disturbance and in some cases high frequency measurement noise rejection has been obtained for linear SISO system (without time delay). Additionally, AADC has been obtained for linear systems which are in state space form; Hirschorn Inverse has been employed to get inverse of linear state space model. For all the cases considered, this has been shown that performances of AADC outperform the IMC method.

Chapter 4: Modified Active Anti-Disturbance Control for linear SISO systems with time delay

4.1 Chapter Introduction

The time for physical movement of mass or energy is often termed as transportation lag or dead time. The ratio of dead time to time constant indicates the measure of quality to control a feedback loop. If the ratio is small (i.e. dead time is much smaller than the time constant), the loop is fairly easy to control. As the ratio increases, (i.e. dead time is much larger than the time constant), the loop becomes difficult to control. Disturbance rejection, especially high frequency measurement noise rejection in controlling time delay system is a challenging area. DOB structure based IMC for linear time delay system has been documented in [Dasgupta2015]. In [Dasgupta2014a], performance comparison and robustness study has been done for IMC based controllers applicable for plants with large time delay. In [Li2014, Guo2014, Guo2014a], different types of Disturbance Observer (DOB) Based control methods for SISO and MIMO time delay systems have been reported, but DOB based IMC control has not been included there. Only a few work on DOB based IMC were documented in [Chen2011a, Qi-bing2015, Zhang2016]. The main idea was to increase disturbance rejection capability of the overall system. In [Chen2011], they proposed DOB enhanced IMC for SISO FOPDT system. Though the MDOB has been included in IMC structure, in the application part, a cascade control structure has been adopted including an inner-loop PI controller and an outer-loop IMC controller. In [Chen2011a], only measurement disturbance has been attenuated. Similar approach has been recently documented in [Qi-bing2015]. In [Zhang2016], IMC using H_2 analytical decoupling control scheme with multivariable disturbance observer has been proposed which are applicable for both stable and unstable multi-input/multi-output (MIMO) systems with multiple time delay. In [Zhang2016], it has been shown that the process disturbance has been attenuated. For all the cases in [Chen2011, Qi-bing2015, Zhang2016], high frequency measurement noise has not been taken care of.

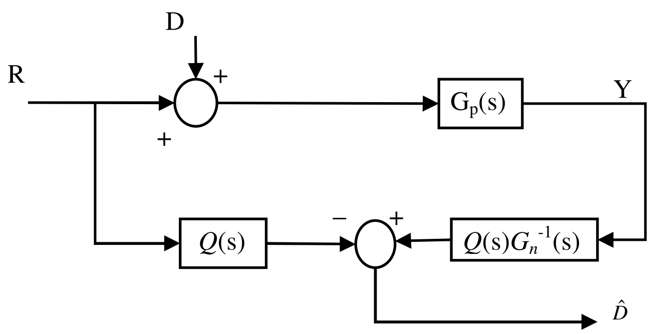
A few recent literature [Kim2015, Jo2013, Jo2016, Zhang2015] exist on high frequency noise reduction capability of DOB. In [Kim2015, Zhang2015], high frequency measurement noise has been attenuated using specially formulated DOB for discrete time cases. In [Jo2013], a Noise Reduction DOB (NR-DOB) which can attenuate process disturbance and high frequency measurement noise, has been proposed which are applicable for a linear SISO system without time delay in continuous domain. A nominal controller and a specially designed DOB were combined in [Jo2013]. Whereas in this current Chapter, low frequency process disturbance, measurement disturbance and high frequency measurement noise attenuation have been obtained for time delay system by using a Modified Active Anti- Disturbance (MAADC) structure where a Noise Reduction Modified Disturbance Observer (NR-MDOB) and IMC were innovatively combined. In case studies, (i) a conical tank system example which is in a simple First Order Plus Delay Time (FOPDT) form has been chosen to appreciate the approach and (ii) a Test Problem – B with Second Order Plus Delay Time (SOPDT) form has been considered to show that this proposed approach also works for higher order systems. For both the cases, set-point tracking, disturbance rejection (including high frequency measurement noise rejection) and robustness with respect to parametric uncertainty have been evaluated.

The contributions of the current chapter are two-fold: firstly Noise Reduction–Modified Disturbance Observer (NR-MDOB) has been specially designed for linear time delay system; secondly, Internal Model Control (IMC) and NR-MDOB have been innovatively combined for linear time delay systems and a Modified Active Anti-Disturbance Control (MAADC) has been designed. In addition to the process disturbance, low frequency measurement disturbance as well as high frequency measurement noise have been mitigated using the proposed MAADC.

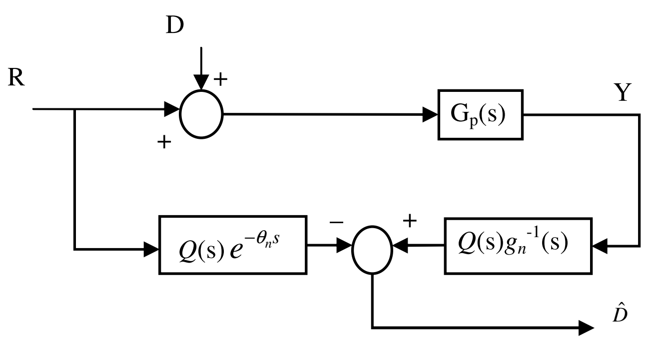
4.1.1 General Comments about IMC Controller Design and DOB design for linear SISO time delay system

Basic framework of AADC is represented in [Li2014]. AADC (as described in Chapter 3 in Figure-3.2.1) employs DOB as the feed-forward controller along with the usual feedback controller. The idea behind AADC is to directly counteract the disturbances by feed-forward control design which is based on disturbance measurement or estimation. Conjugative use of IMC and DOB combine the advantages of both the components. Though IMC has apparent similarities with DOB, but if DOB is used in the forward path to annul disturbances it is going to be faster compared to only IMC based design. Here, IMC works in the feedback loop.

IMC (shown in Figure-3.2.2) acts as a reference and thereby helps to reduce the effects of plant variation and disturbances and thus fortifies such properties which are available in standard feedback control.



(A)



(B)

FIG.-4.1.1: DISTURBANCE OBSERVER STRUCTURE (A) CONVENTIONAL DOB (B) MODIFIED DOB (MDOB) FOR TIME DELAY SYSTEM

For systems with time delay or non-minimum phase zero part, Internal Model Controller design has been obtained in [Brosilow2002]. The process has been depicted below:

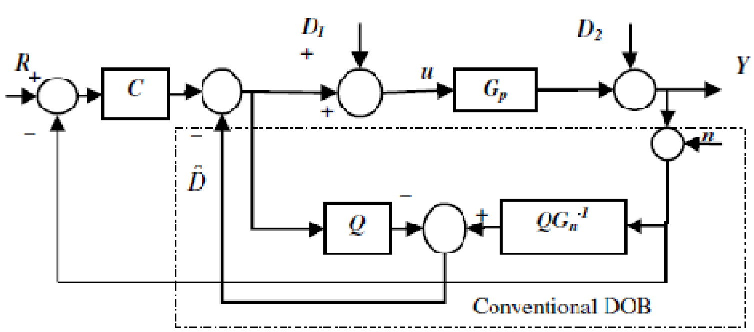
The nominal model $G_n(s)$ is divided into invertible component $G_n^-(s)$ and non-invertible component $G_n^+(s)$; i.e. $G_n(s) = G_n^-(s)G_n^+(s)$. The non-invertible component $G_n^+(s)$, contains terms which if inverted, will lead to instability or realization problems. Thus, $C(s) = G_n^-(s)^{-1}.q(s)$,where $q(s) = \frac{1}{(\lambda s+1)^n}$, λ is the tuning parameter.

While designing DOB for SISO linear time delay systems, a different strategy has been employed by Chen et. al. in [Zhu2005, Chen2009] which is shown in Figure-4.1.1(B).

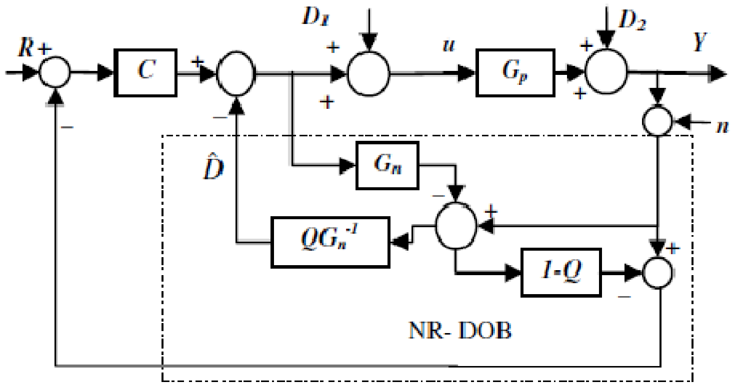
The structure of DOB has been represented in Figure-4.1.1. Here, $G_p(s)$, $G_n(s)$ and $Q(s)$ denote process, nominal model and low-pass filter respectively. Also, signals *R*, *D*, $\hat{D}$, *Y* represent command of the controller, disturbance, estimated disturbance and output respectively. Figure-4.1.1(A) is conventional DOB for linear system without time delay. Figure-4.1.1(B) is Modified DOB for linear system with time delay [Chen2009]. In Figure-4.1.1(B), process $G_p(s)$ is with time delay and corresponding nominal model has been represented as $G_n(s) = g_n(s)e^{-\theta_n s}$ where $g_n(s)$ is without time delay part and $e^{-\theta_n s}$ is time delay part.

4.2 Proposed Noise Reduction DOB (NR-DOB) Design for linear SISO with time delay system

In this section, first, high frequency measurement noise suppression ability of system without time delay for both conventional DOB and NR-DOB have been calculated in the presence of set-point *R*, process disturbance D_1, measurement disturbance D_2 and high frequency measurement noise *n*. Then, the proposed Modified Active Anti-Disturbance Control has been illustrated for time delay system.



(A)



(B)

FIG.-4.2.1: BLOCK DIAGRAM OF AADC FOR SYSTEMS WITHOUT TIME DELAY (A) WITH CONVENTIONAL DOB (B) WITH NR-DOB

AADC has been considered in Figure-4.2.1. The specialty of Figure-4.2.1 is that D_1, D_2 and n have been considered altogether. For systems without time delay, AADC structure has been shown in Figure-4.2.1(A) and Figure-4.2.1(B), using conventional DOB and Noise Reduction-DOB (NR-DOB) respectively. Here, C is the usual feedback controller. Theoretically, high frequency measurement noise suppression ability for both conventional DOB and NR-DOB has been calculated in the presence of R, D_1, D_2 and n.

In AADC (Figure-4.2.1), as Q is a low pass filter, in low frequency range, $|Q(jw)| \approx 1$ and in high frequency range, $|Q(jw)| \approx 0$.

From Figure-4.2.1(A), relationship between output y and various inputs can be represented as:

$$Y(s) = T_{YR}(s)R(s) + T_{YD1}(s)D_1(s) + T_{YD_2}(s)D_2(s) - T_{Yn}(s)n(s) \qquad (4.2.1)$$

Where, $T_{YR}(s) = \dfrac{G_n G_p C}{G_n(1+G_pC)+Q(G_p-G_n)}$; $T_{YD1} = \dfrac{G_n G_p (1-Q)}{G_n(1+G_pC)+Q(G_p-G_n)}$;

$T_{YD2} = \dfrac{G_n(1-Q)}{G_n(1+G_pC)+Q(G_p-G_n)}$ and $T_{Yn}(s) = \dfrac{G_p(Q+G_nC)}{G_n(1+G_pC)+Q(G_p-G_n)}$.

Equation (4.2.1) may be compared with [Jo2013], if D_2=0.

In low frequency range, $\left|T_{YR}(jw)\right| \approx \left|\frac{G_n C}{1+G_n C}(jw)\right|$, $\left|T_{YD_1}(jw)\right| \approx 0$, $\left|T_{YD_2}(jw)\right| \approx 0$ and $\left|T_{Yn}(jw)\right| \approx 1$.

Since, in low frequency range, $D_1(jw), D_2(jw), R(jw)$ are significant and $n(jw) \approx 0$,

$$Y(jw) \approx \frac{G_n C}{1+G_n C}(jw).R(jw) \tag{4.2.2}$$

In high frequency range, $D_1(jw) \approx 0, D_2(jw) \approx 0, R(jw) \approx 0$ and *n(jw)* is significant,

$$Y(jw) \approx -\frac{G_p C}{1+G_p C}(jw).n(jw) \tag{4.2.3}$$

The equation (4.2.3) is equivalent to closed loop transfer function without DOB. So, it can be concluded that noise suppression ability is almost equivalent to the used controller in the structure Figure- 4.2.1(A). Thus, no improved high frequency measurement noise suppression is expected from the structure shown in Figure-4.2.1(A).

In Figure-4.2.1(B), for NR-DOB,

$$T_{YR}(s) = \frac{G_n G_p C}{(1+G_n C)(G_n + Q(G_p - G_n))}; T_{YD1} = \frac{G_n G_p (1-Q)}{G_n + Q(G_p - G_n)}; T_{YD2} = \frac{G_n (1-Q)}{G_n + Q(G_p - G_n)};\ T_{Yn}(s) = \frac{G_p Q}{G_n + Q(G_p - G_n)}.$$

In low frequency range, $\left|T_{YR}(jw)\right| \approx \left|\frac{G_p C}{1+G_n C}(jw)\right|$, $\left|T_{YD_1}(jw)\right| \approx 0$, $\left|T_{YD_2}(jw)\right| \approx 0$ and $\left|T_{Yn}(jw)\right| \approx 1$.

So, $$Y(jw) \approx \frac{G_n C}{1+G_n C}(jw).R(jw) \tag{4.2.4}$$

In high frequency range, $\left|T_{YR}(jw)\right| \approx \left|\frac{G_p C}{1+G_n C}(jw)\right|$, $\left|T_{YD_1}(jw)\right| \approx \left|G_p(jw)\right|$, $\left|T_{YD_2}(jw)\right| \approx 1$ and $\left|T_{Yn}(jw)\right| \approx \left|\frac{G_p Q}{G_n}(jw)\right|$.

$$Y(jw) \approx -\frac{G_p Q}{G_n}(jw).n(jw) \tag{4.2.5}$$

So, *Q* filter can be redesigned to suppress the high frequency noise in structure shown in Figure-4.2.1(B). So, after redesigning *Q* filter, high frequency measurement noise attenuation should be improved in structure shown in Figure-4.2.1(B).

Now, for systems with time delay, AADC structure has been shown in Figure-4.2.2 using MDOB.

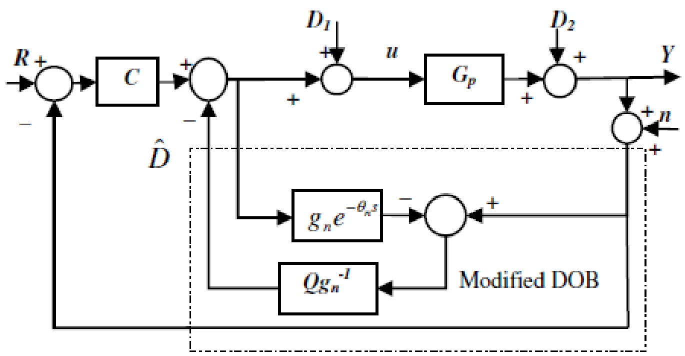


FIG.-4.2.2: BLOCK DIAGRAM OF AADC FOR TIME DELAY SYSTEM WITH MDOB

Now, this AADC in Figure-4.2.2 has been modified and MAADC structure has been designed as shown in Figure-4.2.3, which is applicable for time delay system. Here, Q block (from Figure-4.2.1) has been modified as $Qe^{-\theta_n s}$ (in Figure-4.2.3) and hence, inversed nominal time delay model multiplied with filter Q is possible in Figure-4.2.3 and does not create any realizability problem. Here, controller C has been designed as IMC in unity feedback control form and Q filter has been redesigned. It is to be noted that this will affect the low frequency performance and some compromise may be required. This MAADC can attenuate D_1, D_2 and n successfully for time delay system.

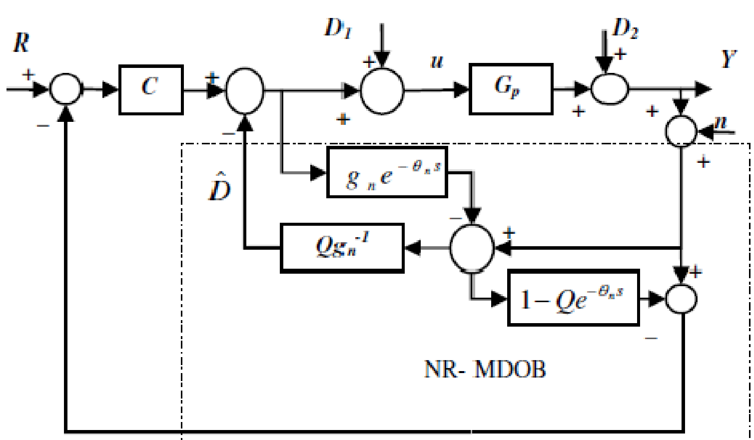


FIG.-4.2.3: PROPOSED STRUCTURE OF MAADC

4.3 Case Study 1-- Conical Tank System

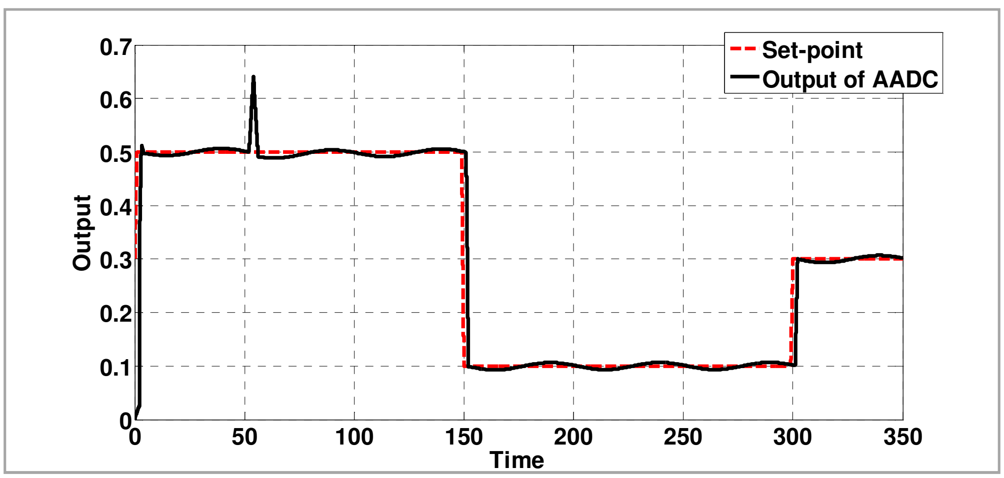
4.3.1 Plant model

In [Venkatesan2012], control of liquid level in a conical tank has been considered. Though the conical tank is nonlinear due to variation of the cross sectional area with change in shape, it was linearized and approximated as a FOPDT system with a transfer function model $G(s)=\frac{12.6}{53.6s+1}e^{-2.05s}$

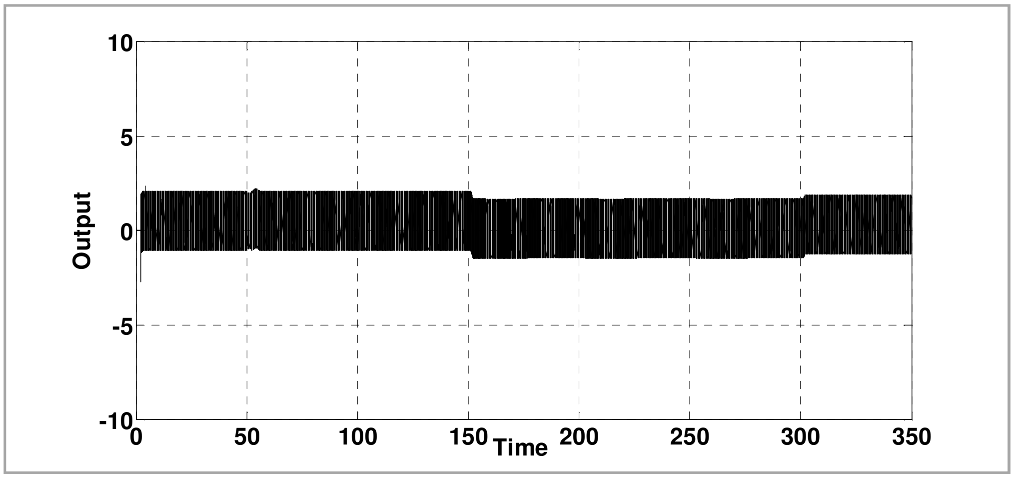
4.3.2 Controller Design and Simulation Results

Internal Model controller has been designed as $C(s)=\frac{(53.6s+1)}{12.6(0.02s+1)}$ where low pass filter time constant has been taken as 0.02. Low pass filter time constant of DOB has been taken as 0.02.

Set-point $r(t)=\begin{cases} 0.5; 0<t<150 \\ 0.1; 150<t<300 \\ 0.3; t>300 \end{cases}$, Process disturbance ($D_1$) of amplitude 0.3 step signal at t=50 Sec and measurement disturbance (D_2) as 0.1sin(pi/25) have been considered.



(A)



(B)

FIG.-4.3.1: NOMINAL PLANT RESPONSE USING AADC (A) WITH PROCESS AND MEASUREMENT DISTURBANCE (B) WITH PROCESS, MEASUREMENT DISTURBANCE AND HIGH FREQUENCY MEASUREMENT NOISE

Initially, AADC has been designed as shown in Figure-4.2.3 assuming $Q(s) = \frac{1}{(0.02s+1)}$ First, high frequency measurement noise *n(t)* has been assumed as zero and nominal plant response has been obtained which is shown in Figure-4.3.1(A). It has been noted that sufficient disturbance rejection have been achieved. Then *n(t)* has been considered and assuming $n(t) = 10\sin(200\pi t)$ with D_1 and D_2, it has been shown that noise is present in the Figure-4.3.1(B). Of-course it will require high bandwidth actuator to follow the high frequency component of the controller output.

Since noise is notified in Figure-4.3.1(B), it can be concluded that in the presence of high frequency measurement noise, the AADC fails to achieve its good set-point tracking and disturbance rejection property for this time delayed system. To take care of this anomaly, a NR-MDOB has been presented in this work and MAADC have been designed. For that purpose, the low pass filter has been redesigned $Q(s) = \frac{1}{(0.02s+1)^6}$ in Figure-4.2.3. It has been noticed in Figure-4.3.2 that some compromises in low frequency disturbance attenuation have been made in attenuating high frequency measurement noise.

Nominal and off nominal plant output have been shown in Figure-4.3.2 and Figure-4.3.3 respectively. After perturbing time constant of plant by ±10%, off-nominal cases have been considered and shown in Figure-4.3.3. It can be noticed that MAADC provides not only good set-point tracking and disturbance rejection properties but also it possesses good robustness with respect to parametric uncertainty.

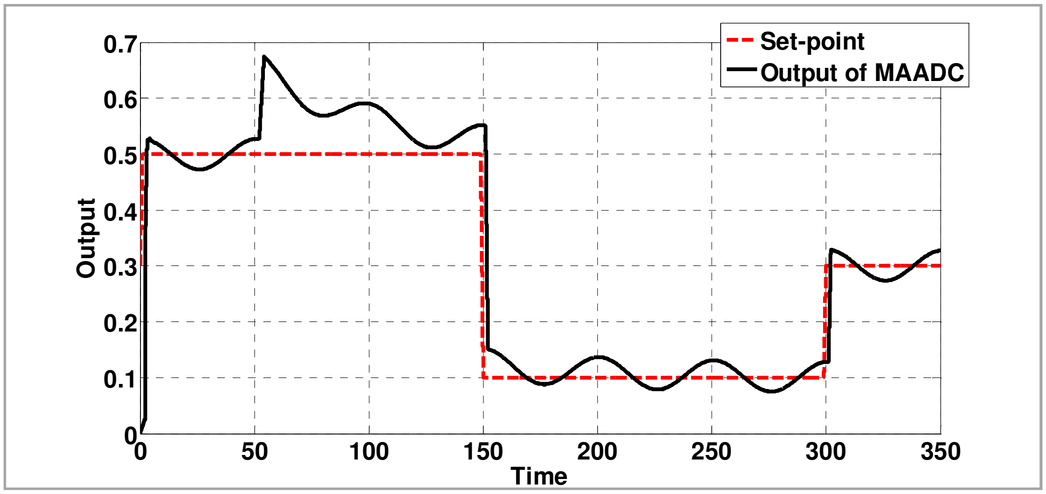


FIG.-4.3.2: NOMINAL PLANT RESPONSE FOR THE MAADC USING NR-MDOB IN THE PRESENCE OF DISTURBANCE AND MEASUREMENT NOISE

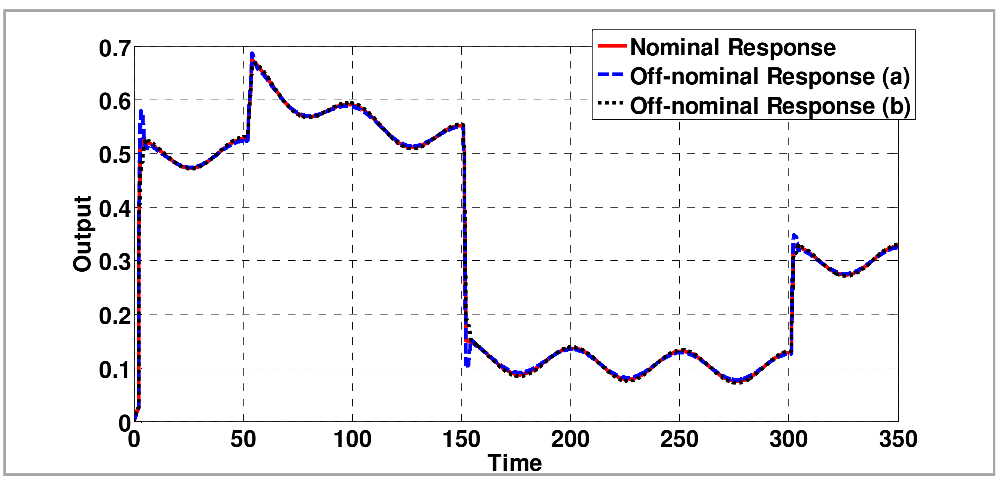


FIG.-4.3.3: OFF-NOMINAL PLANT RESPONSE OF MAADC USING NR-MDOB IN THE PRESENCE OF DISTURBANCE AND MEASUREMENT NOISE (a) -10% PERTURBED TIME CONSTANT (b) +10% PERTURBED TIME CONSTANT

4.4 Case Study 2-- Test Problem-B

4.4.1 Plant Model

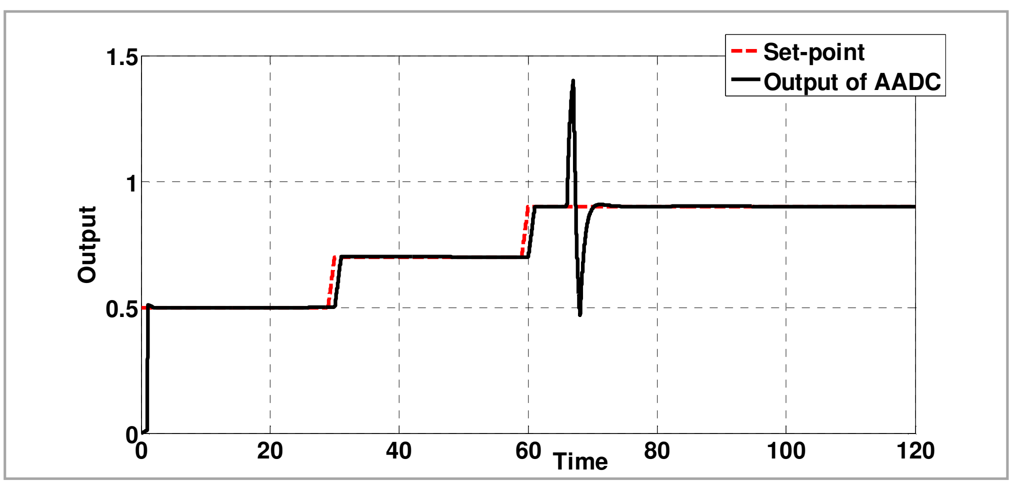
To demonstrate that this methodology also works for higher order systems, a SISO time delay system with second order plus delay time (SOPDT) has been chosen as a test problem.

$$G(s) = \frac{(2s+1)}{(s+1)^2} e^{-s}$$

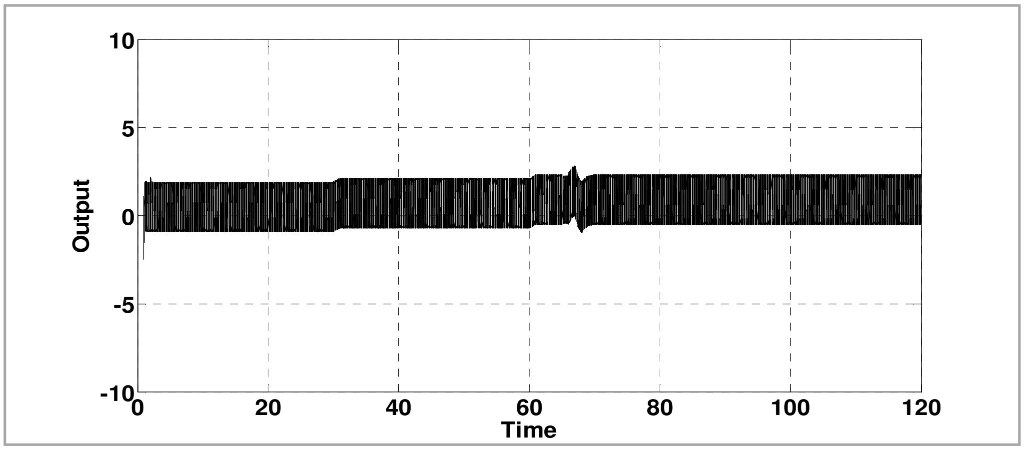
4.4.2 Controller Design and Simulation Results

Internal Model Controller has been designed as *C(s)* where $C(s) = \frac{(s^2 + 2s + 1)}{(2s+1)(0.025s+1)}$ where low pass filter time constant has been taken as 0.025. Low pass filter time constant of DOB has been taken as 0.02.

Set-point as $r(t) = \begin{cases} 0.5; 0 < t < 30 \\ 0.7; 30 < t < 60 \\ 0.9; t > 60 \end{cases}$, measurement disturbance D_2 as 0.1sin (pi/25) and process disturbance D_1 as step signal of amplitude 0.5 at *t*=65 sec have been considered.



(A)



(B)

FIG.-4.4.1: NOMINAL PLANT RESPONSE USING AADC (A) WITH PROCESS AND MEASUREMENT DISTURBANCE (B) WITH PROCESS, MEASUREMENT DISTURBANCE AND HIGH FREQUENCY MEASUREMENT NOISE

Initially, AADC has been designed as shown in Figure-4.2.2 assuming $Q(s) = \frac{1}{(0.02s+1)}$. First, high frequency measurement noise *n(t)* has been assumed as zero and nominal plant response has been obtained which is shown in Figure-4.4.1(A). It has been noted that sufficient disturbances attenuation has been achieved. Then assuming $n(t) = 10\sin(200\pi t)$ with D_1 and D_2, it has been shown that noise is present in the Figure-4.4.1(B). Here also, it will require high bandwidth actuator to follow the high frequency component of the controller output.

In the presence of high frequency measurement noise, the AADC structure shown in Figure-4.2.2 fails to achieve its good set-point tracking and disturbance rejection property for this time delayed system. It has been shown in Figure-4.4.1 (B) that there is noise present in the response. To take care of this anomaly, a NR-MDOB has been presented in this work and MAADC structure has been designed. In Figure-4.2.3, the low pass filter has been redesigned as $Q(s) = \frac{1}{(0.02s+1)^6}$; nominal and off nominal plant outputs have been shown in Figure-4.4.2 and Figure-4.4.3 respectively. It has been noticed that some compromises in low frequency disturbance attenuation have been made in attenuating high frequency measurement noise. Off-nominal cases have been considered by perturbing plant time constant by ±5%. Figure-4.4.3 demonstrates that MAADC not only gives good set-point tracking and disturbance rejection, but also gives good robustness with respect to parametric uncertainty for this higher order system with time delay.

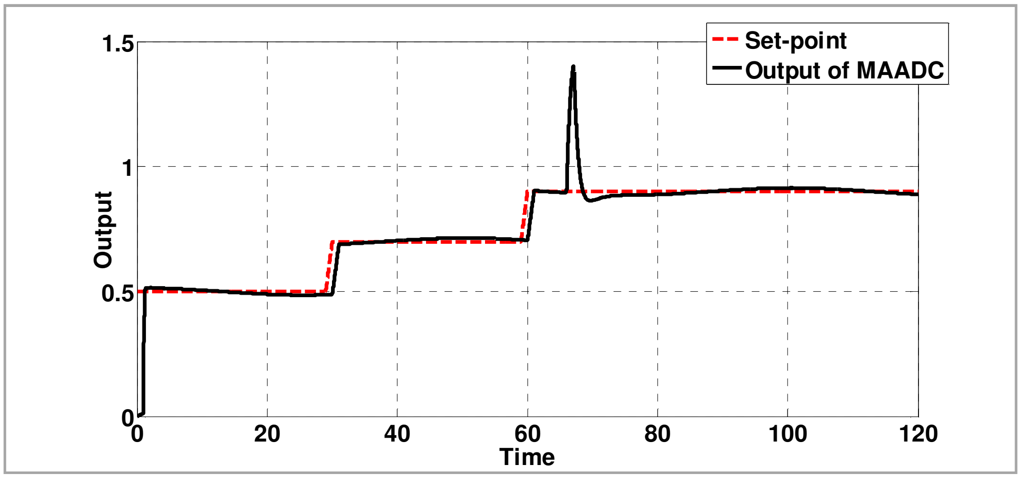


FIG.-4.4.2: NOMINAL PLANT RESPONSE FOR THE MAADC USING NR-MDOB IN THE PRESENCE OF DISTURBANCE AND MEASUREMENT NOISE

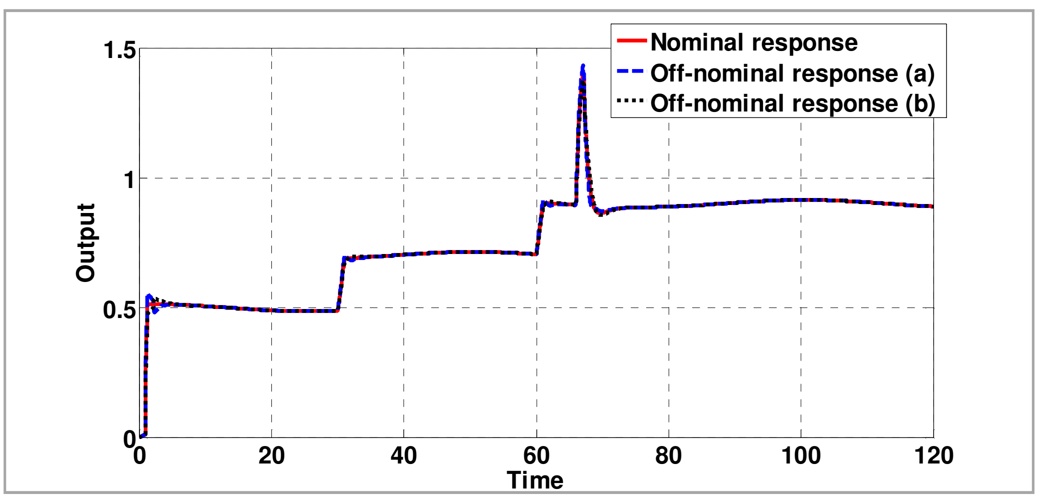


FIG.-4.4.3: OFF-NOMINAL PLANT RESPONSE FOR THE MAADC USING NR-MDOB IN THE PRESENCE OF DISTURBANCE AND MEASUREMENT NOISE (a) ***-5% PERTURBED TIME CONSTANT*** (b) ***+5% PERTURBED TIME CONSTANT***

4.5 Chapter Conclusion

A Noise Reduction Modified Disturbance Observer (NR-MDOB) has been proposed in this chapter for linear systems with time delay which, apart from delivering the benefits of conventional DOB, namely estimating the disturbance input as well as attenuation of low frequency process disturbance or measurement disturbance, can also attenuate high frequency measurement noise. Using an innovative combination of Internal Model Control and NR-MDOB, disturbance rejection, set-point tracking and robustness have been demonstrated using case studies. Disturbance including high frequency measurement noise attenuation have been compared between MAADC with AADC and the efficacy of this proposed approach has been established.

PART-C:

Active Anti-Disturbance Control Applied for Linear MIMO Square Systems

Chapter 5: Decoupling Internal Model Control for Linear MIMO Systems with Time Delay

5.1 Chapter Introduction

Internal Model Control (IMC) based controller designs for MIMO square systems with dead time and with substantial coupling have been proposed in this Chapter. In such systems, the issue of decoupling is a major concern. Two types of coupling structures have been considered, namely systems with P structure [Badelt1997] (also known as P norm coupling [Xutao2009] or P canonical structure [Isermann2013, Jones1987, Warwick1988]) and systems with V structure [Badelt1997] (also known as V norm coupling [Xutao2009] or V canonical structure [Isermann2013, Jones1987, Warwick1988]). Here, decoupling IMC has been designed for both P structured and V structured systems. Additionally, for systems with P structured systems, two types of IMC have been designed using: (i) Direct Method and (ii) Inverted Decoupling Method.

The proposed IMC based controllers ensure satisfactory decoupling within the control bandwidth. The objectives of IMC have been investigated. For this purpose, set-point tracking, disturbance rejection and robustness with respect to parametric uncertainty have been tested for the system model of the plants considered and compared with predecessor approach [Qibing2009]. The robustness study has been done extensively. Root Mean Square Errors of the outputs in frequency domain have been observed and compared with [Qibing2009]. Moreover, the degree of decoupling has been investigated using Gershgorin band.

5.2 Some Relevant Prior Work

The Internal Model Control found wide acceptance in process control systems, due to its simplicity, robustness and good control performance. In [Garcia1982], Internal Model Control has been defined for single input-single output (SISO), discrete time systems and its relationships with other control schemes have been established. Though simple to apply for SISO plants, additional complexities appear for multiple input-multiple output systems. In [Garcia1985], IMC design concept has been extended to multi input-multi output discrete time systems. A good resource for IMC is [Morari1989]. IMC for MIMO system is also discussed in [Arkun1986, Economou1986, Wang2002].

Though Internal Model Control (IMC) has been widely applied in Single SISO process control system, its application in Multiple Input Multiple Output (MIMO) system, for which has been a sustained interest, poses additional requirements. One of the important requirements is the need to decouple the system i.e. after a square system is paired [Rosenbrock1969, Chapter-12], the effect of non-paired input to any output should be negligible. Further such decoupling should be robust enough to parametric uncertainty.

Decoupling IMC for MIMO square time delay systems have been obtained in [Wang2002, Yang2005, Liu2006, Chen2007, Dasgupta2010, Dasgupta2013]. In [Chen2011], decoupling IMC has been proposed for non-square systems.

An inverted decoupling is one of the decoupling methods which are widely used in industrial process control [Gagnon1998]. Its various advantages over the other decoupling methods have been reported in [Gagnon1998, Chen2007a]. Recently, Inverted Decoupling controller design is very popular due to its simple general expression of controller elements [Garrido2010, Garrido2011, Garrido2012, Garrido2013, Garrido2014, Garrido2014a, Garrido2015, Chen2007a]. In [Garrido2014], an Internal Model Controller has been designed for a multivariable time delay system based on the structure of centralized inverted decoupling and a tuning methodology has been proposed in designing that controller. Though both [Garrido2014] and this current approach propose a decoupling IMC controller, the differences between them are as following: (i) [Garrido2014] proposed a different configuration of IMC based centralized inverted decoupling controller for time delay system using analytical decoupling IMC [Liu2006] which was based on H_2 optimal performance objective. In this current work, using conventional IMC paradigm, a decoupling controller has been designed for time delay system. (ii) Used tuning methodologies are different, (iii) In this work, pre-filter has been used to improve set-point tracking and decoupling. In [Garrido2014] a filter was used in feedback path to improve disturbance rejection, (iv) Robustness was evaluated in [Garrido2014] using μ analysis. In the current method, parametric uncertainty has been considered for robustness study. In addition to that, Root Mean Square Errors of outputs are plotted in Bode plot (by varying frequency of a small amplitude sinusoidal disturbance signal) (v) Decoupled outputs were not shown in

[Garrido2014]. In this work, obtained decoupling has been shown using time and frequency response. Moreover, two different structures have been presented; in second structure, a command modifier has been added and improved tracking and decoupling properties have been achieved.

To describe general MIMO systems, two types of transfer function representations are presented in literatures [Badelt1997, Isermann2013, Jones1987, Warwick1988]. Systems with P and V structure have been shown in Figure-5.2.1 and Fig-5.2.2 respectively. In the case of P structure, loop interactions are treated as feed-forward couplings. Here, changes in one transfer function element influence the corresponding output only. Number of outputs may not be equal to number of inputs. For the V structure, interactions are treated as feedback couplings. Changes in one transfer function element affects all outputs. This V structure only holds for square systems [Jones1987].

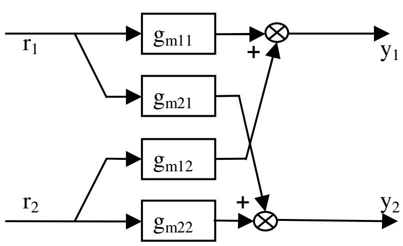


FIG.-5.2.1: P STRUCTURE OR P CANONICAL STRUCTURE

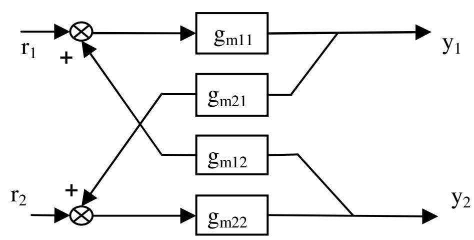


FIG.-5.2.2: V STRUCTURE OR V CANONICAL STRUCTURE

5.3 Overview of IMC Structure

The standard IMC structure is shown in Figure-5.3.1, where $\mathbf{G_p}(s), \mathbf{G}_m(s), \mathbf{C}(s), \mathbf{G}_d(s)$ denote Process, Model, IMC Controller and Disturbance Transfer Matrices respectively. The elements of the $\mathbf{G}$ matrices are denoted as $\{G_{p_{ij}}(s)\}$ etc.

$\mathbf{R}, \mathbf{D}, \mathbf{Y}$ represent: input, disturbance and output vectors respectively.

The relation between input, output and disturbance is given as:

$$\mathbf{Y}(s) = \mathbf{G_p}(s)[\mathbf{I} + \mathbf{C}(s)(\mathbf{G_p}(s) - \mathbf{G_m}(s))]^{-1}\mathbf{C}(s)\mathbf{R}(s) + [\mathbf{I} - \mathbf{G_p}(s)[\mathbf{I} + \mathbf{C}(s)(\mathbf{G_p}(s) - \mathbf{G_m}(s))]^{-1}\mathbf{C}(s)]\mathbf{G_d}(s)\mathbf{D}(s) \tag{5.3.1}$$

When the models are matched i.e. $\mathbf{G_m}(s) = \mathbf{G_p}(s)$, (5.3.1) simplifies to:

$$\mathbf{Y}(s) = \mathbf{G_p}(s)\mathbf{C}(s)\mathbf{R}(s) + [\mathbf{I} - \mathbf{G_p}(s)\mathbf{C}(s)]\mathbf{G_d}(s)\mathbf{D}(s) \tag{5.3.2}$$

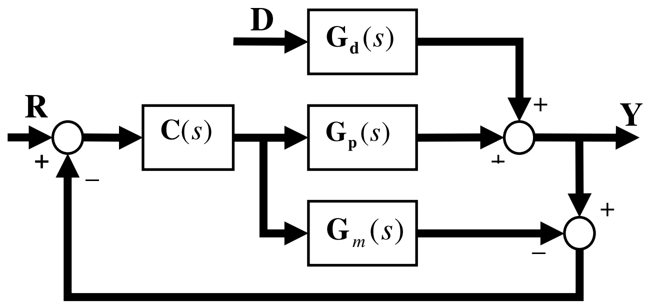


FIG.-5.3.1: BASIC STRUCTURE OF IMC

5.4 Concept of Decoupling using Gershgorin Band: A Brief Review

To study the degree of decoupling, Gershgorin Band can be used [Ho2000]. Gershgorin Band [Maciejowski1989], [Skogestad1996] is a set of Gershgorin circles enclosing the locus of $G_{ii}(jw)$ and it has radius of $\sum_{\substack{j=1 \\ j\neq i}}^{n} |G_{ij}(jw)|$ or $\sum_{\substack{j=1 \\ j\neq i}}^{n} |G_{ji}(jw)|$, where, i and j are no of outputs and no of inputs respectively. In [Garcia2005, Chen2001, Chen2002], PI/PID controller has been designed based on Gershgorin band.

5.5 Proposed Decoupling Internal Model Controller Design Methods for systems with P structure

5.5.1 Direct Method

For MIMO square systems with time delay, a direct method for decoupling Internal Model Controller Design has been proposed in this section. Here, an extension of the predecessor approach [Qibing2009] has been carried out. Using a specially adapted Internal Model control, robustness, decoupling and additive disturbance rejection has been shown for a Multiple Input-Multiple Output (MIMO) process control system. Moreover, in the proposed method: (i) the parameter optimisation approach used in [Qibing2009] has not been followed and instead,

(ii) standard single loop design tool "sisotool" in Matlab control tool box has been used after the open loop system has been approximately decoupled. While designing individual control loop, adequate loop gain has been ensured for fast closed loop response, robustness as well as decoupling. For all the case studies, the proposed IMC method has been compared with [Qibing2009].

5.5.1.1 Design Steps

Let, $\mathbf{G}(s) = \mathbf{G_p}(s)$,

$$\mathbf{G}(s)\mathbf{C}(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} C_{11}(s) & C_{12}(s) \\ C_{21}(s) & C_{22}(s) \end{bmatrix} \tag{5.5.1}$$

Now, for the decoupling condition,

$$G_{11}(s)C_{12}(s) + G_{12}(s)C_{22}(s) = 0 \quad \text{i.e. } C_{12}(s) = -\frac{G_{12}(s)}{G_{11}(s)}.C_{22}(s) \tag{5.5.2}$$

$$G_{21}(s)C_{11}(s) + G_{22}(s)C_{21}(s) = 0 \quad \text{i.e. } C_{21}(s) = -\frac{G_{21}(s)}{G_{22}(s)}.C_{11}(s) \tag{5.5.3}$$

According to the concept of Internal Model Control,

$$G_{11}(s)C_{11}(s) + G_{12}(s)C_{21}(s) = \left(G_{11}(s) - G_{12}(s)\frac{G_{21}(s)}{G_{22}(s)} \right).C_{11}(s) = 1$$

So, $$C_{11}(s) = \frac{1}{\left(G_{11}(s) - G_{12}(s)\frac{G_{21}(s)}{G_{22}(s)} \right)} = \frac{\frac{1}{G_{11}(s)}}{1 - \frac{G_{12}(s)G_{21}(s)}{G_{11}(s)G_{22}(s)}} \tag{5.5.4}$$

Again, $$G_{21}(s)C_{12}(s) + G_{22}(s)C_{22}(s) = \left(-G_{21}(s)\frac{G_{12}(s)}{G_{11}(s)} + G_{22}(s) \right).C_{22}(s) = 1$$

So, $$C_{22}(s) = \frac{1}{\left(G_{22}(s) - G_{21}(s)\frac{G_{12}(s)}{G_{11}(s)} \right)} = \frac{\frac{1}{G_{22}(s)}}{1 - \frac{G_{12}(s)G_{21}(s)}{G_{11}(s)G_{22}(s)}} \tag{5.5.5}$$

Let, $\Delta = 1 - \dfrac{G_{12}(s)G_{21}(s)}{G_{11}(s)G_{22}(s)}$

So, from (5.5.2)-(5.5.5),

$$C_{11}(s)=\frac{1}{G_{11}(s).\Delta} \tag{5.5.6}$$

$$C_{22}(s)=\frac{1}{G_{22}(s).\Delta} \tag{5.5.7}$$

$$C_{12}(s)=-\frac{G_{12}(s)}{G_{11}(s)}C_{22}(s)=-\frac{G_{12}(s)}{G_{11}(s)G_{22}(s)\Delta} \tag{5.5.8}$$

$$C_{21}(s)=-\frac{G_{21}(s)}{G_{22}(s)}C_{11}(s)=-\frac{G_{21}(s)}{G_{22}(s)G_{11}(s)\Delta} \tag{5.5.9}$$

Assuming, $\mathbf{G}=\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}$;

where, $G_{11}=\dfrac{k_1e^{-sT_1}}{1+s\tau_1}$; $G_{12}=\dfrac{k_2e^{-sT_2}}{1+s\tau_2}$; $G_{21}=\dfrac{k_3e^{-sT_3}}{1+s\tau_3}$; $G_{22}=\dfrac{k_4e^{-sT_4}}{1+s\tau_4}$.

Now, from (5.5.6)-(5.5.9), the controller structure becomes:

$$C_{11}=\frac{(1+s\tau_1)(1+sT_1/2)^2}{k_1\Delta}.F_1 \tag{5.5.10}$$

$$C_{22}=\frac{(1+s\tau_4)(1+sT_4/2)^2}{k_4\Delta}.F_2 \tag{5.5.11}$$

$$C_{12}=\frac{-k_2e^{-sT_2}(1+s\tau_1)(1+s\tau_4)(1+sT_4/2)^2}{(1+s\tau_2)k_1e^{-sT_1}k_4\Delta}.F_2 \tag{5.5.12}$$

$$C_{21}=\frac{-k_3e^{-sT_3}(1+s\tau_1)(1+s\tau_4)(1+sT_1/2)^2}{(1+s\tau_3)k_4e^{-sT_4}k_1\Delta}.F_1 \tag{5.5.13}$$

Where F_1, F_2 are filter transfer functions.

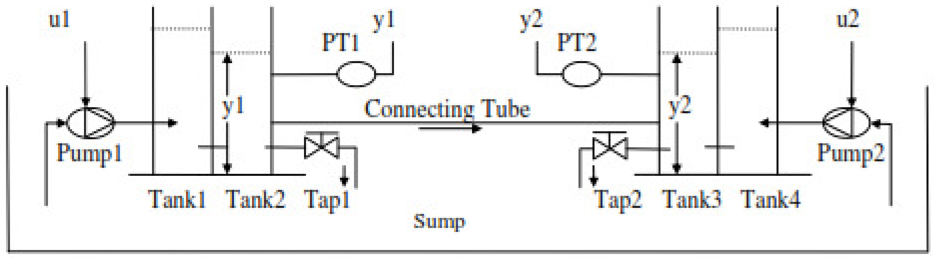
In the steps described in [Qibing2009], parameters of the filters $F_1(s), F_2(s)$ are obtained by parameter optimization (N.L.J. optimization), the present authors however found that the parameters may be simply obtained from the order of the concerned TF terms and frequency domain considerations.

5.5.1.2 Case Study -- Four Tank System

In this section, Case Study has been given using Four Tank System for Direct Method.

- ***Plant model and Controller Design***

The plant structure of four mutually coupled tanks, which is shown in Figure-5.5.1, has been used from [Gawthrop1990].



PT1, PT2: Pressure Transmitter.
u1: Input voltage to pump1, u2: Input voltage to pump2,
y1: Tank2 level measurement, y2: Tank3 level measurement.

FIG.-5.5.1: FOUR TANK SYSTEM

From [Ho2000], the continuous time model of this Four Tank system is given as

$$\mathbf{G_p}(s) = \begin{bmatrix} \dfrac{0.6}{256s+1}e^{-60s} & \dfrac{0.41}{256s+1}e^{-120s} \\ \dfrac{0.42}{186s+1}e^{-120s} & \dfrac{0.56}{186s+1}e^{-60s} \end{bmatrix}$$

IMC Controller using the proposed method for the Four tank system is given below:

$$C_{11} = \frac{(256s+1)(1+30s)^2}{0.2925(53s+1)^3}; C_{22} = \frac{(186s+1)(1+30s)^2}{0.2730(39s+1)^3}; C_{12} = -2.5029e^{-60s}\frac{(186s+1)(1+30s)^2}{(39s+1)^3};$$

$$C_{21} = -2.5641e^{-60s}\frac{(256s+1)(30s+1)^2}{(53s+1)^3}.$$

IMC Controller using [Qibing2009] for the Four Tank System is designed as:

$$C_{11} = 3.4188\frac{(256s+1)}{(\lambda_1 s+1)}; C_{22} = 3.663\frac{(186s+1)}{(\lambda_2 s+1)}; C_{21} = -2.5641e^{-60s}\frac{(256s+1)}{(\lambda_1 s+1)};$$

$$C_{12} = -2.5030e^{-60s}\frac{(186s+1)}{(\lambda_2 s+1)}$$

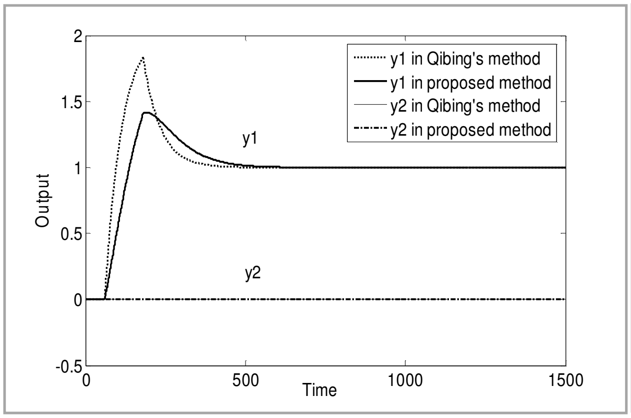
Where λ_1 and λ_2 are filter time constants.

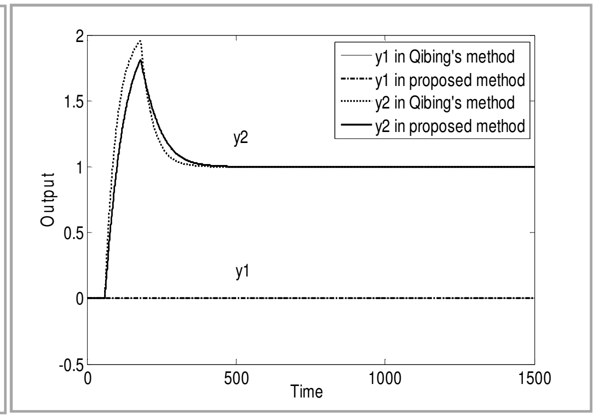
Using standard single loop design tool "sisotool" in Matlab Control Toolbox of MATLAB R2008a, we get the values of $\lambda_1 = 53$ and $\lambda_2 = 39$ by Internal Model Control (IMC) Tuning (a GUI Approach), after the open loop system has been approximately decoupled.

- ***Performance comparison with a predecessor approach***

  - *Setpoint Tracking*

One of the objectives of IMC is setpoint tracking, which has been investigated here using time response.





(A) ***(B)***

FIG.-5.5.2: NOMINAL PLANT OUTPUTS FOR STEP INPUT (A) AT INPUT 1 (B) AT INPUT 2

Figure-5.5.2 (A), a step input at t=0 Sec at input 1 has been used. Here, the response y1 is shown in which set-point tracking has been obtained. In addition to that, y2 is successfully decoupled with respect to input 1. In Figure-5.5.2 (B), a step input at t=0 Sec at input 2 has been applied. Here, the response y2 is shown, which clearly shows that set-point tracking has been achieved. A good decoupling result is obtained from y1 in the same Figure-5.5.2 (B).

In Figure-5.5.2, comparison has been shown between the proposed method and Qibing's method [Qibing2009] and it can be observed that set-point tracking, and decoupling are achieved for both the methods. In addition to that, tracking is better with smaller overshoot and decoupling is almost equivalent in the proposed method. Smaller overshoot is always more acceptable in process control system and good decoupling is a very crucial factor in coupled MIMO system with significant dead time like Four Tank System.

In Figure-5.5.3 and Figure-5.5.4, set-point tracking is investigated using frequency response.

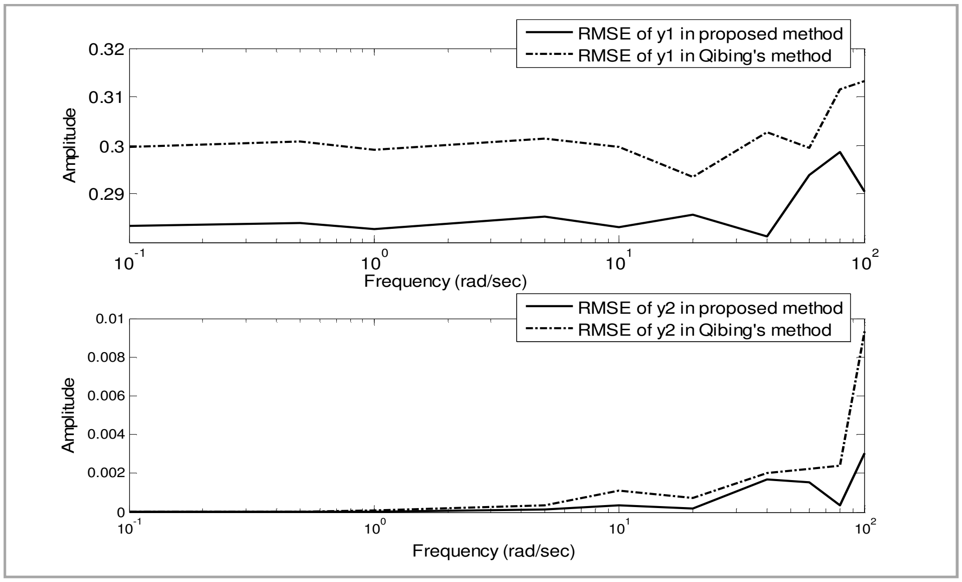


FIG.-5.5.3: RMSE OF NOMINAL MODEL SUBJECTED TO STEP INPUT AT INPUT 1 WITH SINUSOIDAL DISTURBANCE AT INPUT 1

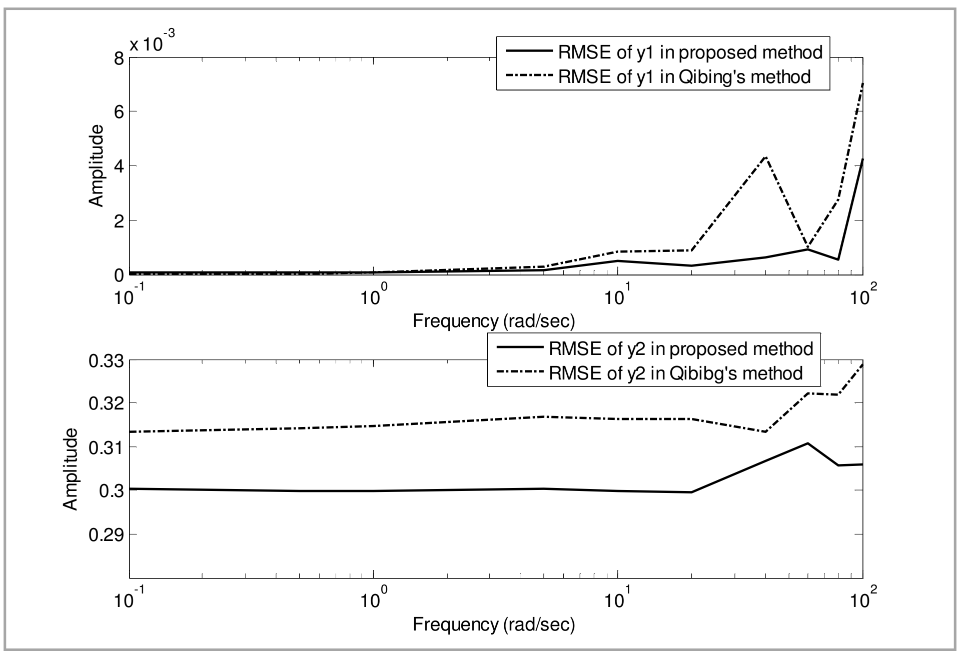


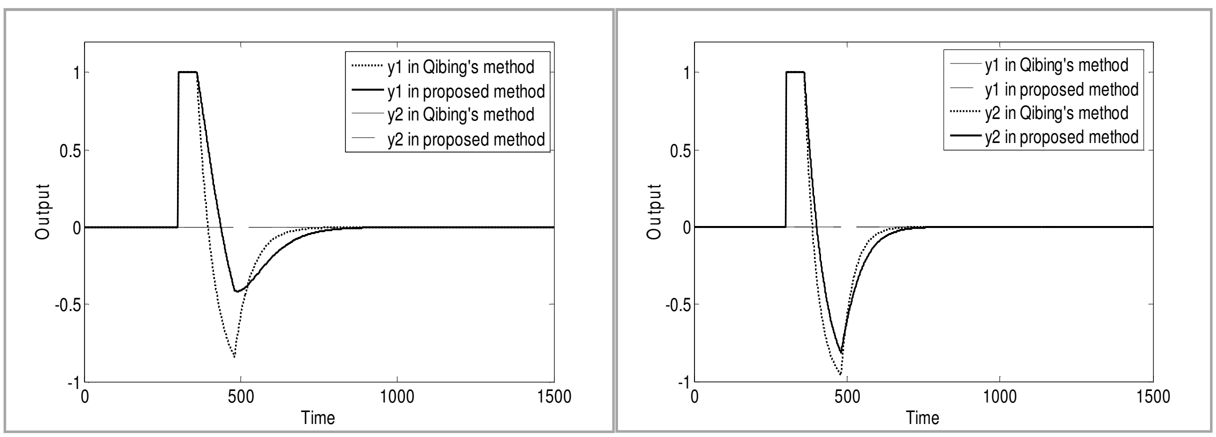
FIG.-5.5.4: RMSE OF NOMINAL MODEL SUBJECTED TO STEP INPUT AT INPUT 2 WITH SINUSOIDAL DISTURBANCE AT INPUT 2

In Figure-5.5.3, a unit step signal at t=0 at input 1 and a sinusoidal disturbance with amplitude 0.1 at external disturbance input 1 have been used. The frequencies of sinusoidal signal have been considered as w=0.1, 0.5, 1, 5, 10, 20, 40, 60, 80 and 100 rad/sec respectively and compared the Root Mean Square Error (RMSE) in Bode Plot for both the proposed and Qibing's Method [Qibing2009].

Similarly, in Figure-5.5.4, a unit step signal at t=0 at input 2 and a sinusoidal disturbance with amplitude 0.1 at external disturbance input 2 have been used. The RMS Errors in Bode Plot have been compared for the proposed and Qibing's methods [Qibing2009] using the above mentioned frequencies of sinusoidal disturbance. From Figure-5.5.3 and Figure-5.5.4, it can be observed that RMS Error is smaller in our proposed method for both the outputs. Thus, this can be inferred that both set-point tracking and decoupling are superior in our proposed method.

- *Disturbance Rejection*

Disturbance rejection property is investigated here using time response.



(A) ***(B)***

FIG.-5.5.5: NOMINAL PLANT OUTPUTS FOR STEP DISTURBANCE (A) AT INPUT 1 (B) AT INPUT 2

In the Figure-5.5.5 (A), a step disturbance of unit amplitude at t= 300Sec at input 1 has been used. Here, the response y1 is shown in which disturbance rejection has been obtained. In addition to that, y2 is successfully decoupled with respect to input 1. In the Figure-5.5.5 (B), a step disturbance of unit amplitude at t= 300 Sec at input 2 has been applied. Here, the response y2 is shown, which clearly shows that disturbance rejection is achieved. A good decoupling result is obtained from y1 in the same figure. In addition to that, comparison between our proposed method and Qibing's method [Qibing2009] has been carried out in Figure-5.5.5. It has been shown that disturbance rejection with smaller undershoot is achieved in our proposed method. It has been shown In Figure-5.5.3 and Figure-5.5.4, that RMSE is smaller at different frequencies of sinusoidal disturbance in our proposed method. Thus, superior disturbance rejection property is ensured in our proposed method using frequency response also.

➢ *Robustness Studies*

Here, an extensive robustness study with respect to parametric uncertainty has been performed.

(A) The time constant of one of the transfer function elements of process by +10% has been perturbed and the results without disturbance have been observed.

When time constant of G11 is perturbed by +10%, results are observed in Figure-5.5.6.

When time constant of G12 is perturbed by +10%, results are observed in Figure-5.5.7.

When time constant of G21 is perturbed by +10%, results are observed in Figure-5.5.8.

When time constant of G22 is perturbed by +10%, results are observed in Figure-5.5.9.

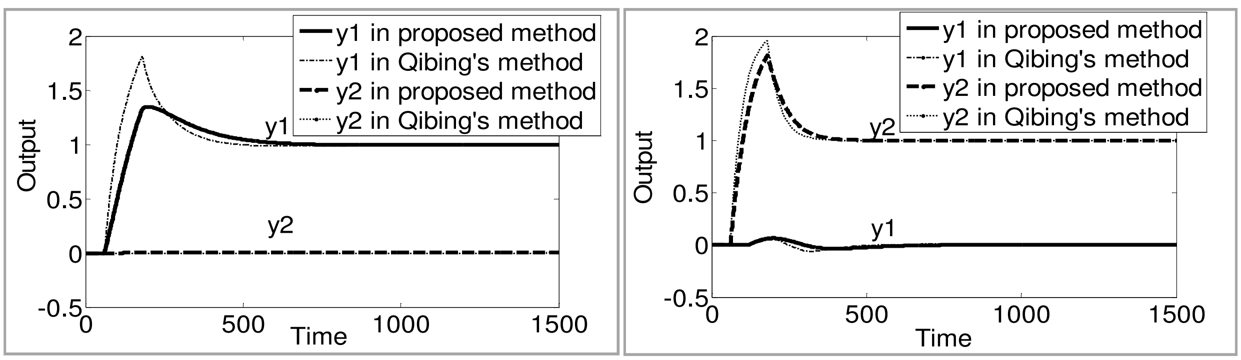


FIG.-5.5.6: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY.

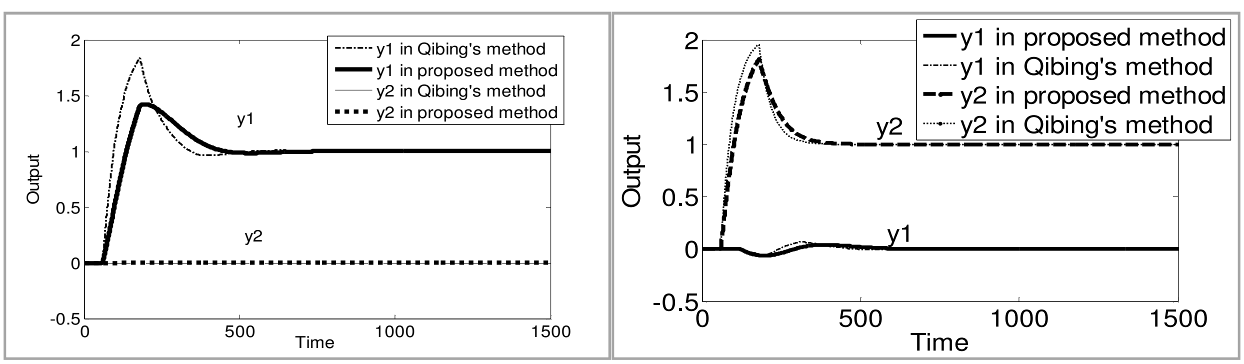


FIG.-5.5.7: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY.

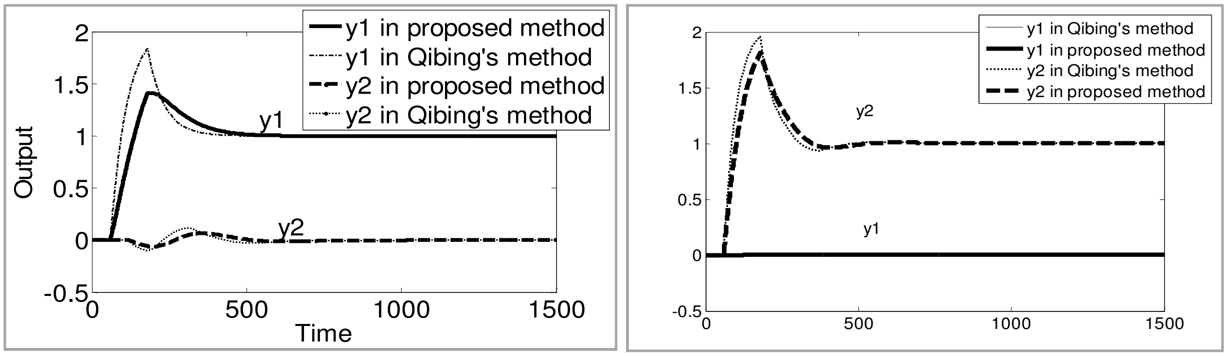


FIG.-5.5.8: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY.

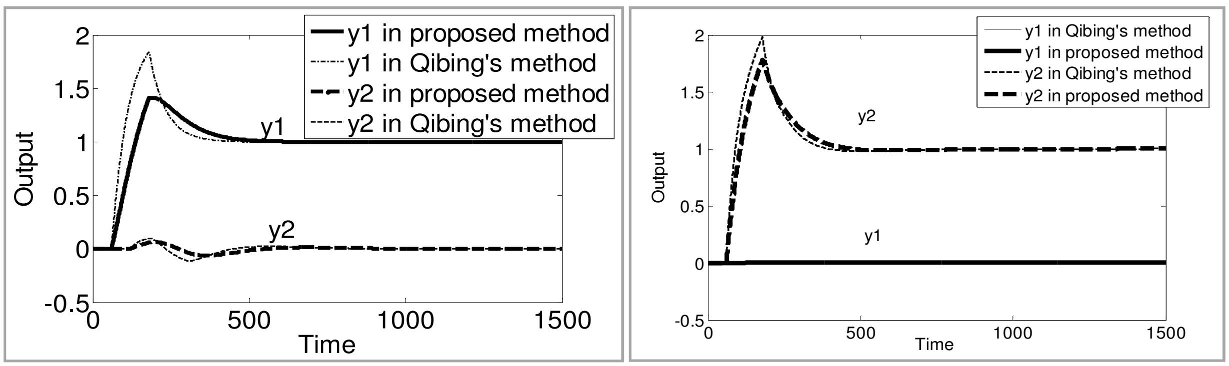


FIG.-5.5.9: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY.

(B) Here, time delay of one of the transfer function elements of process has been perturbed by +10% and results without disturbance have been observed.

When time delay of G11 is perturbed by +10%, results are observed in Figure-5.5.10.

When time delay of G12 is perturbed by +10%, results are observed in Figure-5.5.11.

When time delay of G21 is perturbed by +10%, results are observed in Figure-5.5.12.

When time delay of G22 is perturbed by +10%, results are observed in Figure-5.5.13.

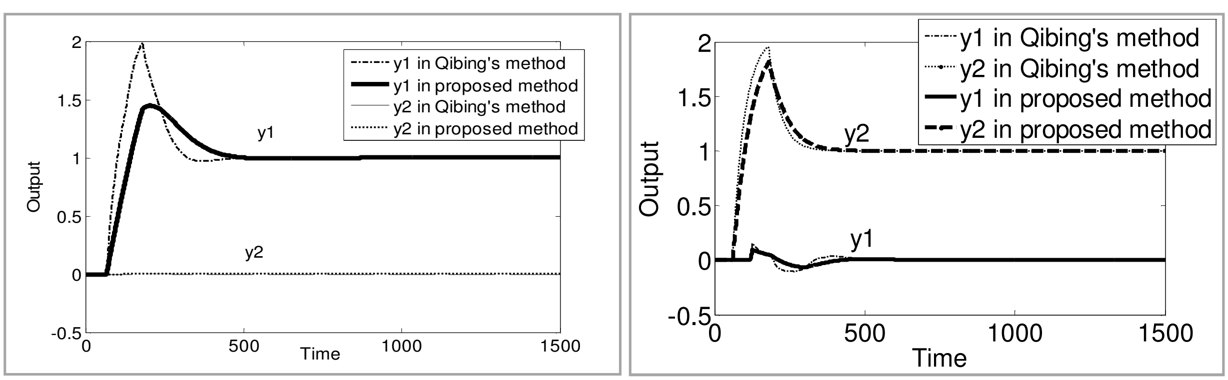


FIG.-5.5.10: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY.

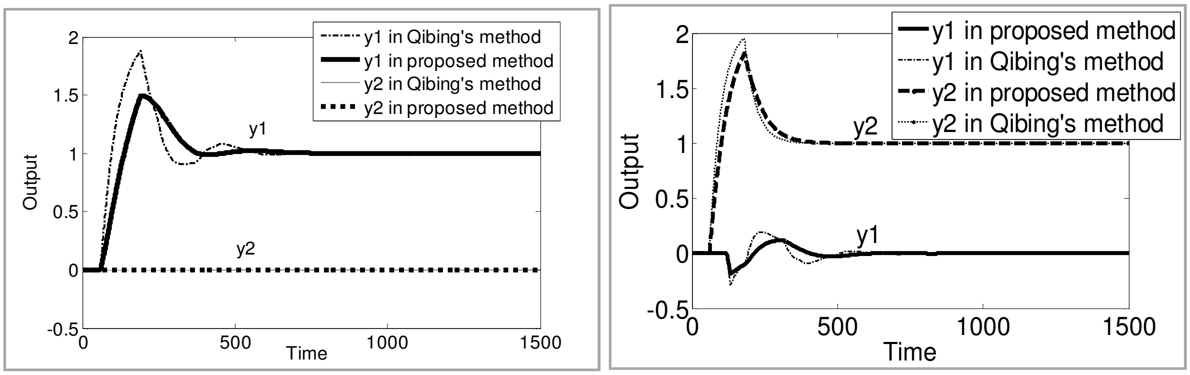


FIG.-5.5.11:OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

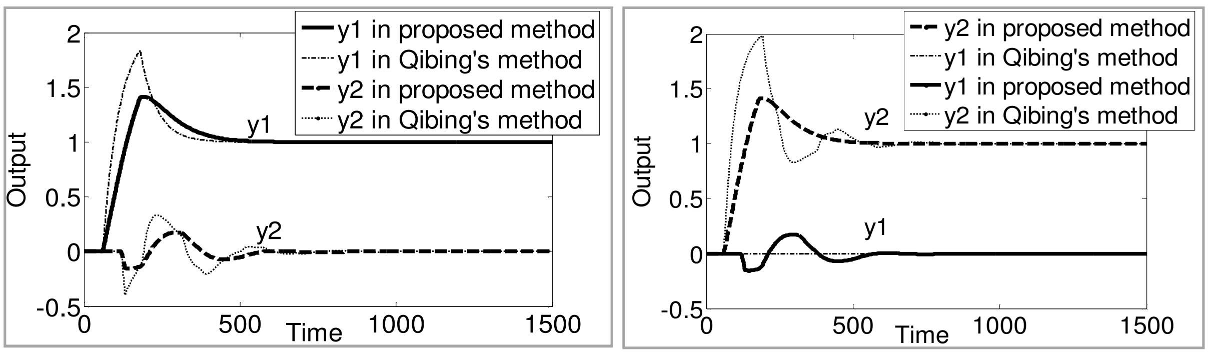


FIG.-5.5.12: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

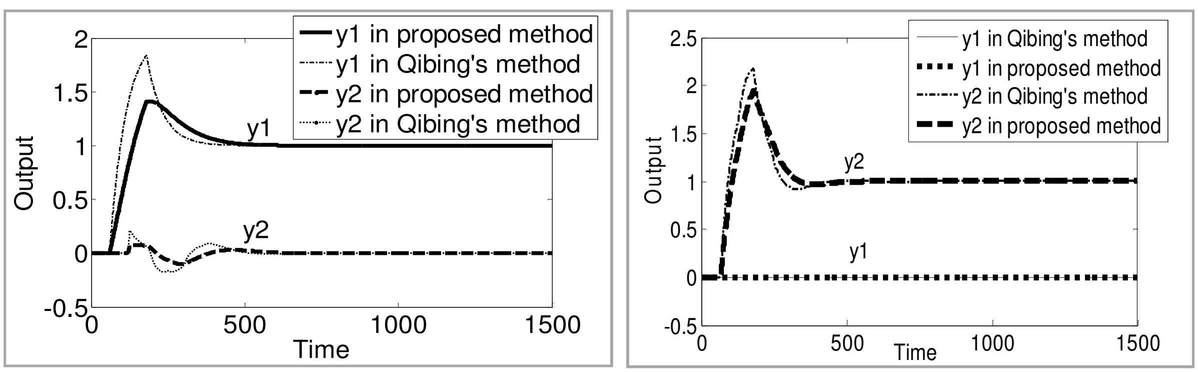


FIG.-5.5.13: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

In Figure-5.5.6 - 5.5.13, robustness of Decoupling Internal Model Controller has been studied and the proposed controller is compared with [Qibing2009]. In all the cases, set-point tracking with lesser overshoot is eminent in the proposed method. Additionally, in most of the cases decoupling is improved in the proposed method and in the remaining cases, the decoupling is of almost an equivalent degree.

- ***Gershgorin Band interpretation of Decoupling***

Row wise Gershgorin bands are evaluated for the uncompensated system in Figure-5.5.14. The radius of Gershgorin circles indicates that the uncompensated Four Tank System is a coupled one. Similarly, row wise Gershgorin bands for the compensated system are evaluated in Figure-5.5.15. Here Gershgorin circles are of sufficiently smaller radius. This demonstrates that a satisfactory degree of decoupling is achieved.

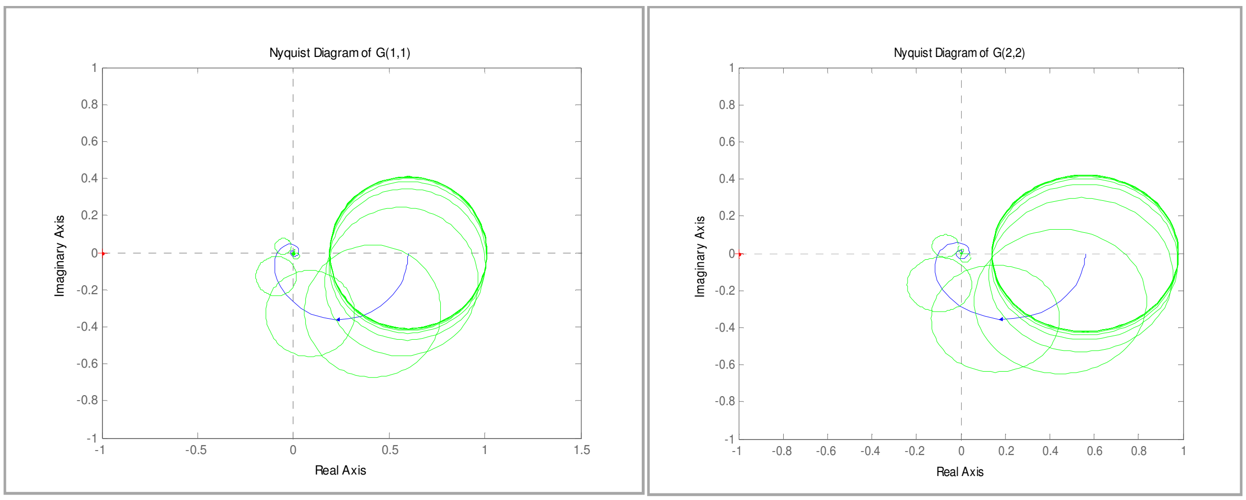


FIG.-5.5.14: GERSHGORIN BAND (ROW-WISE) FOR UNCOMPENSATED FOUR TANK SYSTEM

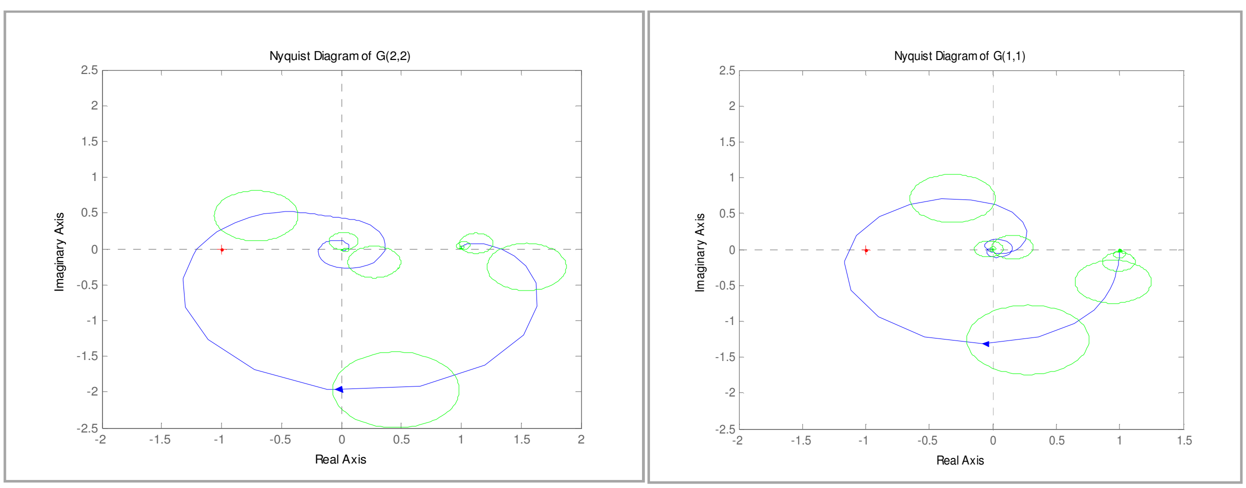
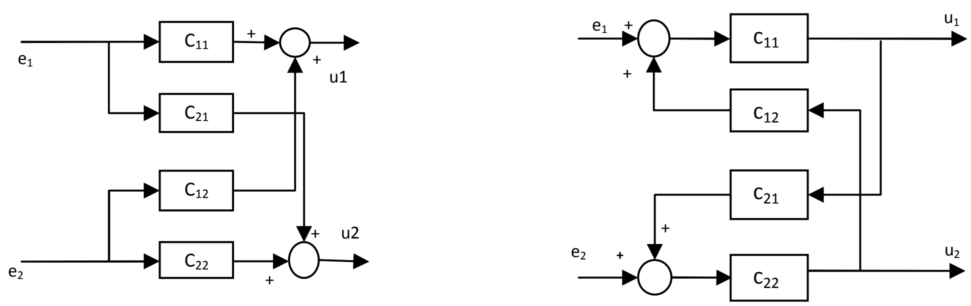


FIG.-5.5.15: GERSHGORIN BAND (ROW-WISE) FOR COMPENSATED FOUR TANK SYSTEM

5.5.2 Inverted Decoupling Method

For conventional case, controller elements are connected with each other as shown below (Figure-5.5.16(A)). Centralized inverted control structure is shown in (Figure-5.5.16(B)).



(A) ***(B)***

FIG.-5.5.16: CONTROLLER STRUCTURE (A) WITH CONVENTIONAL COUPLING (B) WITH CENTRALIZED INVERTED COUPLING

The centralized inverted decoupling structure for TITO processes presented in [Garrido2012, Garrido2013] has been adapted in this work to present a new method for decoupling internal model control of a multivariable system with dead time. The proposed method has been compared with an existing method [Qibing2009]. In addition to that, a pre-filter or command modifier has been added to improve tracking and decoupling properties. The objectives of IMC have been investigated using a Distillation Column 2X2 system with dead time. For this purpose, set-point tracking, disturbance rejection and robustness with respect to parametric uncertainty have been carried out for the system model of this plant and compared with [Qibing2009]. An extensive robustness study has been done in this work. Root Mean Square Errors of the outputs in frequency plot have been observed and compared with and without pre-filter.

The contribution is as follows: Primarily, new method of decoupling internal model control has been proposed for multivariable system with dead time. Two design structures have been proposed for that purpose. They are (1) using inverted decoupled Internal Model Controller design (2) incorporating a command modifier with the previous one.

5.5.2.1 Design Steps

(A) From (Figure-5.5.16(B)),

$$u_1 = c_{11}(e_1 + c_{12}u_2) \tag{5.5.14}$$

$$u_2 = c_{22}(e_2 + c_{21}u_1) \tag{5.5.15}$$

From Equations (5.5.14) and (5.5.15),

$$u_1 = \frac{c_{11}}{(1 - c_{11}c_{12}c_{22}c_{21})}e_1 + \frac{c_{11}c_{12}c_{22}}{(1 - c_{11}c_{12}c_{22}c_{21})}e_2 \tag{5.5.16}$$

$$u_2 = \frac{c_{11}c_{21}c_{22}}{(1-c_{11}c_{12}c_{22}c_{21})}e_1 + \frac{c_{22}}{(1-c_{11}c_{12}c_{22}c_{21})}e_2 \qquad (5.5.17)$$

So from Equations (5.5.16) and (5.5.17), $\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$

where, $C_{11} = \dfrac{c_{11}}{(1-c_{11}c_{12}c_{22}c_{21})}$ (5.5.18)

$$C_{12} = \frac{c_{11}c_{12}c_{22}}{(1-c_{11}c_{12}c_{22}c_{21})} \qquad (5.5.19)$$

$$C_{21} = \frac{c_{11}c_{21}c_{22}}{(1-c_{11}c_{12}c_{22}c_{21})} \qquad (5.5.20)$$

$$C_{22} = \frac{c_{22}}{(1-c_{11}c_{12}c_{22}c_{21})} \qquad (5.5.21)$$

Assuming no process-model mismatch, for decoupling condition, $L(s) = G(s)C(s)$ should be a diagonal transfer function matrix.

i.e. $\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} l_{01} & 0 \\ 0 & l_{02} \end{bmatrix}$

Since, $G_{11}C_{12} + G_{12}C_{22} = 0$, $-\dfrac{G_{12}}{G_{11}} = \dfrac{C_{12}}{C_{22}}$

From Equations (5.5.19) and (5.5.21),

$$-\frac{G_{12}}{G_{11}} = c_{11}c_{12} \qquad (5.5.22)$$

Since, $G_{21}C_{11} + G_{22}C_{21} = 0$, $-\dfrac{G_{21}}{G_{22}} = \dfrac{C_{21}}{C_{11}}$

From Equations (5.5.18) and (5.5.20),

$$-\frac{G_{21}}{G_{22}} = c_{21}c_{22} \qquad (5.5.23)$$

Since, $G_{11}C_{11} + G_{12}C_{21} = l_{01}$

From Equations (5.5.18), (5.5.20) and (5.5.22),

$$c_{11} = \frac{l_{01}}{G_{11}} \tag{5.5.24}$$

From Equations (5.5.22) and (5.5.24),

$$c_{12} = -\frac{G_{12}}{G_{11}}.\frac{1}{c_{11}} = -\frac{G_{12}}{l_{01}} \tag{5.5.25}$$

Since, $G_{21}C_{12} + G_{22}C_{22} = l_{02}$

From Equations (5.5.19), (5.5.21) and (5.5.23),

$$c_{22} = \frac{l_{02}}{G_{22}} \tag{5.5.26}$$

From Equations (5.3.41) and (5.3.44),

$$c_{21} = -\frac{G_{21}}{G_{22}}.\frac{1}{c_{22}} = -\frac{G_{21}}{l_{02}} \tag{5.5.27}$$

Controller elements are rewritten as:

$$c_{11} = \frac{l_{01}}{G_{11}};c_{22} = \frac{l_{02}}{G_{22}};c_{12} = -\frac{G_{12}}{G_{11}}.\frac{1}{c_{11}} = -\frac{G_{12}}{l_{01}};c_{21} = -\frac{G_{21}}{G_{22}}.\frac{1}{c_{22}} = -\frac{G_{21}}{l_{02}}$$

Now, the controller elements should be stable and realizable. In IMC framework, first G_{11} and G_{22} elements are divided into invertible and non-invertible parts. In this case, as the TF elements are time delay functions, the delay free parts are invertible and thus reversed; then multiplied by l_{0i} ($i=1,2$) to get , c_{11} and c_{22} respectively. The l_{0i} ($i=1,2$) are selected as low pass filter transfer functions to get relative degree of c_{ii} as zero or greater than zero; i.e. proper controller transfer function elements. As c_{11} and c_{22} are known, c_{12} and c_{21} are easy to obtain from the above relationship.

(B) Introduction of Pre-filter or Command Modifier

A pre-filter or Command Modifier can be introduced by applying a low pass filter with suitable time constant, to the set-point i.e. outside the closed loop system. By proper designing, the pre-filter has the capability of reducing or eliminating the overshoot of the closed loop system, thus tracking result can be improved. By using pre-filtering of the reference signal, decoupling result can also be improved [Goodwin2009].

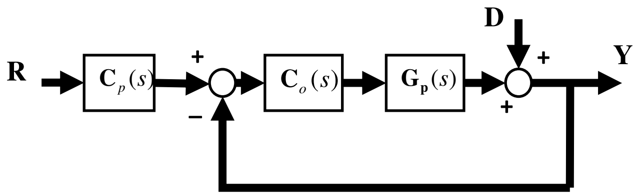


FIG.-5.5.17: CLOSED LOOP CONTROL WITH PRE-FILTER

From Figure-5.3.27, the transfer function matrix between output $\mathbf{Y}$ and reference $\mathbf{R}$ is $\mathbf{G_{YR}}$.

$$\mathbf{G_{YR}} = [\mathbf{I} + \mathbf{G_p}(s)\mathbf{C_o}(s)]^{-1}\mathbf{G_p}(s)\mathbf{C_o}(s)\mathbf{C_p}(s)$$

By choosing suitable pre-filter $\mathbf{C_p}(s)$, enhanced decoupling result can be obtained. Here, $\mathbf{C}_o(s)$ is the Internal Model Controller in unity feedback control form.

5.5.2.2 Case Study -- Distillation Column System

- ***Plant model and Controller Design***

The system is Methanol-Water Distillation Column of Wood and Berry [Luyben1986, Ho1997] with strong interaction between overhead and bottom composition. The system transfer function matrix is

$$\begin{bmatrix} X_D(s) \\ X_B(s) \end{bmatrix} = \begin{bmatrix} \dfrac{12.8e^{-s}}{16.7s+1} & \dfrac{-18.9e^{-3s}}{21s+1} \\ \dfrac{6.6e^{-7s}}{10.9s+1} & \dfrac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \begin{bmatrix} R(s) \\ S(s) \end{bmatrix}$$

The inputs are reflux flow rate (R) and steam flow rate (S). The outputs are Composition of Distillation (X_D) and Composition of bottom (X_B).

Controller structure for our proposed scheme is as follows:

$$c_{11}(s) = \frac{(16.7s+1)}{12.8(\lambda_1 s+1)};\ c_{22}(s) = \frac{-(14.4s+1)}{19.4(\lambda_2 s+1)};\ c_{12}(s) = \frac{18.9(\lambda_1 s+1)e^{-2s}}{(21s+1)};\ c_{21}(s) = \frac{-6.6(\lambda_2 s+1)e^{-4s}}{(10.9s+1)}$$

Where λ_1 and λ_2 are filter time constants. These controller structure elements are connected as shown in (Figure-5.5.16(B)).

Controller structure using Qibing's method is shown below:

$$C_{11}(s) = \frac{0.1570(16.7s+1)}{(\lambda_1 s+1)};\ C_{22}(s) = \frac{-0.1036(14.4s+1)}{(\lambda_2 s+1)};$$

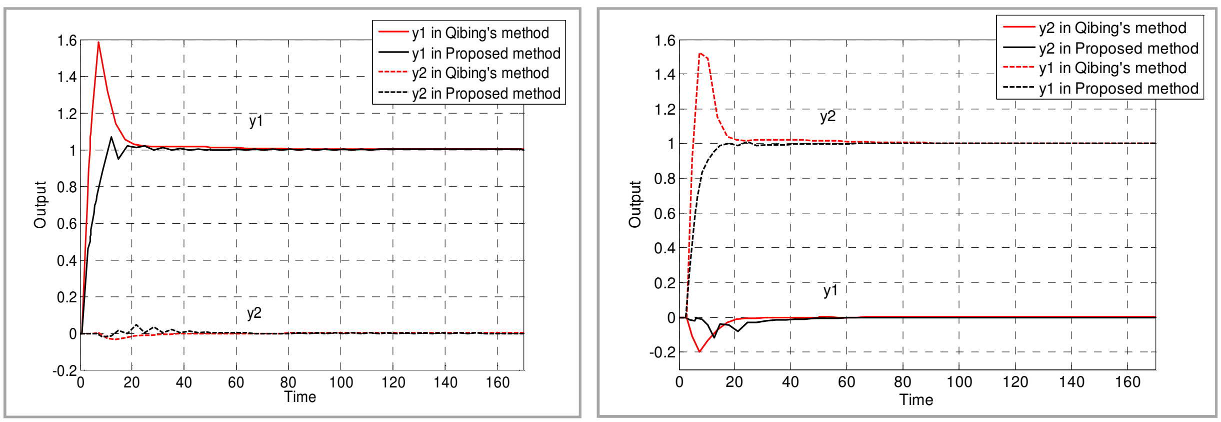
$$C_{12}(s) = \frac{-0.1529(16.7s+1)(14.4s+1)e^{-2s}}{(21s+1)(\lambda_2 s+1)} \qquad C_{21}(s) = \frac{0.0534(16.7s+1)(14.4s+1)e^{-4s}}{(10.9s+1)(\lambda_1 s+1)}$$

Where λ_1 and λ_2 are filter time constants.

These controller structure elements are connected as shown in Figure-5.5.16(A).Using standard single loop design tool "sisotool" in Matlab Control Toolbox of MATLAB R2008a, we get the values of $\lambda_1=4$ and $\lambda_2=3$ by Internal Model Control (IMC) Tuning (a GUI Approach), after the open loop system has been approximately decoupled.

- ***Performance comparison with a predecessor approach***

➢ *Set-point Tracking*



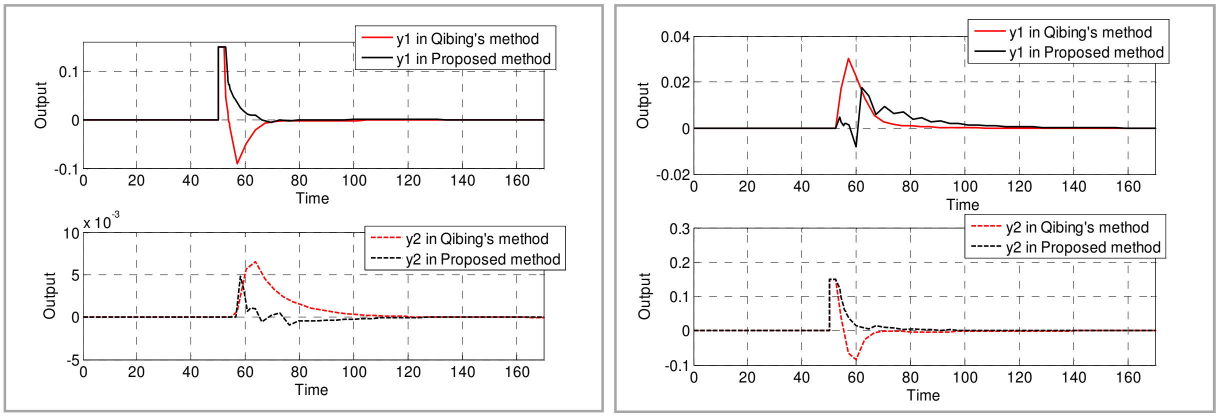
(A) ***(B)***

FIG.-5.5.18: NOMINAL PLANT OUTPUT FOR STEP INPUT (A) AT INPUT 1 (B) AT INPUT 2

A step input at t=0 Sec at input 1 has been used and nominal response has been shown in Figure-5.5.18(A). Again, a step input at t=0 Sec at input 2 has been applied and nominal response has been shown in Figure-5.5.18(B).

➢ *Disturbance Rejection*

A step disturbance of 0.15 amplitude at t= 50 Sec at input 1 has been used and responses have been shown in Figure-5.5.19(A). Again, a step disturbance of 0.15 amplitude at t= 50 Sec at input 2 has been applied and nominal plant outputs have been shown in Figure-5.5.19(B). It has been found that for the proposed method disturbance rejection is faster.



(A) ***(B)***

FIG.-5.5.19: NOMINAL PLANT OUTPUT FOR STEP DISTURBANCE (A) AT INPUT 1 (B) AT INPUT 2

- *Robustness Study*

Here, an extensive robustness study with respect to parametric uncertainty has been performed.

(A) The time constant of one of the transfer function elements of process by +10% has been perturbed and the results without disturbance have been observed.

(i) When time constant of G_{11} is perturbed by +10%, results are observed in Figure-5.5.20.

(ii)When time constant of G_{12} is perturbed by +10%, results are observed in Figure-5.5.21.

(iii)When time constant of G_{21} is perturbed by +10%, results are observed in Figure-5.5.22.

(iv) When time constant of G_{22} is perturbed by +10%, results are observed in Figure-5.5.23.

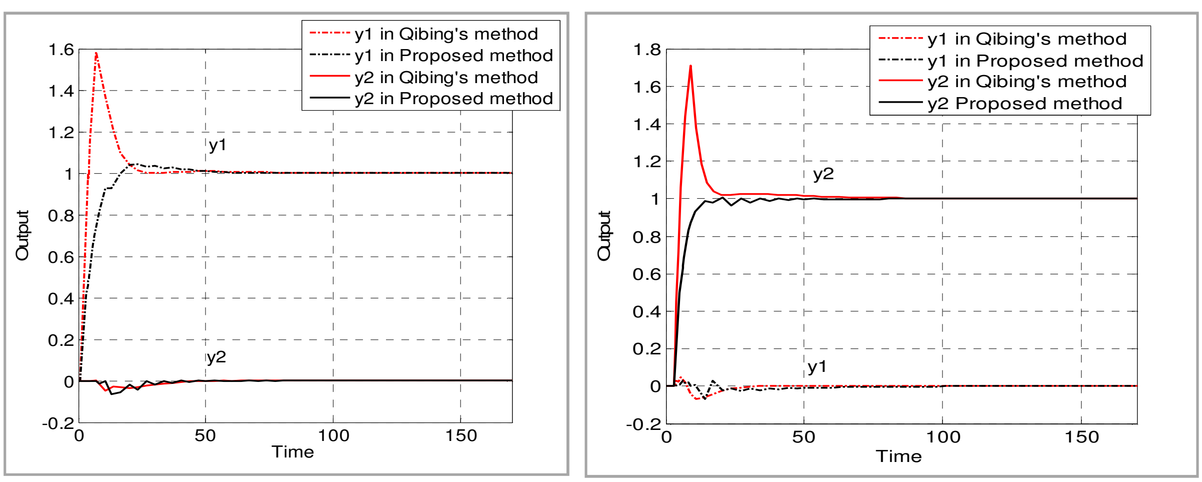


FIG.-5.5.20: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

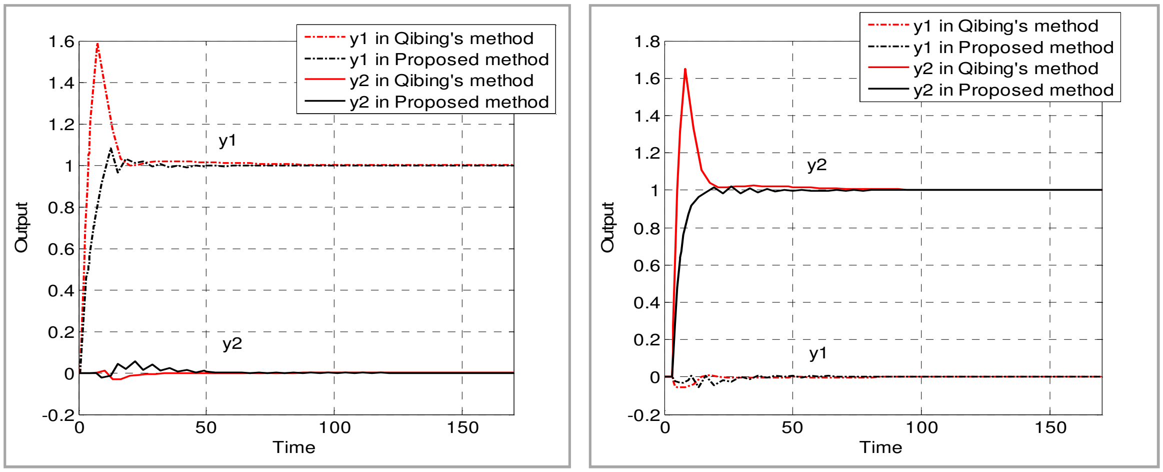


FIG.-5.5.21: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

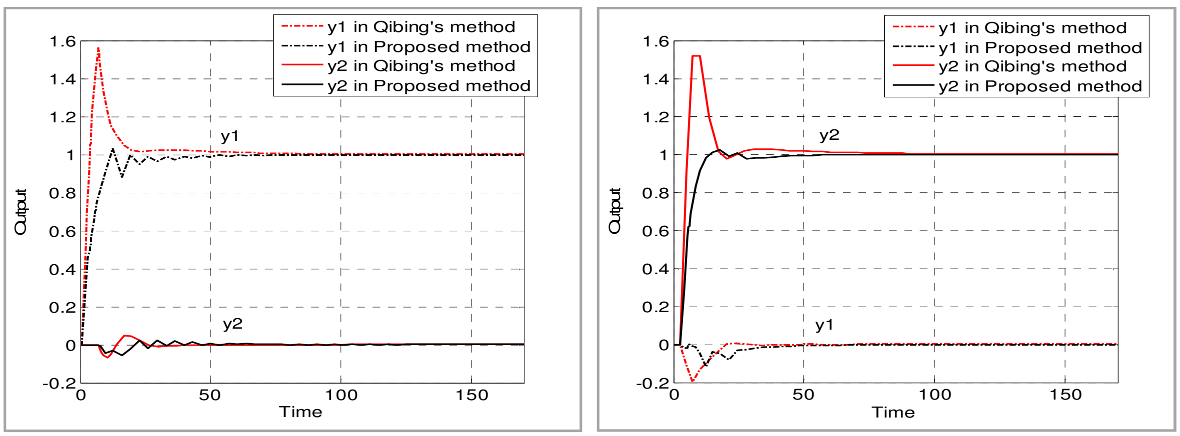


FIG.-5.5.22: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

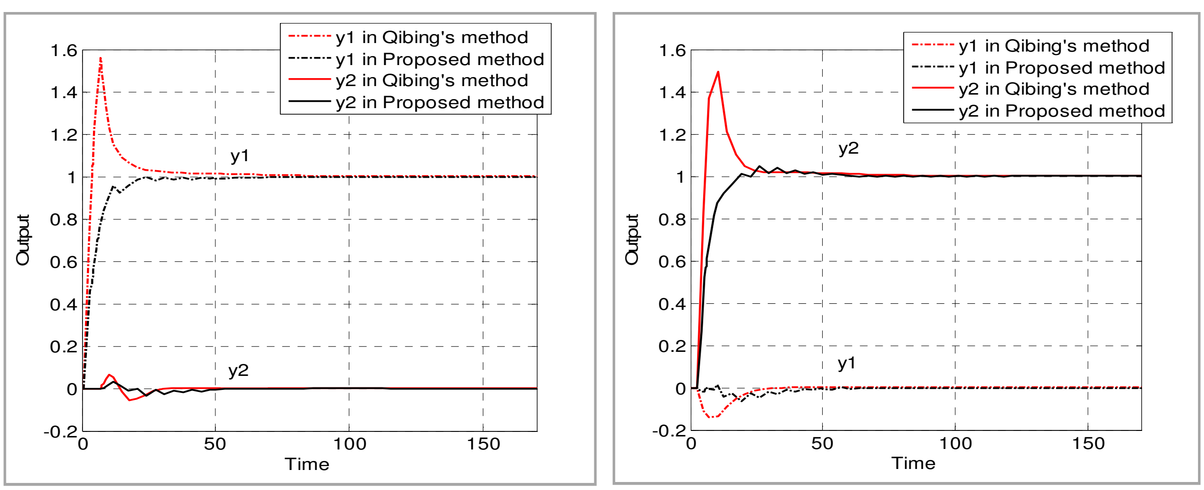


FIG.-5.5.23: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

(B) Here, time delay of one of the transfer function elements of process has been perturbed by +10% and results without disturbance have been observed.

(i) When time delay of G_{11} is perturbed by +10%, results are observed in Figure-5.5.24.

(ii) When time delay of G_{12} is perturbed by +10%, results are observed in Figure-5.5.25.

(iii)When time delay of G_{21} is perturbed by +10%, results are observed in Figure-5.5.26.

(iv)When time delay of G_{22} is perturbed by +10%, results are observed in Figure-5.5.27.

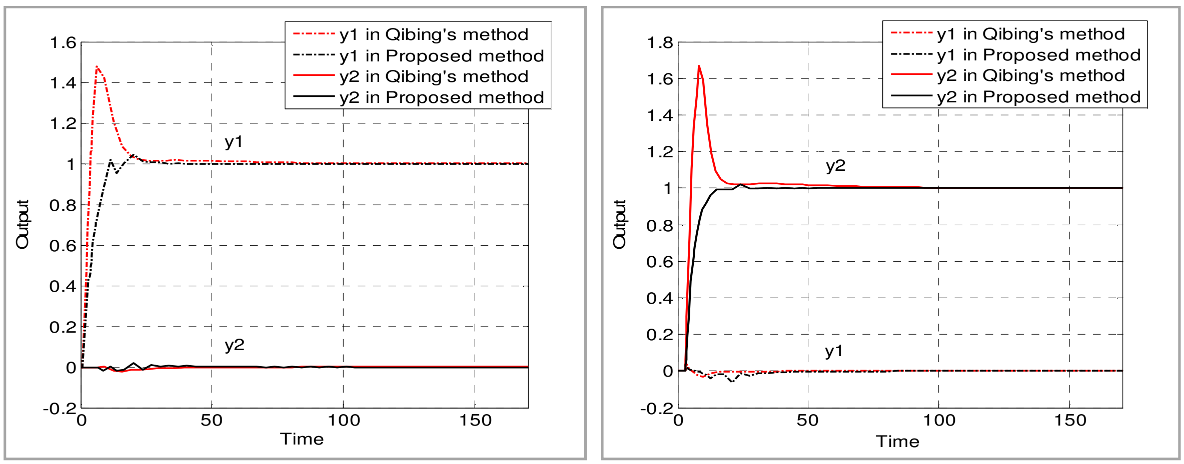


FIG.-5.5.24: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

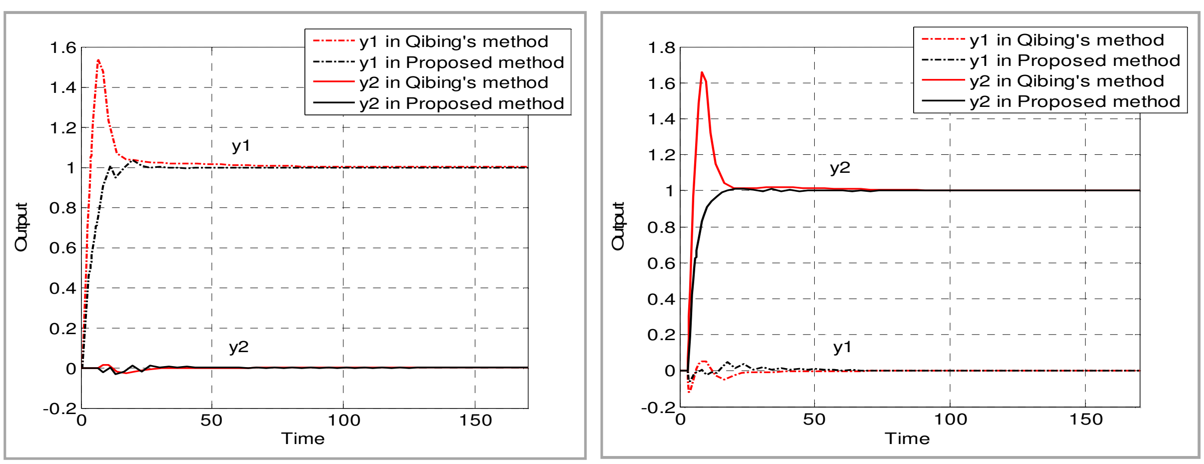


FIG.-5.5.25: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

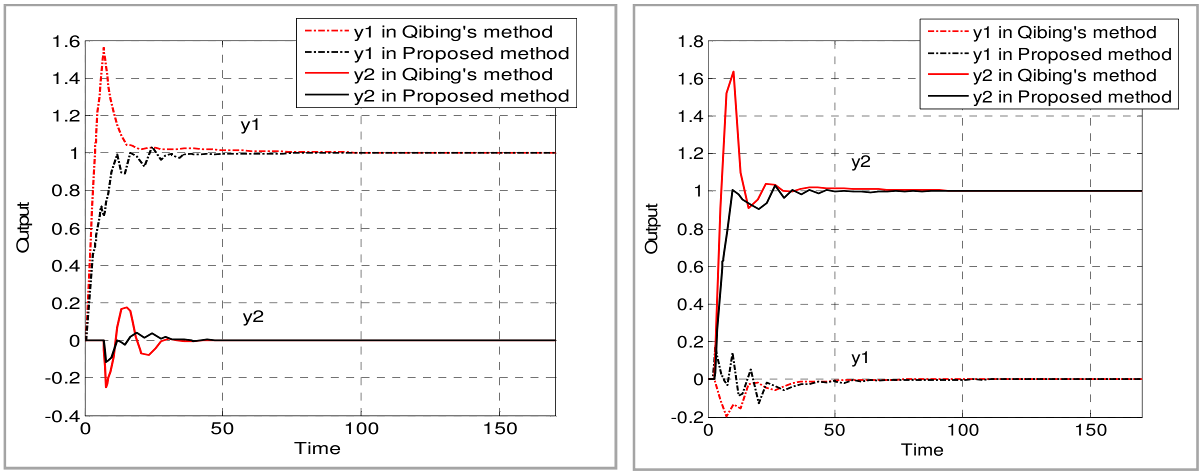


FIG.-5.5.26: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

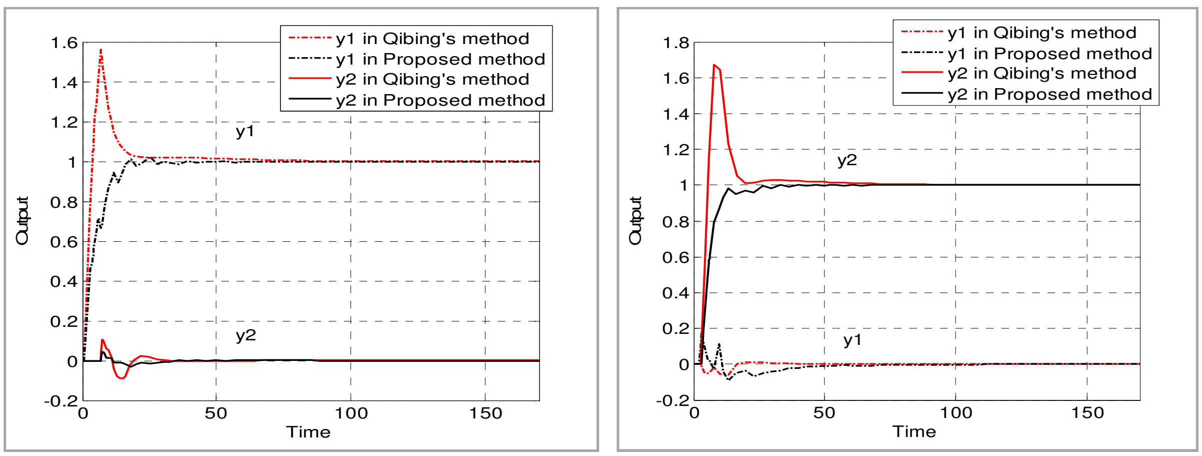


FIG.-5.5.27: OFF-NOMINAL PLANT OUTPUTS FOR STEP INPUT AT INPUT 1 & 2 RESPECTIVELY

- ***Pre-filter Design***

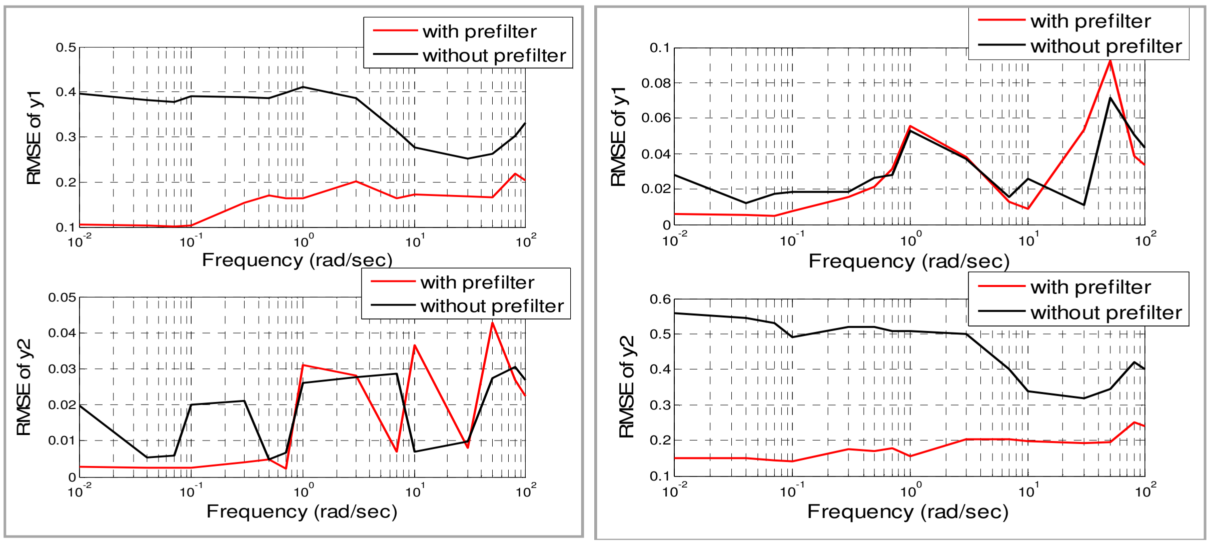
To improve tracking and decoupling results, a pre-filter or command modifier of transfer function $\frac{1}{5s+1}$ has been added without unduly slowing down the closed loop system. The pre-filter time constant has been chosen by selecting tuning compensator parameter using the SISO Design Tool in Matlab Control Toolbox of MATLAB R2008. Using this tuning parameter, satisfactory closed loop responses have been observed by LTI viewer.

- ***Tracking and Decoupling Results using Command Modifier***

To show the effectiveness of this pre-filter, frequency response has been used to plot Root Mean Square Error of the outputs and comparison has been done with and without pre-filter in Figure-

5.5.28. For this purpose, an external disturbance which was denoted by *D* in Figure-5.5.17 as a sinusoidal signal of amplitude 0.1 has been considered and by varying the frequency, Root Mean Square Error (RMSE) of output has been plotted in frequency domain. The frequencies of w= 0.01, 0.04, 0.07, 0.1, 0.3, 0.5, 0.7, 1, 3, 7, 10, 30, 50, 80, and 100 rad/sec have been considered for that purpose.

In Figure-5.5.28, tracking and decoupling results have been improved by adding a Command Modifier, without unduly slowing down the closed loop system.



(A) ***(B)***

FIG.-5.5.28: NOMINAL ROOT MEAN SQUARE ERROR (RMSE) OF OUTPUTS FOR UNIT STEP INPUT AND SINUSOIDAL DISTURBANCE (A) AT INPUT 1 (B) AT INPUT 2

5.6 Proposed Decoupling Internal Model Controller Design for Systems with V-structure

5.6.1 Design Steps

The Figure-5.5.16(B) is representing a 2X2 system with V structure.

From Figure-5.5.16(B),

$$\begin{aligned} y_1 &= g_{m11}(r_1 + g_{m12}y_2) \\ y_2 &= g_{m22}(r_2 + g_{m21}y_1) \end{aligned} \tag{5.6.1}$$

From (5.6.1) we get,

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \frac{g_{m11}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} & \frac{g_{m11}g_{m12}g_{m22}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} \\ \frac{g_{11}g_{21}g_{22}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} & \frac{g_{m22}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} \tag{5.6.2}$$

i.e. $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} G_{m11} & G_{m12} \\ G_{m21} & G_{m22} \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \end{bmatrix}$

where,

$$\frac{g_{m11}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} = G_{m11} \tag{5.6.3}$$

$$\frac{g_{m11}g_{m12}g_{m22}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} = G_{m12} \tag{5.6.4}$$

$$\frac{g_{m11}g_{m21}g_{m22}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} = G_{m21} \tag{5.6.5}$$

$$\frac{g_{m22}}{1-g_{m11}g_{m12}g_{m21}g_{m22}} = G_{m22} \tag{5.6.6}$$

- ***Controller realization***

Let, $\mathbf{G_m}(s)\mathbf{C}(s) = \begin{bmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{bmatrix}$ (5.6.7)

From (5.6.2), we can say that when the model is matched, if the system has to be decoupled, then $G_p(s)C(s)$ or $G_m(s)C(s)$ should be a diagonal matrix i.e. $h_{12}=0, h_{21}=0$. To satisfy this decoupling condition, the off-diagonal terms of the controller matrix are constrained as (using (5.6.3)- (5.6.7):

$$C_{12}(s) = -\frac{G_{m12}(s)}{G_{m11}(s)} C_{22}(s) = -g_{m12}(s).g_{m22}(s).C_{22}(s) \tag{5.6.8}$$

$$C_{21}(s) = -\frac{G_{m21}(s)}{G_{m22}(s)} C_{11}(s) = -g_{m11}(s).g_{m21}(s).C_{11}(s) \tag{5.6.9}$$

The off-diagonal terms are determined when diagonal terms are known and the diagonal terms are known from (5.6.7) using the concept of Internal Model Control as:

$$\begin{aligned} h_{11} &= G_{m11}(s).C_{11}(s) + G_{m12}(s).C_{21}(s) = 1 \\ h_{22} &= G_{m21}(s).C_{12}(s) + G_{m22}(s).C_{22}(s) = 1 \end{aligned} \tag{5.6.10}$$

From, (5.6.3) - (5.6.6) and (5.6.8) - (5.6.10) we get,

$$C_{11}(s) = \frac{1}{g_{m11}(s)}; C_{22}(s) = \frac{1}{g_{m22}(s)} \tag{5.6.11}$$

Now, according to the IMC principle, the minimum phase part of the transfer functions ($g_{m11}(s)$ and $g_{m22}(s)$) are inverted and then filters of suitable orders are added with the same. Thus $C_{11}(s)$ and $C_{22}(s)$ are obtained as proper transfer functions.

By adding filter transfer functions of suitable order $n1$ and $n2$ respectively,

$$C_{11}(s) = \frac{1}{g_{m11}(s)} * \frac{1}{(1+\lambda_1 s)^{n1}} \tag{5.6.12}$$

$$C_{22}(s) = \frac{1}{g_{m22}(s)} * \frac{1}{(1+\lambda_2 s)^{n2}} \tag{5.6.13}$$

Here, λ_1 and λ_2 are filter time constants. These tuning parameters can be obtained from the standard single loop design tool in Control System Toolbox.

5.6.2 Case Study -- Four Tank system

5.6.2.1 Plant model and Controller Design

The continuous time model of the Four Tank system (as shown in Figure-5.5.1) is obtained as

$$G_p(s) = \begin{bmatrix} \frac{0.6}{256s+1} e^{-60s} & \frac{0.41}{256s+1} e^{-120s} \\ \frac{0.42}{186s+1} e^{-120s} & \frac{0.56}{186s+1} e^{-60s} \end{bmatrix}$$

According to the design method described in Section 5.6.1, Internal Model Based Decoupling Controller is designed for Four Tank System with V structure [Dasgupta2014].

Let Internal Model Controller be $\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$.

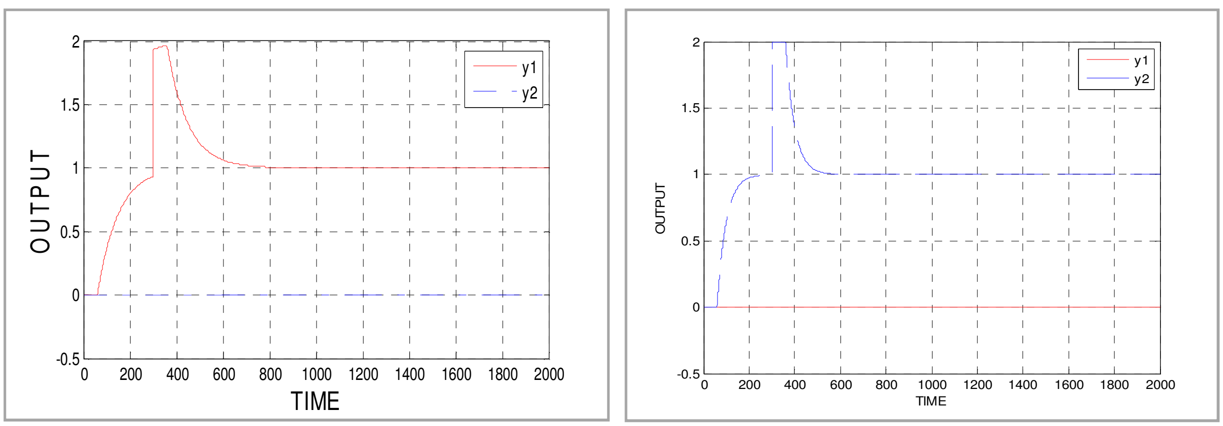
From (5.6.8), (5.6.9), (5.6.12), (5.6.13)

$$C_{11} = \frac{(256s+1)}{0.6(\lambda_1 s+1)};\ C_{22} = \frac{(186s+1)}{0.56(\lambda_2 s+1)}; C_{12} = -\frac{0.41}{(256s+1)(\lambda_2 s+1)} e^{-180s}; C_{21} = -\frac{0.42}{(186s+1)(\lambda_1 s+1)} e^{-180s}$$

The values of λ_1=89 and λ_2=39 are obtained by Internal Model Control (IMC) Tuning (a GUI Approach) using standard single loop design tool "sisotool" in Matlab Control Toolbox of MATLAB R2008a.

5.6.2.2 Simulation Results

The objectives of Internal Model Based Decoupling Control (i.e. tracking, disturbance rejection , robustness and decoupling) have been investigated. For this purpose, we have used a step input at t=0 Sec and a step disturbance of unit amplitude at t= 300Sec at input 1. In Figure-5.6.1(A), the response y1 is shown in which set-point tracking and disturbance rejection have been achieved. In addition to that, y2 is successfully decoupled with respect to input 1. Again, we have applied a step input at t=0 Sec and a step disturbance of unit amplitude at t= 300Sec at input 2. In the Figure-5.6.1(B), the response y2 is shown. It clearly shows that set-point tracking and disturbance rejection are achieved. A good decoupling result is obtained from y1 in the same Figure-5.6.1(B).

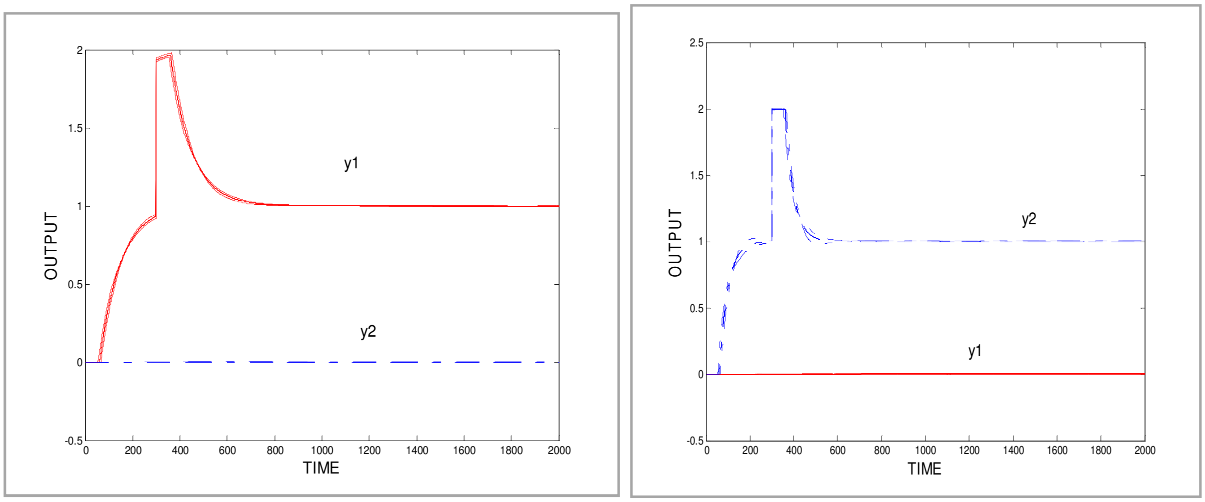


(A) *(B)*

FIG.-5.6.1: NOMINAL PLANT OUTPUT FOR STEP DISTURBANCE AND STEP INPUT (A) AT INPUT 1 (B) AT INPUT 2

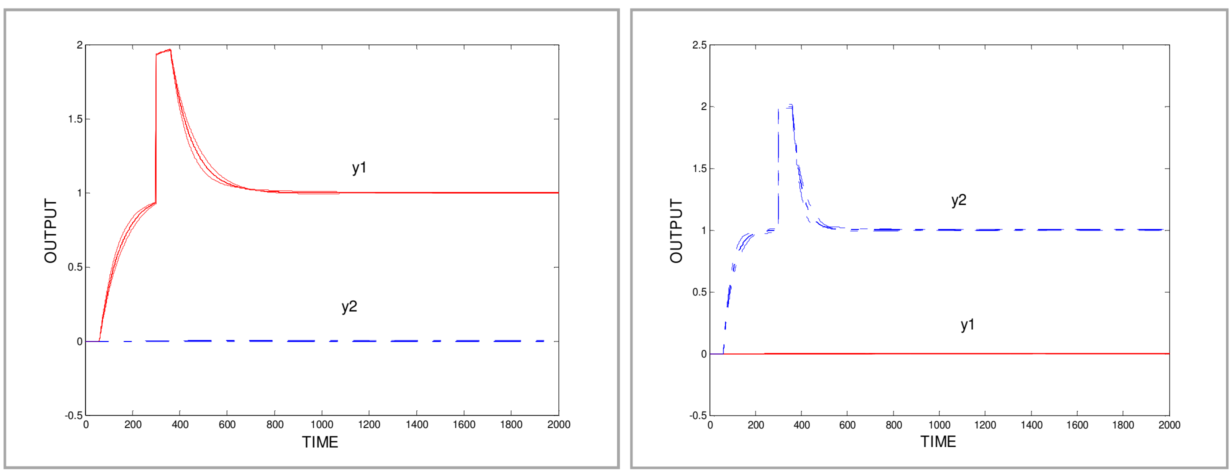
- ***Robustness Study***

Here, the parameters of the Process, namely Time Delay and Time Constant have been perturbed by ±10% to inspect the robustness of the system. Each element of the process transfer function matrix has been considered and perturbed, one at a time. It has been shown in Figure-5.6.2- 5.6.3, that a minor change in the outputs is there in the off-nominal condition. This indicates the robustness of the system with respect to parameter uncertainty.



(A) *(B)*

FIG.-5.6.2: OFF-NOMINAL PLANT (±10% PERTURBATION ON TIME DELAY) OUTPUTS FOR STEP DISTURBANCE AND STEP INPUT (A) AT INPUT 1 (B) AT INPUT 2



(A) *(B)*

FIG.-5.6.3: OFF-NOMINAL PLANT (±10% PERTURBATION ON TIME CONSTANT) OUTPUTS FOR STEP DISTURBANCE AND STEP INPUT (A) AT INPUT 1 (B) AT INPUT 2.

5.6.2.3 Gershgorin Band Interpretation of Decoupling

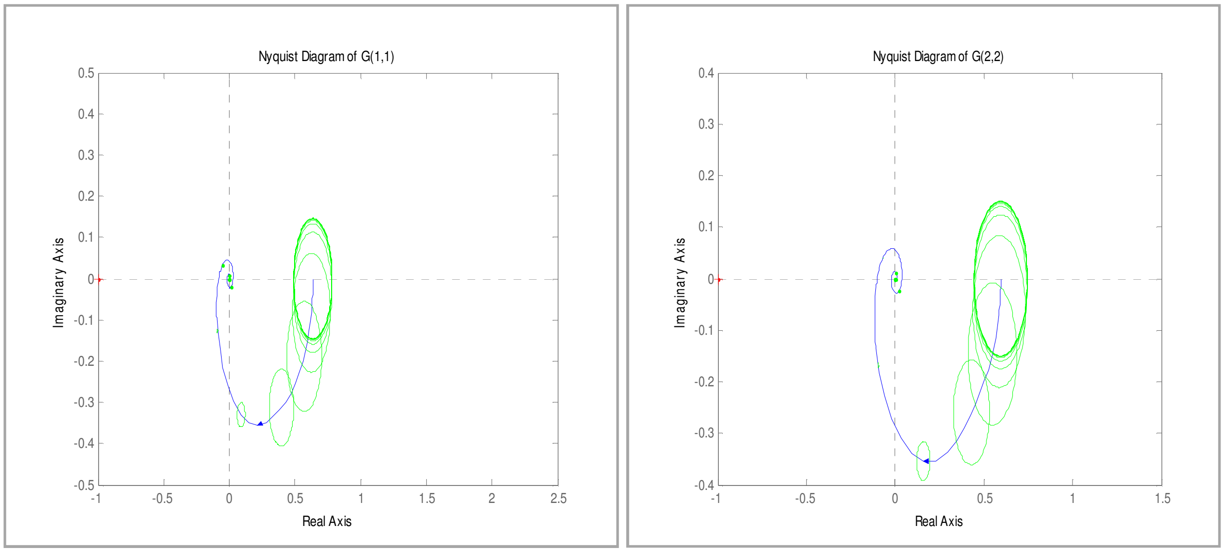


FIG.-5.6.4: GERSHGORIN BAND (ROW-WISE) FOR UNCOMPENSATED FOUR TANK SYSTEM

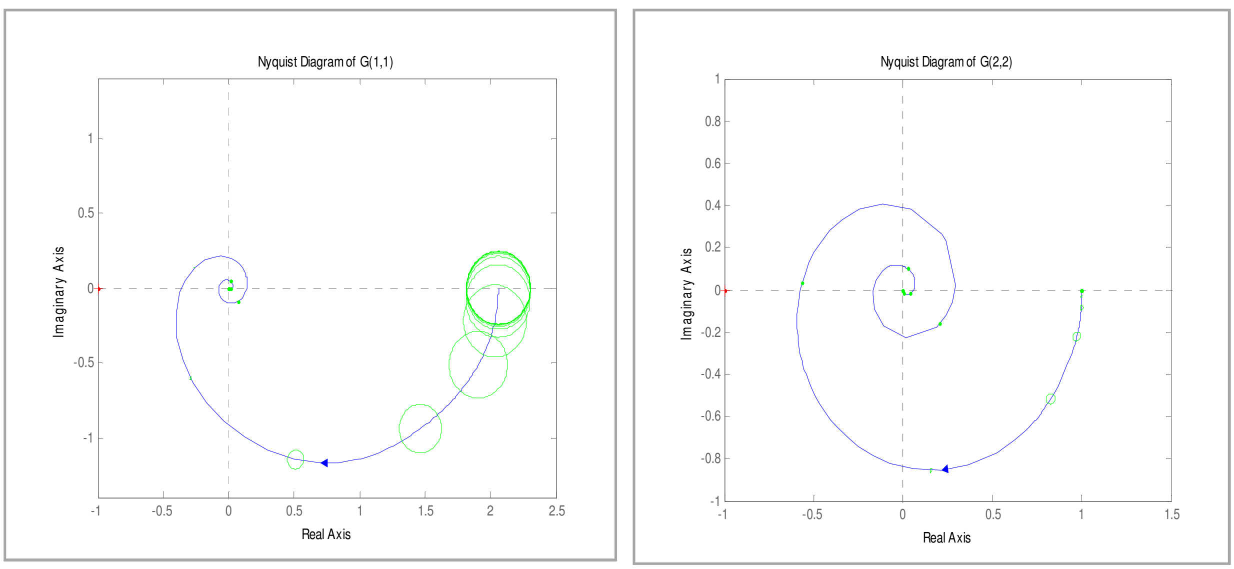


FIG.-5.6.5: GERSHGORIN BAND (ROW-WISE) FOR COMPENSATED FOUR TANK SYSTEM

Row wise Gershgorin bands are evaluated for the uncompensated system in Figure-5.6.4. The radius of Gershgorin circles indicate that the Four Tank System is a coupled one. Similarly, row wise Gershgorin bands for the compensated system are evaluated in Figure-5.6.5. Here Gershgorin circles are of sufficiently smaller radius, though some coupling is present at adequately low order frequencies (below 0.0009 rad/sec). Similar low frequency decoupling can be observed in time response by using a sinusoidal input with appropriate frequency. This demonstrates that a satisfactory degree of decoupling is achieved.

5.7 Chapter Conclusion

In this work, some new methods of Decoupling Internal Model control is proposed for MIMO time delay system with P and V structure. The Internal Model Controller that has been designed can decouple the system, provided that the system is square and stable. The aspects of IMC are compared between the proposed IMC method and an existing IMC method using different benchmark problems. It has been shown that the proposed controllers provide superior set-point tracking, disturbance rejection, robustness with respect to parametric uncertainty. Moreover, good degree of decoupling in proposed methods have been demonstrated by using Gershgorin Bands. Additionally, an Internal Model Based Inverted Decoupling controller design has been proposed in a straight forward and simplified manner and applied for MIMO systems with multiple time delay. Superior set-point tracking, decoupling, disturbance rejection and robustness results have been demonstrated in this work than predecessor approach.

Chapter 6: Modified Active Anti-Disturbance Control for linear MIMO systems with time delay

6.1 Chapter Introduction and previous work

Time delay and non-minimum phase systems are very common in Industrial process control applications. Research on control of MIMO time delay (or with non-minimum phase) systems with coupling are increasing research trend [Wang2003]. Modified Active Anti-Disturbance Control architecture (MAADC) for MIMO time delay or non-minimum phase systems has been proposed in this chapter.

In IMC literature, several publications exist on MIMO time delay systems. In [Wang2002], an approach to the decoupling Internal Model Control (IMC) analysis and design based on model reduction procedure has been proposed for multivariable stable processes with multiple time delays. Another method based on linear matrix inequality (LMI) for designing multivariable internal model control has been proposed in [Yang2005]. In [Liu2006], a decoupling IMC scheme has been proposed for a 2X2 process with time delay. An analytical design and tuning method for the multivariable controller for stable, linear, MIMO process with multiple time delay and non-minimum phase zero has been proposed In [Chen2007b]. In [Chen2011], a method using Internal Model Control was proposed to design Smith delay compensation decoupling controller for multivariable non-square systems with transfer function elements consisting of first order and time delay.

Linear MIMO DOB has been surveyed in [Shahruz2008, Chen2009, G¨uvenc2010, Zhou2012, Li2013, Zhou2014, Zhang2015]. Here, mainly two types of strategies have been documented. In [Zhou2014, Zhang2015], MIMO DOB has been designed by considering all the elements of the plant transfer function (without using input-output pairing). In the rest of the papers [Shahruz2008, Chen2009, G¨uvenc2010, Zhou2012, Li2013], input-output pairing has been used. In [Shahruz2008], MIMO (without delay) DOB structure is in the form of IMC has been proposed. But, without using system inversion, design has been done using two techniques: (i) Technique based on minimization of a H_∞ norm and (ii) Technique based on parametric optimization. In [Chen2009], a ball mill grinding circuit (a MIMO time delay system) has been considered. A feasible variable pairing u1-y1 and u2 -y2 have been done according to RGA analysis. Then MDOB has been designed for diagonal elements of transfer function matrix G_{11} and G_{22} (based on [Zhu2005]). A decoupling-type MIMO disturbance observer architecture was formulated in [G¨uvenc2010] for square systems. A multi-objective parameter space DOB design procedure satisfying certain D-stability, mixed sensitivity, and desired phase margin objectives was presented. In [Zhou2012] an improved DOB (IDOB) has been proposed for MIMO non-minimum phase time delay system. Then disturbance rejection performance of MPC has been improved by using a compound control scheme (IDOB-MPC). In [Li2013], Bank-to-Turn (BTT) missile dynamics were divided into three subsystems and DOB was introduced for each subsystem to estimate both the nonlinear couplings and the external disturbances. In [Zhou2014], a MDOB has been proposed for a Grinding circuit (a MIMO system with multiple time delay and non-minimum phase zero). In [Zhang2015], MDOB for both stable and unstable MIMO system with multiple time delay has been proposed.

There are a handful of papers [Chen2011, Zhang2016, Qi-bing2015] available using linear MIMO IMC and DOB which have been used together to design AADC. In Chen2011, as an inner-loop controller, IMC and as an outer-loop controller, PI were used for SISO time delay systems. In addition to that, IMC and DOB were combined to get better disturbance rejection than using IMC alone. Zhang et. al. have been proposed in [Zhang2016], a H_2 analytical decoupling control scheme with multivariable DOB for both stable and unstable MIMO systems with multiple time delay; using IMC and H_2 optimal decoupling design method, controller has been designed. Active disturbance rejection internal model control has been used in [Qi-bing2015] using IMC plus DOB for SISO time delay system (FOPDT and SOPDT).

The contribution of the chapter is that a Modified Active Anti-Disturbance control (AADC) architecture (using linear MIMO IMC and linear MIMO DOB) has been used for linear MIMO time delay systems with non-minimum phase part. Also, sensitivity analysis has been done for systems with process-model uncertainty. It has been found that in the presence of process model mismatch, measurement disturbance rejection capability of AADC is superior than IMC. An IMC controller formulation developed in Section 5.5 has been adopted in this chapter. In Grinding circuit case study, existing MIMO DOB [Zhou2012] has been added with this IMC and disturbance rejection for AADC has been achieved. Additionally, this AADC has been compared with IMC. In another case study, DOB for MIMO system with multiple time delay has been taken from [Zhang2016].

6.2 Proposed Methodology for Decoupling Control using MIMO IMC and MIMO DOB for systems with time delay

Internal Model Controller design for MIMO systems with time delay has been depicted in Chapter 5. As described in [Shahruz2008], MIMO DOB has been shown in Figure -6.2.1. Here, $\mathbf{G_p}$ is linear MIMO system, $\mathbf{G_m}$ is linear MIMO model, $\mathbf{G_m}^{-1}$ is MIMO model inverse and $\mathbf{Q}$ is the low pass filter. $\hat{\mathbf{D}}, \mathbf{D}, \mathbf{U}, \mathbf{Y}$ denote estimated disturbance, process disturbance, command of the controller (which is not shown in figure) and output of the process respectively.

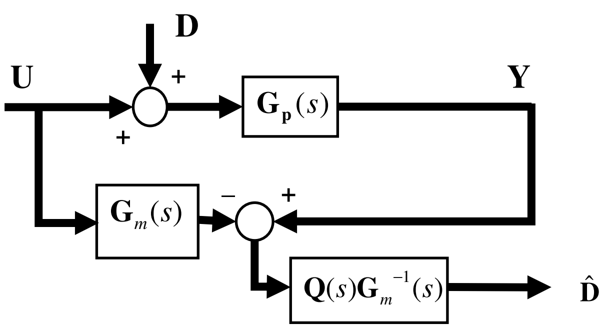


FIG.-6.2.1: DOB STRUCTURE FOR MIMO LINEAR SYSTEMS

Using IMC and DOB for linear MIMO systems with time delay or non-minimum phase part, an AADC architecture has been reiterated in Figure-6.2.2. In this current figure, AADC architecture has been used for linear MIMO system, where $\mathbf{C}$ is the Internal Model Controller. The IMC section and DOB section has been shown using dotted lines. Here, $\mathbf{Q}, \hat{\mathbf{D}}, \mathbf{D}, \mathbf{D}_1, \mathbf{R}, \mathbf{Y}$ denote low pass filter, estimated disturbance, process disturbance, measurement disturbance, set-point and output respectively.

Internal model controller $\mathbf{C}(s)$ has been designed as combination of inverse of the process model transfer function matrix $\mathbf{G_m}^{-1}(s)$ and low pass transfer function matrix $\mathbf{Q}_1(s)$. Thus, $\mathbf{C}(s) = \mathbf{G_m}^{-1}(s).\mathbf{Q}_1(s)$.

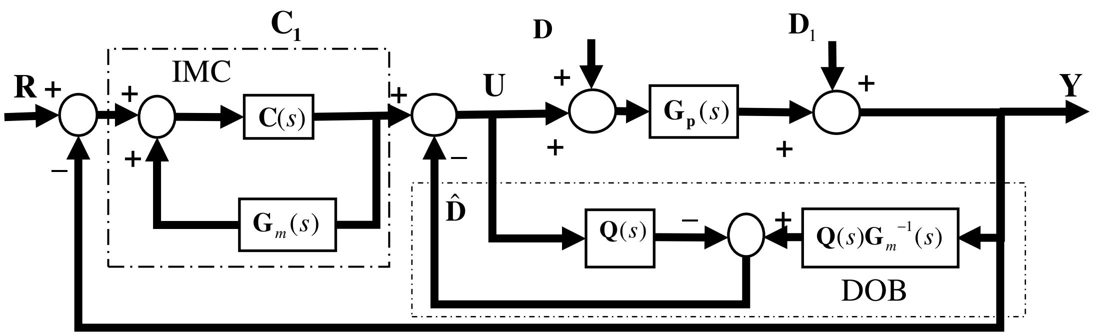


FIG.-6.2.2: MAADC STRUCTURE

In case of IMC, transfer function between $\mathbf{Y}$ and $\mathbf{D_1}$ is represented by $T_{1\mathbf{YD_1}}$ (block diagram of IMC alone has been presented in section-5.3), where $T_{1\mathbf{YD_1}}(s) = \dfrac{1-\mathbf{C}(s)\mathbf{G_m}(s)}{1+\mathbf{C}(s)(\mathbf{G_p}(s)-\mathbf{G_m}(s))}$.

As, $\mathbf{C}(s) = \mathbf{G_m}^{-1}(s).\mathbf{Q}_1(s)$ and at low frequency range, $|\mathbf{Q}_1(jw)| \approx 1$.So, in low frequency range, $|\mathbf{T_{1YD_1}}(jw)| \approx 0$; which implies low frequency measurement disturbance rejection can be obtained for IMC.

For MAADC as shown in Figure-6.2.2, transfer function matrix between $\mathbf{Y}$ and $\mathbf{D_1}$ is represented as $\mathbf{T_{YD_1}}$; transfer function matrix between $\mathbf{Y}$ and $\mathbf{D_2}$ is represented as $\mathbf{T_{YD_2}}$.

Where, $\mathbf{T_{YD1}}(s) = \dfrac{\mathbf{G_m}(s)\mathbf{G_p}(s)(1-\mathbf{Q}(s))}{\mathbf{G_m}(s)(1+\mathbf{G_p}(s)\mathbf{C}_1(s)) + \mathbf{Q}(s)(\mathbf{G_p}(s)-\mathbf{G_m}(s))}$;

$$\mathbf{T_{YD2}}(s) = \frac{\mathbf{G_m}(s)(1-\mathbf{Q}(s))}{\mathbf{G_m}(s)(1+\mathbf{G_p}(s)\mathbf{C}_1(s)) + \mathbf{Q}(s)(\mathbf{G_p}(s)-\mathbf{G_m}(s))}$$

Here, $\mathbf{C_1}(s) = \dfrac{\mathbf{C}(s)}{1-\mathbf{C}(s)\mathbf{G_m}(s)}$

At low frequency range, $|\mathbf{Q}(jw)| \approx 1$.

Thus, in low frequency range, $|\mathbf{T_{YD_1}}(jw)| \approx 0$ and $|\mathbf{T_{YD_2}}(jw)| \approx 0$ which implies that low frequency measurement disturbance and process disturbance rejection can be obtained for AADC.

Now, for process-model mismatch, sensitivity study has been performed and it has been found that AADC posses superior measurement disturbance rejection capability than the IMC.

For process model mismatch, it has been assumed that $\mathbf{G}_{\mathbf{m}}(s) = \gamma.\mathbf{G}_{\mathbf{p}}(s)$.

It has been assumed as γ is close to the value 1. i.e. $1-\gamma \rightarrow 0$. Also, $Q \approx Q_1$ has been assumed.

For IMC, $\dfrac{\partial T_{YD_2}}{\partial \gamma} \approx \dfrac{(Q - Q^2)}{\gamma^2}$.

For AADC, $\dfrac{\partial T_{YD_2}}{\partial \gamma} \approx \dfrac{(Q - Q^2)}{\gamma^2}.(1-Q)^2$.

As, $Q \rightarrow 1$, $(1-Q)^2$ is a small positive value and $(1-Q)^2 << 1$.

Thus, $\dfrac{\partial T_{YD_2}}{\partial \gamma}$ for AADC is smaller than IMC. It can be said that sensitivity with respect to process-model mismatch for IMC is greater than AADC when measurement disturbance rejection is concerned. Similar thing can be proved for process disturbance rejection also.

6.3 Case Study I-- Shell Heavy Oil Process

In Case Study-1, a Shell Heavy Oil Process has been used, which is a Two Input Two Output (TITO) linear system with multiple time delay. In this section, the Modified AADC has been designed and comparison has been evaluated between AADC and IMC.

6.3.1 Plant model and Controller Design

For Shell Heavy Oil 2 X 2 process [Zhang2016], model transfer function matrix has been denoted as $\mathbf{G}_{\mathbf{m}}(s)$.

$$\mathbf{G}_{\mathbf{m}}(s) = \begin{bmatrix} \dfrac{4.05}{27s+1}e^{-27s} & \dfrac{1.77}{60s+1}e^{-28s} \\ \dfrac{5.39}{50s+1}e^{-18s} & \dfrac{5.72}{60s+1}e^{-14s} \end{bmatrix},$$

where, $G_{m11} = \frac{4.05}{27s+1}e^{-27s} = \frac{4.05}{27s+1}.\frac{1}{(1+13.5s)^2}$; $G_{m12} = \frac{1.77}{60s+1}e^{-28s}$; $G_{m21} = \frac{5.39}{50s+1}e^{-18s}$;

$G_{m22} = \frac{5.72}{60s+1}e^{-14s} = \frac{5.72}{60s+1}.\frac{1}{(1+7s)^2}$.

The real plant transfer function of the Shell Heavy Oil process [Zhang2016] has been denoted as $\mathbf{G_p}(s)$.

$$\mathbf{G_p}(s) = \begin{bmatrix} \frac{4.86}{29.7s+1}e^{-29.7s} & \frac{1.416}{54s+1}e^{-22.4s} \\ \frac{6.468}{45s+1}e^{-21.6s} & \frac{4.676}{66s+1}e^{-11.2s} \end{bmatrix},$$

where, $G_{p11} = \frac{4.86}{29.7s+1}e^{-29.7s}$; $G_{mp2} = \frac{1.416}{54s+1}e^{-22.4s}$; $G_{p21} = \frac{6.468}{45s+1}e^{-21.6s}$; $G_{p22} = \frac{4.676}{66s+1}e^{-11.2s}$.

The method described in Section 5.3, has been followed to design the Internal Model Controller ($\mathbf{C}(s)$) for the above Shell Heavy Oil process. Here, $\mathbf{C}(s) = \begin{bmatrix} C_{11}(s) & C_{12}(s) \\ C_{21}(s) & C_{22}(s) \end{bmatrix}$.

$$\Delta = 1 - \left.\frac{G_{m12}G_{m21}}{G_{m11}G_{m22}}\right|_{s=0} = 0.5882.$$

$$C_{11} = \frac{1}{G_{m11}.\Delta}.F_1 = \frac{(27s+1)(1+13.5s)^2}{4.05}.\frac{1}{0.5882}.\frac{1}{(a_1s+1)^3};$$

$$C_{22} = \frac{1}{G_{m22}.\Delta}.F_1 = \frac{(60s+1)(1+7s)^2}{5.72}.\frac{1}{0.5882}.\frac{1}{(a_2s+1)^3}$$

$$C_{12} = -\frac{G_{12}}{G_{11}}C_{22} = -\frac{0.1299(27s+1)(7s+1)^2e^{-s}}{(a_2s+1)^3}$$

$$C_{21} = -\frac{G_{21}}{G_{22}}C_{11} = -\frac{0.3956(60s+1)(27s+1)(13.5s+1)^2e^{-4s}}{(50s+1)(a_1s+1)^3}$$

Where low pass filter time constants have been taken as a_1 and a_2. In the simulation, filter time constants have been taken as $a_1 = a_2 = 80$ [Zhang2016].

6.3.2 Simulation Results

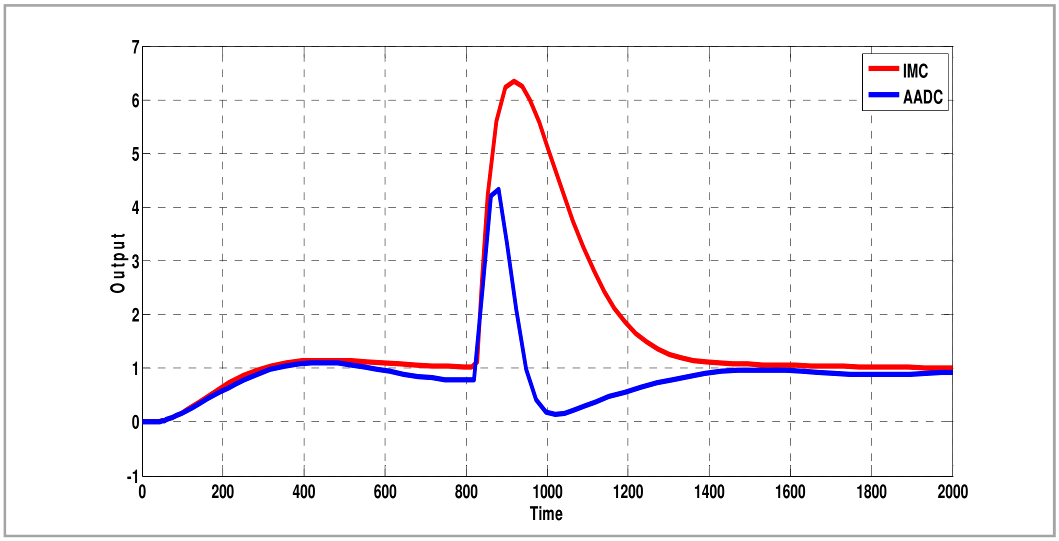


FIG.-6.3.1: RESPONSE Y1 WHEN R1=UNIT STEP, R2=0 AND PROCESS DISTURBANCES ARE UNIT STEP AT T=800S

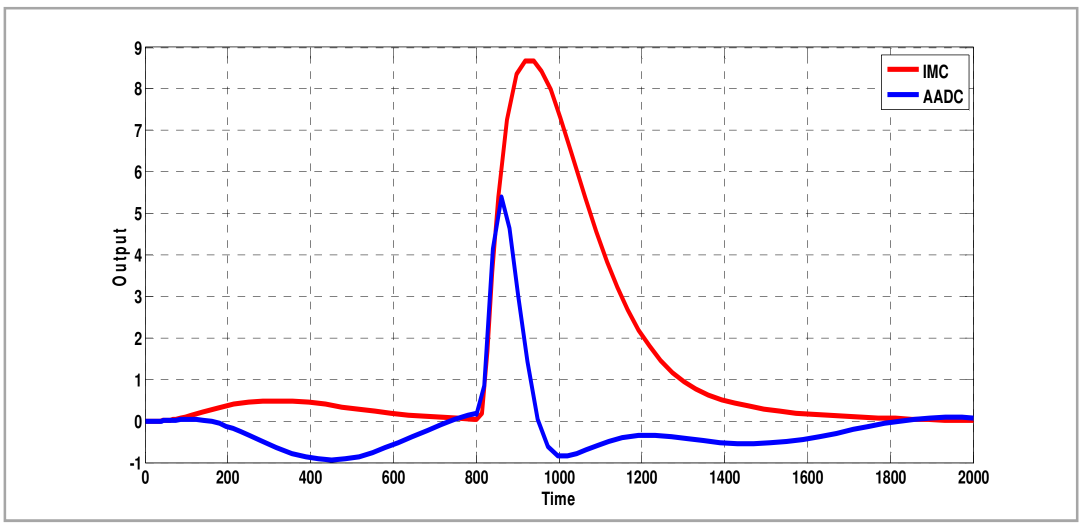


FIG.-6.3.2: RESPONSE Y2 WHEN R1=UNIT STEP, R2=0 AND PROCESS DISTURBANCES ARE UNIT STEP AT T=800S

In this section, process disturbance rejection has been compared between IMC and AADC.

In Figure-6.3.1 and Figure-6.3.2, unit step input has been applied to input 1, considering other input as zero. For both the cases, process disturbances have been added as another type of step signal starting from 800 Sec. In Figure-6.3.1, output 1 has been shown where process disturbances are added in disturbance input 1 and disturbance input 2 simultaneously. Similarly, in Figure-6.3.2, output 2 has been shown. For all the cases, IMC and Modified AADC have been compared. It has been noted that Modified AADC achieved superior disturbance rejection than using IMC alone.

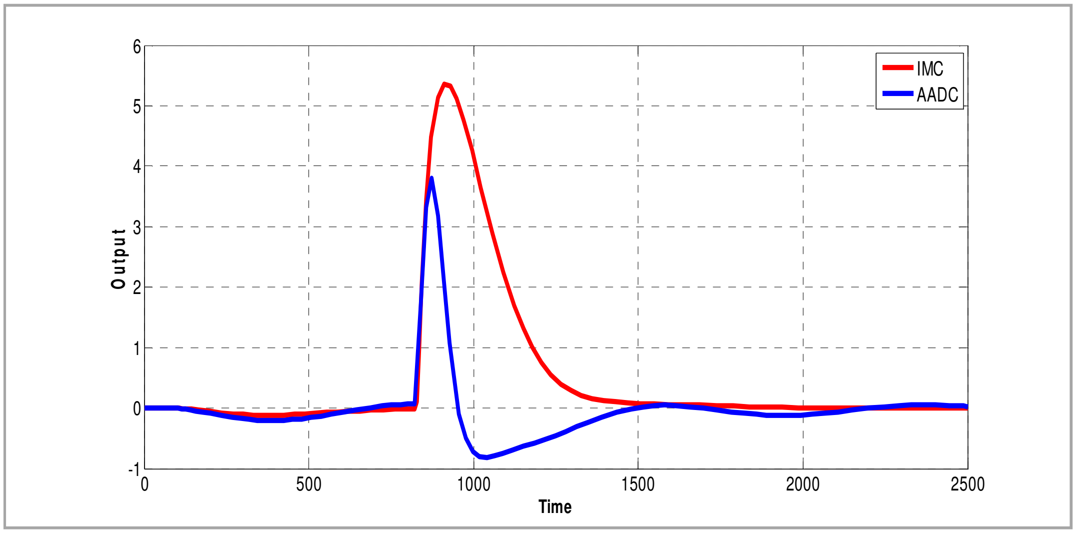


FIG.-6.3.3: RESPONSE Y1 WHEN R1=0, R2= UNIT STEP AND PROCESS DISTURBANCES ARE UNIT STEP AT T=800S

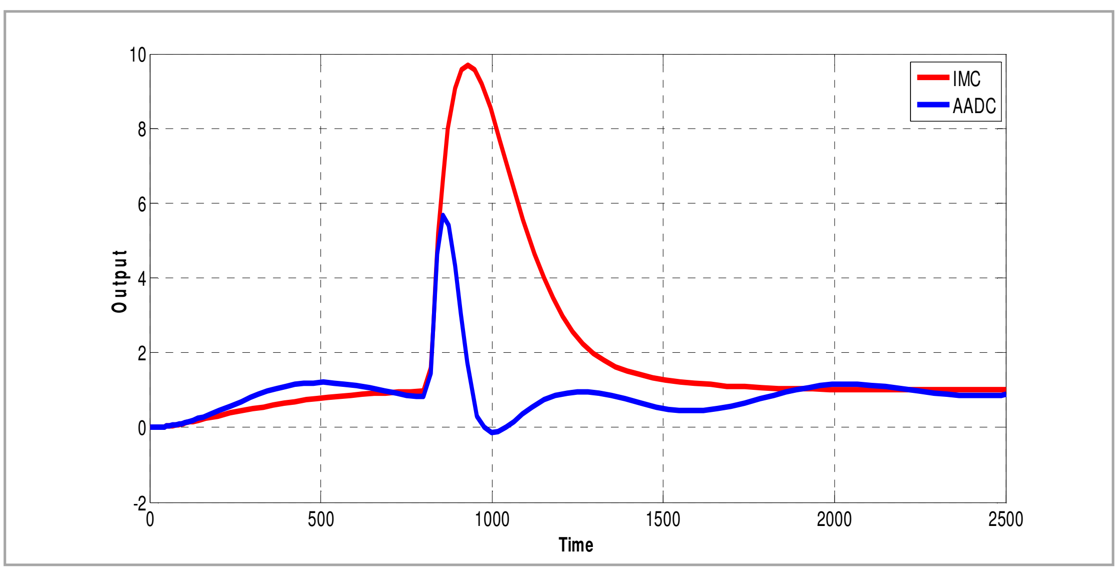


FIG.-6.3.4: RESPONSE Y2 WHEN R1=0, R2= UNIT STEP AND PROCESS DISTURBANCES ARE UNIT STEP AT T=800S

In Figure-6.3.3 and Figure-6.3.4, unit step input has been applied to input 2, considering other input as zero. For both the cases, process disturbances have been added as another type of step signal starting from 800 Sec in process disturbance 1 and 2 simultaneously. In Figure-6.3.3 and in Figure-6.3.4, output 1 and output 2 has been shown respectively. For all the cases, it has been shown that Modified AADC posses better disturbance rejection capability than IMC.

6.4 Case Study II-- Grinding Circuit

Grinding circuit is a significantly used plant in process control applications. Here, a Two Input Two Output (TITO) model of Grinding circuit with non-minimum phase and time delay has been used and performance comparison has been shown between AADC and IMC.

6.4.1 Plant model and Controller Design

Multivariable Grinding circuit system [Zhou2012] has been shown where real process $\mathbf{G_p}(s)$ has been given, where $\mathbf{G_p}(s) = \begin{bmatrix} \dfrac{-0.45(-1.8s+1)}{(0.9s+1)(17s+1)}e^{-9s} & \dfrac{0.06(64s+1)}{(2s+1)(20s+1)}e^{-1.8s} \\ \dfrac{3.15}{(16s+1)(2.5s+1)}e^{-6.4s} & \dfrac{1.05(-5s+1)}{(4s+1)(2.8s+1)}e^{-1.1s} \end{bmatrix}$;

Here, $G_{p11} = \dfrac{-0.45(-1.8s+1)}{(0.9s+1)(17s+1)}e^{-9s}$; $G_{p12} = \dfrac{0.06(64s+1)}{(2s+1)(20s+1)}e^{-1.8s}$; $G_{p21} = \dfrac{3.15}{(16s+1)(2.5s+1)}e^{-6.4s}$;

$G_{p22} = \dfrac{1.05(-5s+1)}{(4s+1)(2.8s+1)}e^{-1.1s}$

Model transfer function of Grinding Circuit system is denoted as $\mathbf{G_m}(s)$.

$$\mathbf{G_m}(s) = \begin{bmatrix} \dfrac{-0.5(-2.2s+1)}{(1.2s+1)(20s+1)}e^{-8.5s} & \dfrac{0.057(70s+1)}{(1.8s+1)(17s+1)}e^{-1.5s} \\ \dfrac{2.67}{(14s+1)(2s+1)}e^{-6s} & \dfrac{0.91(-4.8s+1)}{(3.6s+1)(2.2s+1)}e^{-0.8s} \end{bmatrix},$$

Where $G_{m11} = \dfrac{-0.5(-2.2s+1)}{(1.2s+1)(20s+1)}e^{-8.5s}$; $G_{m12} = \dfrac{0.057(70s+1)}{(1.8s+1)(17s+1)}e^{-1.5s}$; $G_{m21} = \dfrac{2.67}{(14s+1)(2s+1)}e^{-6s}$;

$G_{m22} = \dfrac{0.91(-4.8s+1)}{(3.6s+1)(2.2s+1)}e^{-0.8s}$

- ***IMC Design***

IMC design has been performed as depicted in Section 5.3.

$$\frac{G_{m21}}{G_{m22}} = \frac{2.67e^{-6s}}{(14s+1)(2s+1)}.\frac{(3.6s+1)(2.2s+1)}{0.91(-4.8s+1)e^{-0.8s}}$$

$$\frac{G_{m12}}{G_{m11}} = \frac{-0.057(70s+1)e^{-1.5s}}{(1.8s+1)(17s+1)}.\frac{(1.2s+1)(20s+1)}{0.5(-2.2s+1)e^{-8.5s}}$$

Now, Q_1 is RHS part of $\frac{G_{m21}}{G_{m22}}$ and Q_2 is RHS part of $\frac{G_{m12}}{G_{m11}}$.

So, $Q_1 = \frac{1}{(-4.8s+1)}$; $Q_2 = \frac{1}{(-2.2s+1)e^{-7s}}$

Let Internal model controller is $\mathbf{C}(s) = \begin{bmatrix} C_{11}(s) & C_{12}(s) \\ C_{21}(s) & C_{22}(s) \end{bmatrix}$,

Where $C_{11}(s) = \frac{1}{G_{11}(s)\Delta}.F_1.Q_1^{-1}$; $C_{22}(s) = \frac{1}{G_{22}(s)\Delta}.F_2.Q_2^{-1}$;

$C_{12} = -\frac{G_{12}(s)}{G_{11}(s)}C_{22}(s)$; $C_{21} = -\frac{G_{21}(s)}{G_{22}(s)}C_{11}(s)$

Since, $\Delta = 1 - \left.\frac{G_{12}G_{21}}{G_{11}G_{22}}\right|_{s=0}$ =1.3345.

$$C_{11}(s) = -\frac{1.4987(1.2s+1)(20s+1)(4.25s+1)^2(-4.8s+1)}{(\lambda_1 s+1)^5};$$

$$C_{22}(s) = \frac{0.8235(3.6s+1)(2.2s+1)(0.4s+1)^2(-2.2s+1)}{(\lambda_2 s+1)^5}e^{-7s};$$

$$C_{12}(s) = \frac{0.0939(70s+1)(1.2s+1)(20s+1)(3.6s+1)(2.2s+1)(0.4s+1)^2}{(1.8s+1)(17s+1)(\lambda_2 s+1)^5};$$

$$C_{21}(s) = \frac{4.3973(3.6s+1)(2.2s+1)(1.2s+1)(20s+1)(4.25s+1)^2}{(14s+1)(2s+1)(\lambda_1 s+1)^5}e^{-5.25s};$$

- ***DOB Design***

An improved MIMO DOB has been used as designed in [Zhou2012].

Here, low pass filter $\mathbf{Q}$ has been represented as $\mathbf{Q}(s) = \begin{bmatrix} Q_{11}(s) & 0 \\ 0 & Q_{22}(s) \end{bmatrix}$,

where $Q_{11}(s) = \dfrac{(-2.2s+1)e^{-8.5s}}{(2.2s+1)(a_{11}s+1)}$; $Q_{22}(s) = \dfrac{(-4.8s+1)e^{-0.8s}}{(4.8s+1)(a_{22}s+1)}$;

a_{11} and a_{22} are low pass filter time constants.

$$\mathbf{K}(s) = \mathbf{Q}(s)\mathbf{G_m}(s)^{-1} = \begin{bmatrix} Q_{11}(s)G_{m11}(s)^{-1} & 0 \\ 0 & Q_{22}(s)G_{m22}(s)^{-1} \end{bmatrix};$$

where $Q_{11}(s)G_{m11}(s)^{-1} = \dfrac{-2(1.2s+1)(20s+1)}{(2.2s+1)(a_{11}s+1)}$; $Q_{m22}(s)G_{22}(s)^{-1} = \dfrac{(3.6s+1)(2.2s+1)}{0.91(4.8s+1)(a_{22}s+1)}$;

6.4.2 Simulation Results

In this section, zero set-point has been assumed and it has been shown that (i) input disturbance and (ii) output disturbance have been injected. For each cases, outputs have been compared with MAADC and IMC; two types of time constants for low pass filter of DOB have been considered as used in [Zhou2012].

In Internal Model Controller, low pass filter time constants have been chosen as $a_1 = 10; a_2 = 5$.

In [Zhou2012], tuning parameters of DOB have been taken as $a_{11} = a_{22}$ =25 and $a_{11} = a_{22}$ =40 for two different cases. However, it has been noted in [Zhou2012] that if a_{11} and a_{22} are selected too small, it will make the control system be too sensitive to measurement noise and even destroy the system stability.

In this section, a square wave type of output disturbance has been injected as output disturbance port 1 of Grinding circuit as shown in Figure-6.4.1 and the same square wave output disturbance has been injected as output disturbance port 2 in Figure-6.4.2. For all the cases zero set-point and two types of tuning parameters of DOB has been considered. This can be inferred in Figure-6.4.1 and Figure-6.4.2 that smaller tuning parameter values of DOB, response can be faster but it becomes jittery to some extent. Overall performance of Modified Active Anti-Disturbance

Control and IMC has been compared and it has been found that superior output disturbance rejection has been obtained.

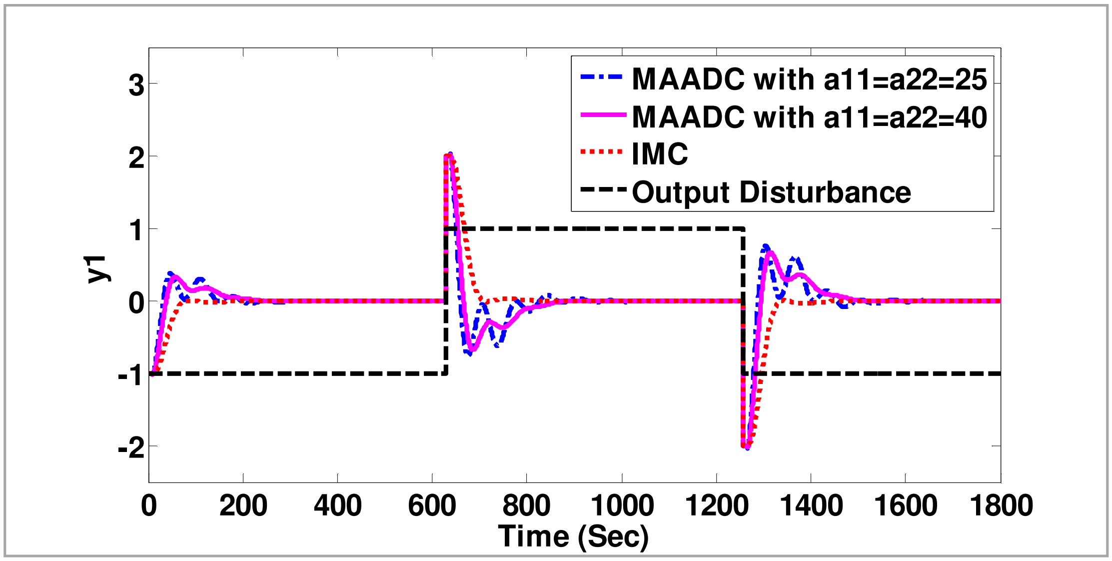


FIG.-6.4.1: OUTPUT DISTURBANCE ATTENUATION SUBJECT TO SQUARE WAVE TYPE OF DISTURBANCE THAT APPLIED INTO INPUT1

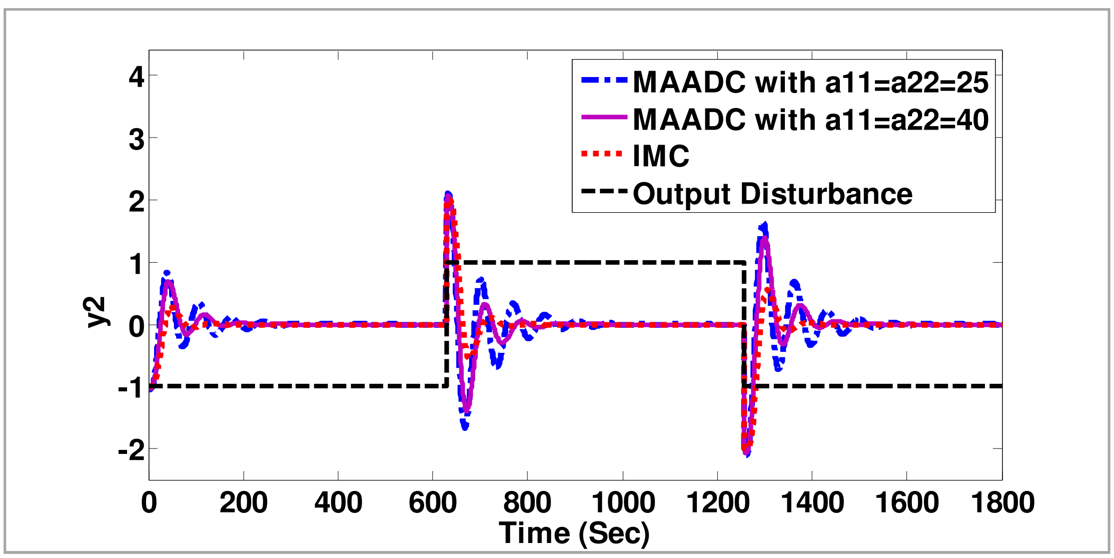


FIG.-6.4.2: OUTPUT DISTURBANCE ATTENUATION SUBJECT TO SQUARE WAVE TYPE OF DISTURBANCE THAT APPLIED INTO INPUT2

As shown in Figure-6.4.3 and Figure-6.4.4, sine wave type of input disturbance have been applied to input disturbance 1 and input disturbance 2 respectively. For all the cases zero set-point has been considered. Disturbance rejection has been conducted and performance comparison has been done between MAADC using IMC plus DOB and IMC considering DOB with two different tuning parameters.

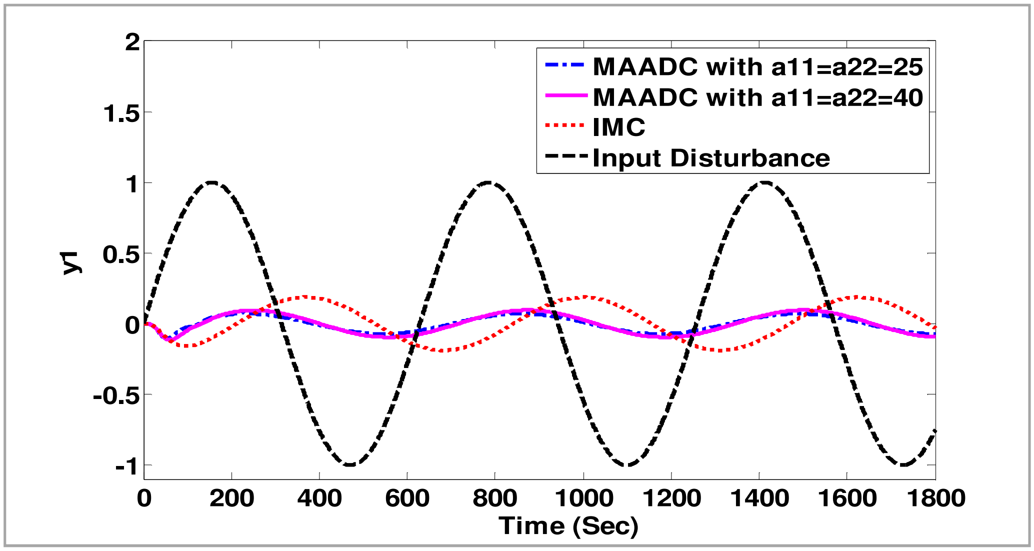


FIG.-6.4.3: INPUT DISTURBANCE ATTENUATION SUBJECT TO SIN WAVE TYPE OF DISTURBANCE THAT APPLIED INTO INPUT1

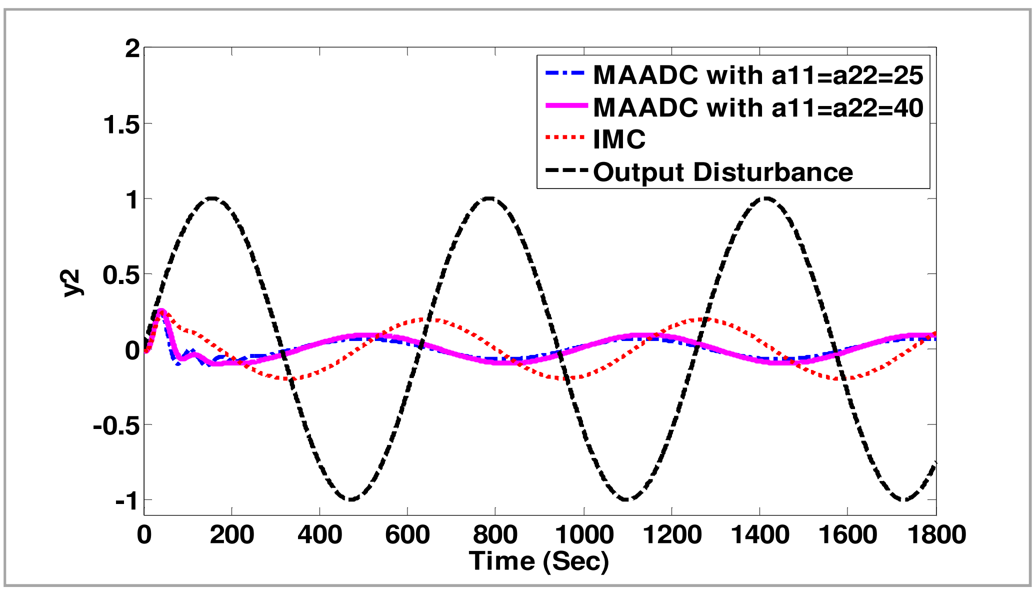


FIG.-6.4.4: INPUT DISTURBANCE ATTENUATION SUBJECT TO SIN WAVE TYPE OF DISTURBANCE THAT APPLIED INTO INPUT2

This can be inferred from Figure-6.4.3 and Figure-6.4.4 that with smaller tuning parameters of DOB, initial response becomes jittery, but for higher value of tuning parameter, initial response becomes more acceptable. It has been found in Figure-6.4.3 and Figure-6.4.4 that superior input disturbance rejection has been obtained.

So, it can be concluded from Figure-6.4.1 - 6.4.4 that the disturbance rejection is superior for the proposed MAADC to the IMC.

6.5 Chapter Conclusion

In this chapter, Modified Active Anti-Disturbance architecture for linear MIMO systems with multiple time delay (or sometimes with non-minimum phase part) has been proposed. Industrially relevant two plants namely Shell-Heavy Oil process and Grinding circuit have been used in case studies. This has been shown that proposed method of MAADC outperform the IMC in terms of disturbance rejection.

PART-D:

Active Anti-Disturbance Control Applied for Nonlinear Systems

Chapter 7: Disturbance Observer for Nonlinear SISO systems with direct utilization of state variables

7.1 Chapter Introduction and previous work

Disturbance Observer (DOB), possibly first introduced by [Ohishi1987], has found wide acceptance in the industry for cancellation of exogenous disturbances in controlled plants. DOB is a deterministic disturbance estimation technique which may be fruitfully employed in control architectures to make such systems robust with respect to unknown disturbances. Specifically, the Active Anti-Disturbance Control (AADC) [Li2014, Guo2014, Guo2014a] employs DOB for feed-forward control, along with the usual feedback controller. The feed-forward scheme uses the reconstructed disturbance signal from the DOB, and thereby annuls the effects of such exogenous disturbances faster than that achievable by feedback controller alone [Zhou2012].

While the theory of disturbance observer for linear systems is well understood, the same for nonlinear plants are yet to mature. For nonlinear plants, a globally applicable theory of stability and convergence of disturbance observers is not yet available. This calls for further investigations towards the development of new algorithms to construct DOBs for nonlinear plants.

In a survey paper [Chen2016], Disturbance Observer Based Control (DOBC) and related methods have been reviewed. Both frequency domain and time domain approaches to DOB design have been reported in the literature [Li2014], of which, only the time domain approach is applicable for nonlinear plants. For most of the DOBs for nonlinear systems reported in literature, the algorithm had been derived assuming restricted disturbance waveform e.g. constant disturbance estimation in [Chen2000a], harmonic disturbance estimation in [Chen2003], time varying disturbance (generated by specified exogenous system) estimation in [Chen2004] and higher order disturbance estimation in [Kim2010]. However, it can be empirically demonstrated that a majority of such observers can also accommodate other disturbance waveforms with varying degrees of accuracy.

Nonlinear DOB design approaches available in literature have been used in applications like robotic manipulators [Chen2000a, Chen2004, Mohammadi2013, Mohammadi2011, Gupta2011, Mohammadi2012, Lichiardopol2010], missile systems [Yang2011a], magnetic bearing systems [Chen2004a], permanent magnet synchronous motors [Yang2012], flight control systems [Guo2005], small scale helicopters [Liu2012], Reusable Launch Vehicles (RLV) [Wang2016], etc. Disturbance observers can not only be used to estimate externally applied disturbance but can also estimate load and friction. In robotic teleoperation, where use of load torque sensors are not economic or convenient and hinge friction is non-negligible, disturbance observers can be usefully deployed in the feed-forward path. Some of the typical applications are reported in [Chen2000a, Mohammadi2011, Gupta2011, Mohammadi2012, Lichiardopol2010]. DOB has also been used to estimate network delay in distributed control systems [Mohammadi2012, Natori2010].

In the domain of chemical processes, several recent publications [Chen2009, Zhang2016, Zhou2014, Ali2015] have appeared which report the use of DOB. However, mostly linear plant models have been used in such publications. In contrast, a new method has been proposed in this chapter for designing nonlinear DOB which are applicable in nonlinear process control system. Instead of the gain based nonlinear observer approach used by previous workers, we use Hirschorn Inverse, which allows inversion of nonlinear system models in state variable form, to design the proposed DOB. Hirschorn Inverse along with its applicability is described in [Hirschorn 1979, Henson1997], where the technique has been used for feedback linearization, as well as Internal Model Control [Economou1986, Henson1991] but not for DOB design. In this chapter, design of DOB for nonlinear systems has been proposed using Hirschorn Inverse and state variables.

7.2 Overview of Hirschorn Inverse

A general form of SISO nonlinear system (plant) in control affine form has been considered as:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})v \\ y &= h(\mathbf{x}) \end{aligned} \tag{7.2. 1}$$

where $\mathbf{x}$ is an n dimensional state vector, y is a scalar controlled output and v is a scalar manipulated input.

It is assumed that $\mathbf{f}$, $\mathbf{g}$ and h are sufficiently smooth in a domain $\Xi \subset \mathbf{R}^n$. The mappings $\mathbf{f}: \Xi \to \mathbf{R}^n$ and $\mathbf{g}: \Xi \to \mathbf{R}^n$ are called vector fields on Ξ. Let us now consider the case when the plant is globally asymptotically stable, though this restriction may be relaxed. Additionally, boundedness of the input and disturbance signals and BIBO stability (with respect to the input and disturbance) are assumed to make the disturbance observation problem meaningful in the context of feed-forward compensation, mentioned earlier.

The equivalent disturbance at the input of the plant is denoted by d. The duty of the disturbance observer is to estimate the disturbance ($\hat{d}$) as closely as possible. The estimation error $\varepsilon = \hat{d} - d$ and its time derivative would be of interest.

The proposed DOBs for nonlinear systems requires the concept of relative degree [Li2014], (which is somewhat analogous to a similar concept in linear systems) for choosing an appropriate low-pass filter. The relative degree (r) for a nonlinear system is determined [Li2014, Henson1997] as follows.

From (7.2.1),

$$\dot{y} = \frac{\partial h}{\partial x}[\mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})v] = L_{\mathbf{f}} h(\mathbf{x}) + L_{\mathbf{g}} h(\mathbf{x})v \tag{7.2.2}$$

where, $L_{\mathbf{f}} h(\mathbf{x}) = \frac{\partial h}{\partial x}\mathbf{f}(\mathbf{x})$, $L_{\mathbf{g}} h(\mathbf{x}) = \frac{\partial h}{\partial \mathbf{x}}\mathbf{g}(\mathbf{x})$.

Here, $L_{\mathbf{f}} h(\mathbf{x})$ is called the Lie Derivative [Slotine1991] or Directional Derivative of h with respect to $\mathbf{f}$ or along $\mathbf{f}$.

If the right hand side of equation (7.2.2) contains a term involving the input v, by definition, the relative degree is 1. In case the right hand side does not contain any term involving the input v, i.e., $\dot{y} = L_{\mathbf{f}} h(\mathbf{x})$, successive differentiation is to be carried out till the term $L_{\mathbf{g}} L_{\mathbf{f}}^{r-1} h(\mathbf{x})$ becomes non-zero. When this is obtained, by definition, the relative degree is r.

At such a step, equation of $y^{(r)}$ with non zero coefficient of v becomes

$$y^{(r)} = L_f^r h(\mathbf{x}) + L_{\mathbf{g}} L_{\mathbf{f}}^{r-1} h(\mathbf{x})v \tag{7.2.3}$$

where, r is relative degree.

From (7.2.3),

$$v = \frac{1}{L_{\mathbf{g}} L_{\mathbf{f}}^{r-1} h(\mathbf{x})} [-L_{\mathbf{f}}^{r} h(\mathbf{x}) + y^{(r)}] \tag{7.2.4}$$

The above is an expression for left Hirschorn inverse, which reconstructs the input from the plant output and its derivatives. An alternative explanation of Hirschorn inverse may be obtained from [Henson1997].

7.3 Proposed DOB design method

The proposed DOB is structurally different from the conventional time-domain based nonlinear DOB approach as reported in literature, but superficially resembles the structure of a frequency domain DOB as had been used for linear systems. However, the detailed implementation of the proposed DOB as explained later differs from both these previous approaches.

The proposed DOB may be applicable for any smooth, stable and observable process model expressed in state variable form and with a well-defined relative degree. Although Hirschorn Inverse has reportedly been used in designing controllers for nonlinear systems [Henson1997] with or without employing feedback linearization, its application to DOB has not appeared in previous work.

But, Hirschorn Inverse has not been used in Disturbance Observer earlier except [Dasgupta2016] where the DOB did not have access to the state variables or their derivatives. It may be noted that [Chen2004] and several other DOB's mentioned in [Li2014] require the access of the state variables of the process. In the current work, design strategy of nonlinear DOB using Hirschorn Inverse, is different from [Dasgupta2017] in the sense that the proposed DOB has access to the state variables of the process. Thus, in this work, nonlinear DOB design has been proposed in simpler method than in [Dasgupta2017]. Additionally, inversion of process has been done in this current work using process states and output.

In the proposed DOB, use of low pass filter is required for proper implementation. Such filters additionally ensure that high frequency noise from sensors and other exogenous sources are attenuated.

7.3.1 Structure and Formulation

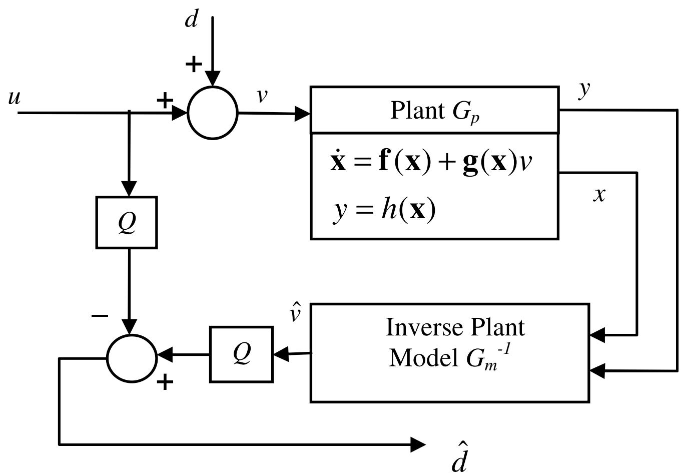


FIG.- 7.3.1: BLOCK DIAGRAM OF NONLINEAR DISTURBANCE OBSERVER

In Figure-7.3.1, the conceptual structure of the proposed disturbance observer is shown. Where, u, d, $\hat{d}$, G_m^{-1} are the manipulated variable (which generally comes from the controller but not shown here), equivalent process disturbance, the estimated disturbance and the Hirschorn inverse of the nonlinear model (to be described in the next section) respectively. Here, the Hirschorn Inverse needs not only the system output but system states as well. Note that the plant is excited by the composite input, v, defined as $v = u + d$.

Apparently there are similarities of this proposed structure with that described in [Chen2009]. But in [Chen2009], a frequency domain approach to construct the DOB for linear systems has been designed. The proposed method is defined in the time domain with a state variable representation of the nonlinear plant model. The structure presented in Figure-7.3.1 is hybrid because it also embodies frequency domain filters. This unconventional approach has been taken to show the structural simplicity and also to contrast the proposed DOB structure with that of other time-domain DOB structures [e.g., fig 2.6 in [Li2014]]. In Figure-7.3.1, G_p symbolically represents the nonlinear SISO plant. The block G_m^{-1} represents the Hirschorn inverse of its nonlinear model, which is followed by a low-pass filter as represented by $Q(s)$ of appropriate degree as explained later. Here, Figure-7.3.1 describes the conceptual structure of the proposed

DOB. Implementation details of QG_m^{-1} (i.e., one of the low pass filters along with the Hirschorn inverse) is shown in Figure-7.3.2.

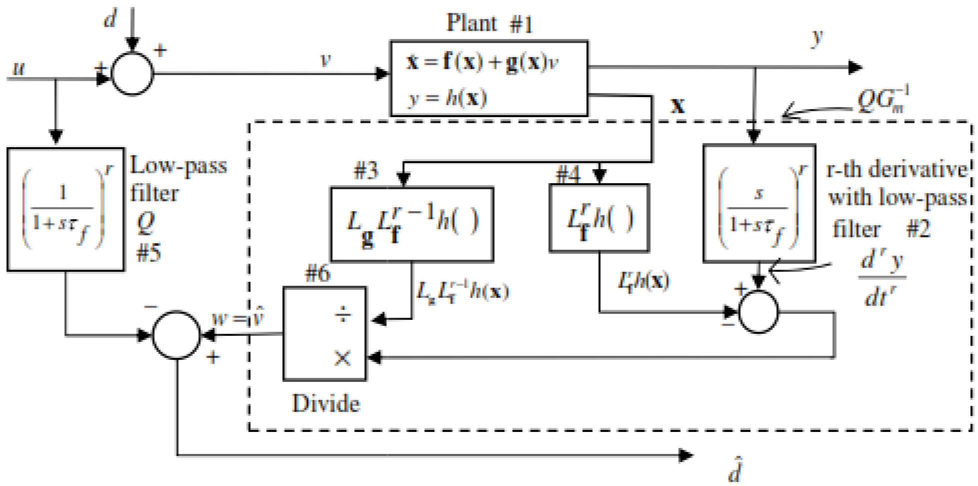


FIG.-7.3.2: IMPLEMENTATION OF THE DISTURBANCE OBSERVER

However, to obtain the true Hirschorn inverse from (7.2.4), the above expression requires state variable x. The observed composite input $(\hat{v})$ is to be used because the actual input (v) is not available due to the unknown disturbance component. The observed composite input $(\hat{v})$ may, however, be computed using (7.2.4) and the fact that $v = u + d$. The observed value of the disturbance signal $(\hat{d})$ is given by

$$\hat{d} = \frac{\frac{d^r y}{dt^r} - L_\mathbf{f}^r h(\mathbf{x})}{L_\mathbf{g} L_\mathbf{f}^{r-1} h(\mathbf{x})} - u \qquad (7.3.1)$$

Note that the denominator in (7.3.1) is a scalar.

For simplicity, it is assumed that $u = 0$.

The proposed DOB should have access to the state variables or their derivatives, like [Chen2004] and several other DOB's mentioned in [Li2014] which require the same. In the derivation of the proposed DOB, asymptotic stability of the plant was assumed. However, this restriction can be relaxed fairly easily by using a stabilizing feedback as has been proposed in [[Li2014], (in section 5.2)]. It should be noted that the purpose of the DOB is to add feed-forward to such feedback control scheme so that the existence of such a stabilizing feedback may be assumed. Though the assumption about stability of the plant is not an explicit requirement of the DOB in [Chen2004], but for the application of the same, existence of a feedback for performance improvement and/or stabilization would be required in any case.

The proposed DOB implementation has been shown in Figure-7.3.2. In Figure-7.3.2, plant has been denoted by block #1. Here, an approximate differentiator with low pass filter of r-th degree has been shown in block #2. Noting that obtaining derivatives of signals worsens the signal to noise ratio,. filter has been applied to the inverse model in Figure-7.3.1. Here, τ_f is the filter time constant, which has to be chosen appropriately [Chen2009]. The corresponding low pass filter for the control input u is shown in block #5. In (7.3.1), the numerator has two components of which the subtrahend is performed in block #4. The concerned denominator is computed in block #3. Lastly, using the divide block #6, implementation of (7.3.1) is complete.

The above theory and the corresponding implementation are applicable for nonlinear single-input-single-output (SISO) systems. The requirement of global asymptotic stability of the plant has already been mentioned. Also required is the condition that the system description is sufficiently smooth to permit computation of the corresponding Lie derivatives. Further implied requirements are that (i) the plant model is observable, and (ii) the relative order of the system as defined above should be independent of the operating point [Slotine1991]. Fortunately, for many chemical process models, the above conditions are satisfactorily met.

An additional requirement for all inversion based observers, like the present one, is that the inverse must be stable. This requires the “zero dynamics” [Henson1997] to be stable and this must be investigated for implementing the proposed DOB.

7.4 Case Study and Comparison

In this section, case studies for the proposed DOB using Hirschorn Inverse and state variables have been illustrated. Comparison has been done between proposed DOB with a well known DOB design method [Chen2004]. Using a Test problem [Goodwin2009] and a Continuous Stirred Tank Reactor (CSTR) plant [Henson1997, Ghaffari2013, Wu2001], case studies have been performed. Several disturbance waveforms have been considered for highly nonlinear CSTR model.

7.4.1 Test Problem-C

7.4.1.1 Problem Statement

To illustrate the performance of the proposed DOB, a nonlinear second order system [Goodwin2009] has been considered which is in state space form.

$$\begin{aligned} \dot{x}_1 &= x_2 + x_2{}^3 \\ \dot{x}_2 &= -2x_1 - 3x_2 + u + 0.1x_1{}^2 u \\ y &= x_2 \end{aligned} \tag{7.4.1}$$

7.4.1.2 Design of DOB

From (7.4.1),

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} x_2 + x_2{}^3 \\ -2x_1 - 3x_2 \end{bmatrix}}_{\mathbf{f}(\mathbf{x})} + \underbrace{\begin{bmatrix} 0 \\ 1 + 0.1x_1^2 \end{bmatrix}}_{\mathbf{g}(\mathbf{x})} u$$

$$y = h(\mathbf{x}) = x_2$$

Since, $L_{\mathbf{g}} h(\mathbf{x}) \neq 0$

$$\therefore L_{\mathbf{g}} L_{\mathbf{f}}^{1-1} h(\mathbf{x}) \neq 0$$

So, relative degree is 1.

Now using Hirschorn's inverse, the inverse system becomes

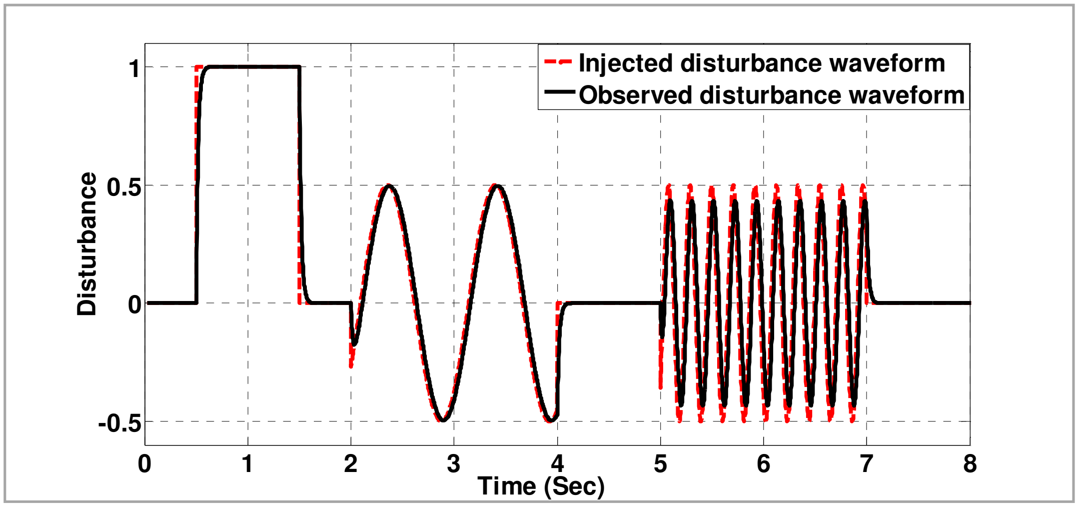
$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x}) \frac{\frac{dy}{dt} - L_{\mathbf{f}}^1 h(\mathbf{x})}{L_{\mathbf{g}} L_{\mathbf{f}}^{1-1} h(\mathbf{x})}$$

$$\Rightarrow \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 + x_2^3 \\ -2x_1 - 3x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 + 0.1x_1^2 \end{bmatrix} \frac{\frac{dy}{dt} + 2x_1 + 3x_2}{1 + 0.1x_1^2}$$

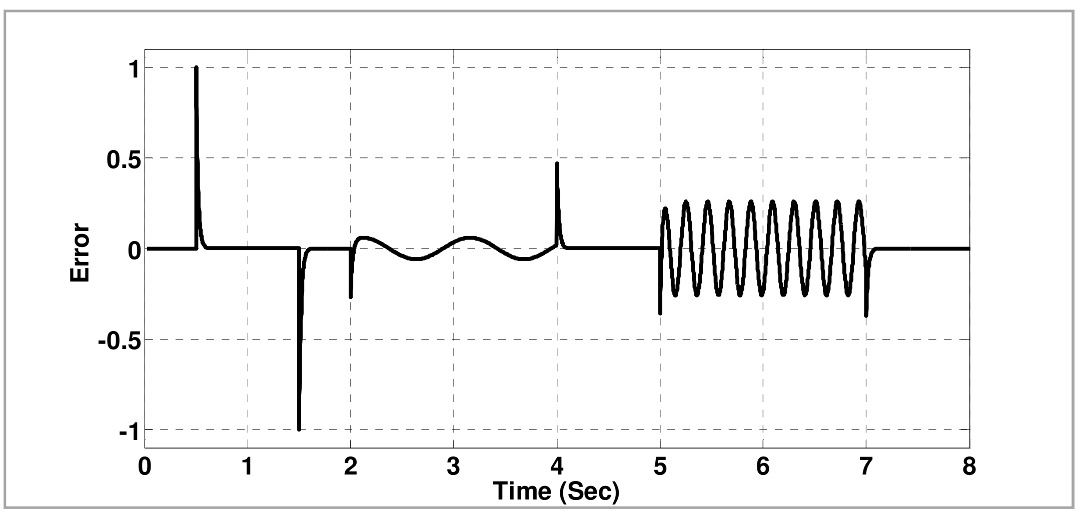
Here, input v has been reconstructed as $\dfrac{\frac{dy}{dt} - L_{\mathbf{f}}^1 h(\mathbf{x})}{L_{\mathbf{g}} L_{\mathbf{f}}^{1-1} h(\mathbf{x})} = \dfrac{\frac{dy}{dt} + 2x_1 + 3x_2}{1 + 0.1x_1^2}$

7.4.1.3 Simulation Results

We have introduced a composite disturbance signal d (shown in Figure-7.4.1(A)) consisting of a pulse followed by two sine wave pulses. This composite disturbance waveform is used to demonstrate the versatility of the proposed DOB as well as the effect of finite bandwidth dictated by the low pass filter.



(A)



(B)

FIG.- 7.4.1: FOR A TEST PROBLEM-C (A) INJECTED DISTURBANCE AND ITS OBSERVED VALUE BY THE PROPOSED DOB (B) OBSERVATION ERROR OF DOB

The specification of the composite waveform is stated below:

Step Pulse height=1, Step Pulse width=1 sec, beginning at 0.5 sec; Sine wave height=1, frequency =6 rad/s, Sine wave Pulse width=2 sec, beginning at 2sec; Sine wave height=1, frequency =30 rad/s, Sine wave Pulse width=2 sec, beginning at 5 sec.

In Figure-7.4.1, it has been shown that disturbance estimation has been obtained successfully. Superimposed on the Figure-7.4.1(A) is the output of the DOB from which it may be inferred that the DOB tracks the disturbance quite acceptably except for the high frequency portion of the waveform as evident from Figure-7.4.1(B). The error in the high frequency sine wave can be seen to be contributed mostly by the phase shift between the actual and the estimated disturbance. This phase shift is contributed primarily by the low pass filter which can be tuned to increase or decrease the bandwidth of the observer.

7.4.2 Continuous Stirred Tank Reactor (CSTR)

7.4.2.1 Problem Statement

A nonlinear CSTR state variable model [Henson1997, Ghaffari2013, Wu2001] has been used as plant to illustrate the performance of the proposed DOB. For generalized analysis, dimensionless form of CSTR has been chosen and dimensionless parameters and process variables have been considered as listed in Table-7.4.1.

$$\begin{aligned}\dot{x}_1 &= -\alpha x_1 + D_\alpha (1-x_1) e^{\frac{x_2}{1+x_2/\gamma}} \\ \dot{x}_2 &= -\alpha x_2 + D_\alpha (1-x_1) e^{\frac{x_2}{1+x_2/\gamma}} + \beta(u - x_2) + \alpha d(t)\end{aligned} \tag{7.4.2}$$

The control objective is to regulate the reactor temperature i.e. $y = x_2$.

The coefficients are taken as $D_\alpha = 1$, $\alpha = 1$, $\beta = 0.3$ and $\gamma = 20$. Also, the plant model has been initialized at its equilibrium point i.e. $x_1(0)$=0.625 and $x_2(0)$=0.48.

Table-7.4.1 Dimensionless CSTR Parameters and variables

Parameter/Variable	Description
x_1	Dimensionless reactant concentration
x_2	Dimensionless reactor temperature
u	Dimensionless cooling jacket temperature surrounding the reactor
γ	Dimensionless activation energy
D_α	Damköhler number
β	Dimensionless heat transfer coefficient

7.4.2.2 Design of DOB

From (7.4.2),

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} -\alpha x_1 + D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} \\ -\alpha x_2 + D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} - \beta x_2 \end{bmatrix}; \mathbf{g}(\mathbf{x}) = \begin{bmatrix} 0 \\ \beta \end{bmatrix}; y = h(\mathbf{x}) = x_2$$

As the procedure outlined in Section 7.3, nonlinear DOB has been derived.

$$L_{\mathbf{g}}h(\mathbf{x}) = \beta \quad ; \quad L_{\mathbf{f}}h(\mathbf{x}) = -\alpha x_2 + D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} - \beta x_2$$

Since, $L_{\mathbf{g}}L_{\mathbf{f}}^{1-1}h(\mathbf{x}) = L_{\mathbf{g}}L_{\mathbf{f}}^{0}h(\mathbf{x}) = L_{\mathbf{g}}h(\mathbf{x}) = \beta \neq 0$, the relative degree of this CSTR model is 1,

i.e. r =1.

Now, the Hirschorn Inverse model of CSTR [Henson1997] (from (7.3.1)):

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\alpha x_1 + D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} \\ -\alpha x_2 + D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} - \beta x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \beta \end{bmatrix} \frac{\frac{dy}{dt} + \alpha x_2 - D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} + \beta x_2}{\beta} \tag{7.4.3}$$

Observed value of disturbance, $\hat{d} = \dfrac{\frac{dy}{dt} + \alpha x_2 - D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} + \beta x_2}{\beta} - u$

As the nonlinear model has a well defined relative degree 1, a first order filter with time constant 0.02 has been used. All state variables of process have been used while implementing the DOB.

7.4.2.3 Zero-Dynamics of CSTR

In this case study, relative degree (r = 1) is less than the order of the system, so analysis of zero dynamics is required. We follow the steps outlined in [Henson1997].

From (7.4.2),

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} -x_1 + D_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} \\ -x_2 + BD_\alpha(1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} - \beta x_2 \end{bmatrix};\ \mathbf{g}(\mathbf{x}) = \begin{bmatrix} 0 \\ \beta \end{bmatrix};\ y = h(\mathbf{x}) = x_2$$

To obtain the Byrnes-Isidori normal form, we use the general form of co-ordinate transformation [Henson1997] as

$$\begin{pmatrix} \boldsymbol{\xi} \\ \boldsymbol{\eta} \end{pmatrix} = \boldsymbol{\varphi}(\mathbf{x}) = \begin{pmatrix} h(\mathbf{x}) \\ L_{\mathbf{f}}h(\mathbf{x}) \\ \vdots \\ L_{\mathbf{f}}^{r-1}h(\mathbf{x}) \\ t_1(\mathbf{x}) \\ \vdots \\ t_{n-r}(\mathbf{x}) \end{pmatrix},$$

where n, r are order and relative degree of the system respectively, $\boldsymbol{\xi}$ is a r dimensional normal state vector and $\boldsymbol{\eta}$ is a $(n-r)$ dimensional normal state vector. The $t_i(x)$ functions are solutions to the partial differential equation $L_{\mathbf{g}}t_i(\mathbf{x}) = 0$. From this transformation, Byrnes-Isidori normal form can be realized as

$$\begin{aligned} \dot{\boldsymbol{\xi}} &= \boldsymbol{\alpha}(\boldsymbol{\xi}, \boldsymbol{\eta}) + \boldsymbol{\beta}(\boldsymbol{\xi}, \boldsymbol{\eta})u \\ \dot{\boldsymbol{\eta}} &= \mathbf{q}(\boldsymbol{\xi}, \boldsymbol{\eta}) \\ \mathbf{y} &= \boldsymbol{\xi} \end{aligned}$$

So, co-ordinate transformation for this case is

$$\begin{pmatrix} \xi \\ \eta \end{pmatrix} = \begin{bmatrix} h(\mathbf{x}) \\ t_1(\mathbf{x}) \end{bmatrix} = \begin{bmatrix} x_2 \\ x_1 \end{bmatrix}$$

Since, $L_{\mathbf{g}}t_1(\mathbf{x}) = 0$

$$\therefore \frac{\partial t_1}{\partial x_2}\beta = 0 \Rightarrow t_1 = x_1$$

The Byrnes-Isidori normal form becomes

$$\begin{aligned}
\dot{\xi} &= \dot{x}_2 = -\xi + BD_\alpha(1-\eta)e^{\frac{\xi}{1+\xi/\gamma}} + \beta(u-\xi) \\
\dot{\eta} &= \dot{x}_1 = -\eta + D_\alpha(1-\eta)e^{\frac{\xi}{1+\xi/\gamma}} \\
y &= \xi
\end{aligned}.$$

Accordingly, the Zero Dynamics is defined by $\dot{\eta} = q(\xi,\eta) = -\eta + D_\alpha(1-\eta)e^{\frac{\xi}{1+\xi/\gamma}}$

and the unforced zero dynamics $\dot{\eta} = q(0,\eta)$ becomes $\dot{\eta} = -(1+D_\alpha)\eta + D_\alpha$.

In the present case, $D_\alpha = 1$. So the unforced zero dynamics is globally stable and this CSTR system is globally minimum phase.

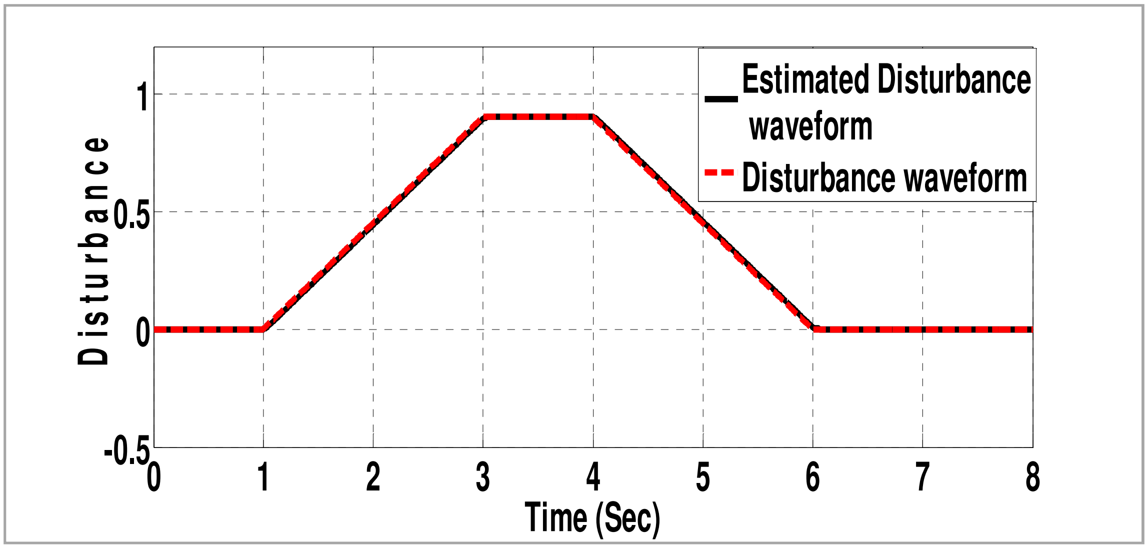
7.4.2.4 Simulation Results

Effectiveness of the proposed nonlinear DOB method has been demonstrated using different forms of disturbance signals. To focus on the disturbance tracking property, the plant model has been initialized at its equilibrium point. Performance of the proposed DOB has been compared against a previously reported [Chen2004] DOB.

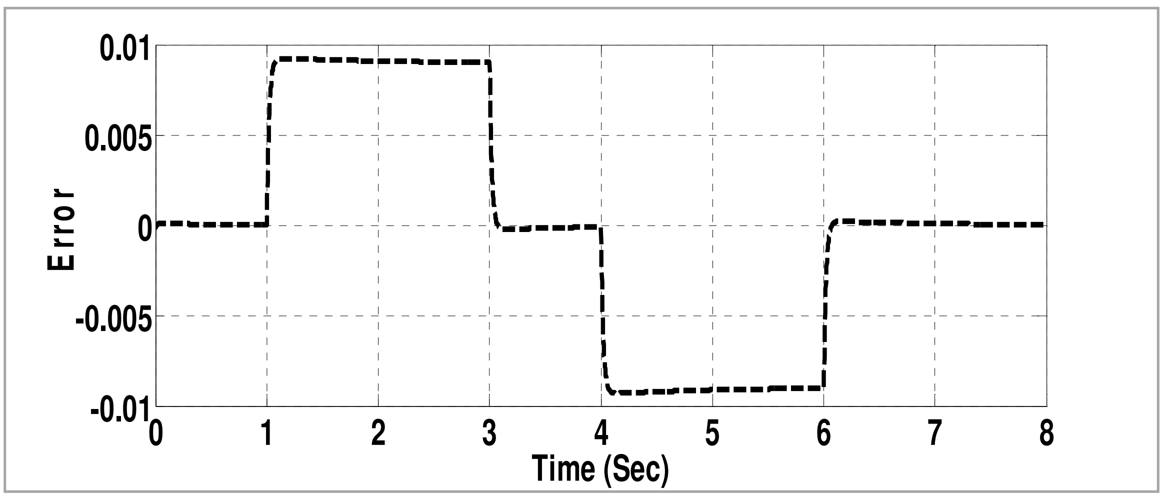
Case (I): A truncated triangular disturbance signal d (as shown in Figure-7.4.2(A)) has been considered, which consists of ramp and step signals as stated below:

$$d = \begin{cases} 0 & 0 \le t < 1 \\ 0.9 + \dfrac{9(t-3)}{20} & 1 \le t < 3 \\ 0.9 & 3 \le t < 4 \\ 0.9 - \dfrac{9(t-4)}{20} & 4 \le t < 6 \\ 0 & 6 \le t \end{cases}$$

From the observed signal shown in Figure-7.4.2(A), it is shown that the observed signal closely tracks the disturbance input. The corresponding observation error is presented in Figure-7.4.2(B), wherefrom it may be seen that the estimation errors are negligible for this case.



(A)

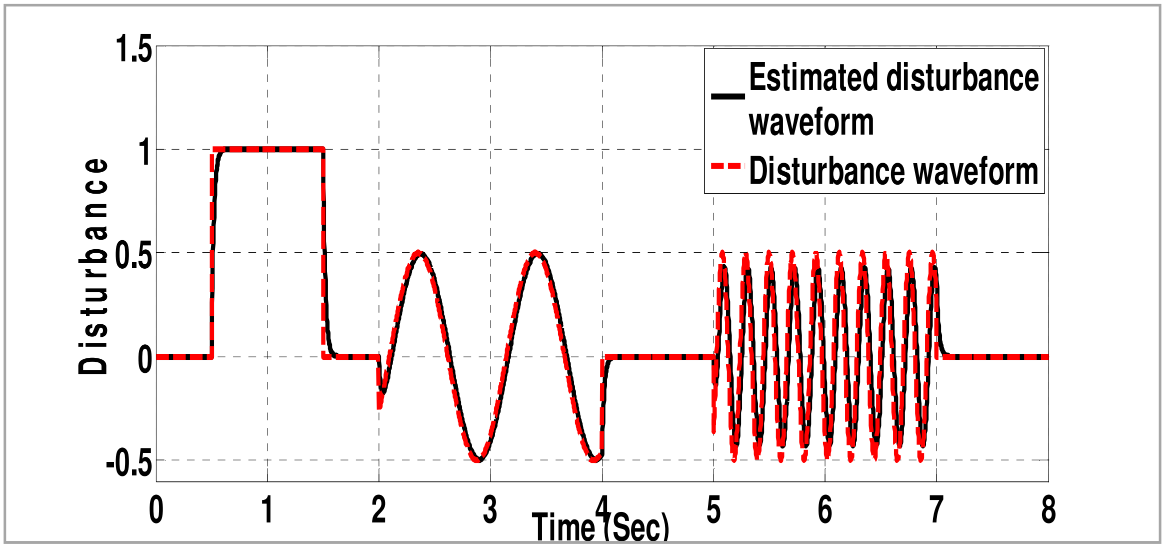


(B)

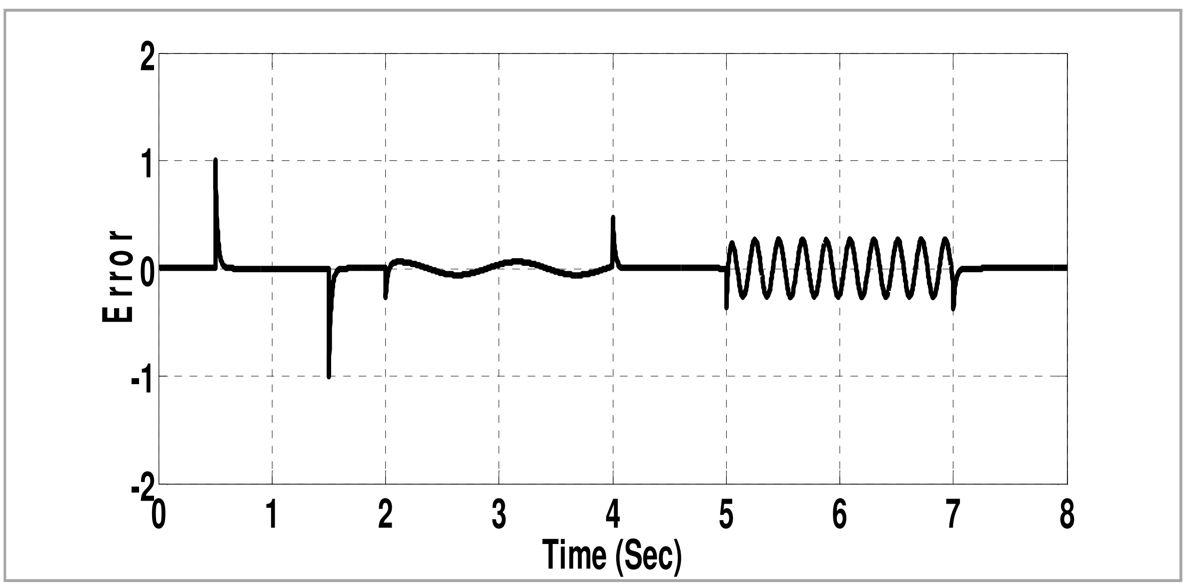
FIG.-7.4.2 FOR CSTR IN CASE (I) (A) INJECTED DISTURBANCE AND ITS OBSERVED VALUE BY THE PROPOSED DOB (B) OBSERVATION ERROR OF DOB

Case (II): A composite disturbance signal (shown in Figure-7.4.3(A)) consisting of a pulse followed by two sine wave pulses is considered in this case. This composite disturbance waveform is used to demonstrate the versatility of the proposed DOB as well as the effect of finite bandwidth dictated by the low pass filter. The specification of the composite waveform is stated below:

Step pulse height=1, step pulse width=1 sec, beginning at 0.5 sec; sine wave height=1, frequency =6 rad/s, sine wave pulse width=2 sec, beginning at 2sec; sine wave height=1, frequency =30 rad/s, sine wave pulse width=2 sec, beginning at 5 sec.



(A)



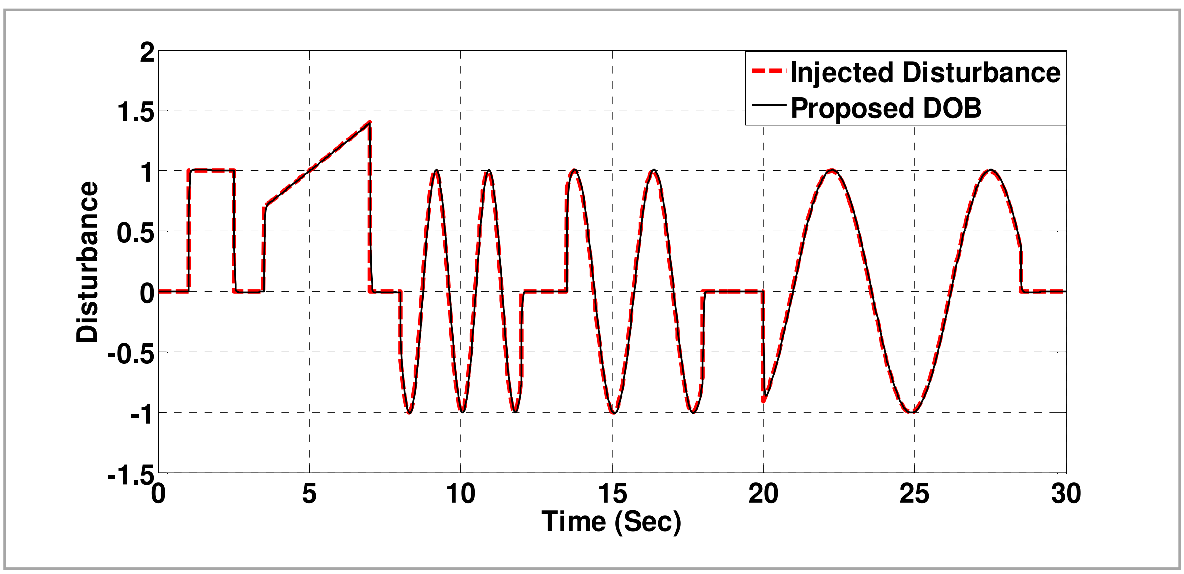
(B)

FIG.-7.4.3 FOR CSTR IN CASE (II) (A) INJECTED DISTURBANCE AND ITS OBSERVED VALUE BY THE PROPOSED DOB (B) OBSERVATION ERROR OF DOB

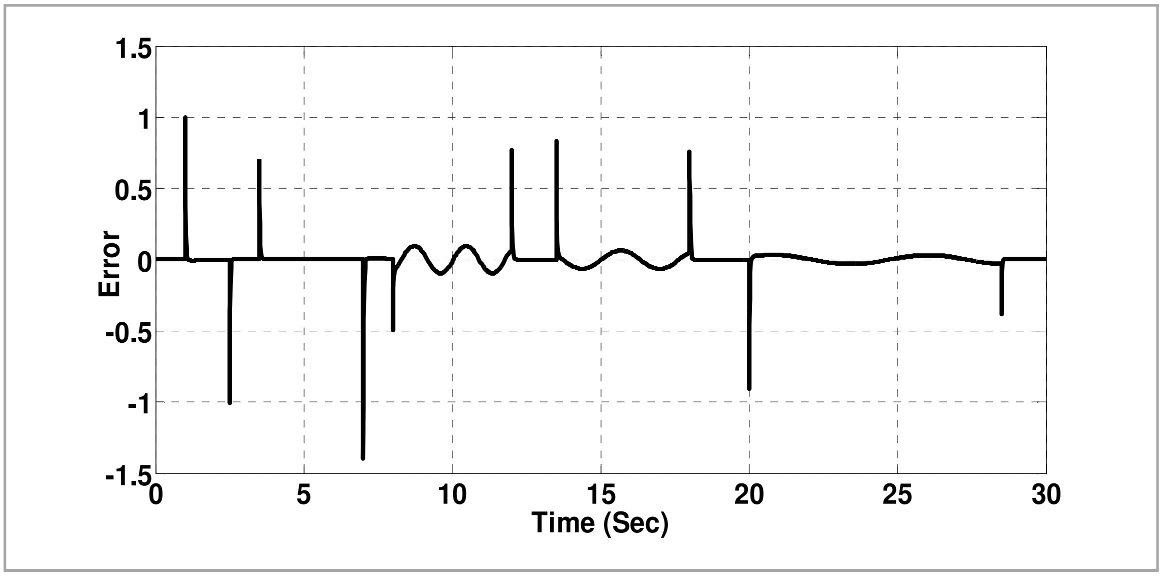
Output of the DOB and injected disturbance have been superimposed on Figure-7.4.3(A). It can be inferred that the DOB tracks the disturbance quite acceptably except for the high frequency portion of the waveform as evident from Figure-7.4.3(B). The error in the high frequency sine wave can be seen to be contributed mostly by the phase shift between the actual and the estimated disturbance. This phase shift is contributed primarily by the low pass filter which can be tuned to increase or decrease the bandwidth of the observer.

Case (III): A composite signal consisting of a square followed by truncated triangle, sinusoidal signal with frequency 3.6 rad/sec, sinusoidal signal with tuned frequency 2.4 rad/sec and sinusoidal signal with frequency 1.2 rad/sec has been used.

A composite signal consisting of a square followed by truncated triangle, sinusoidal signal with frequency 3.6 rad/sec, sinusoidal signal with tuned frequency 2.4 rad/sec and sinusoidal signal with frequency 1.2 rad/sec is considered in this case. This composite disturbance waveform is used to demonstrate the versatility of the proposed DOB as well as the effect of finite bandwidth dictated by the low pass filter.

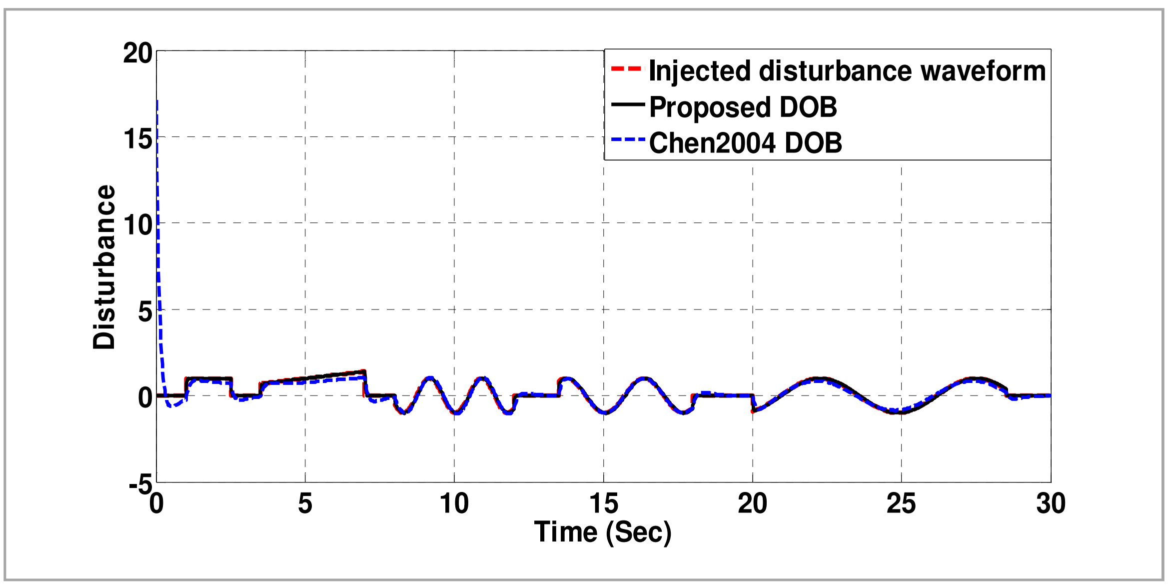


(A)

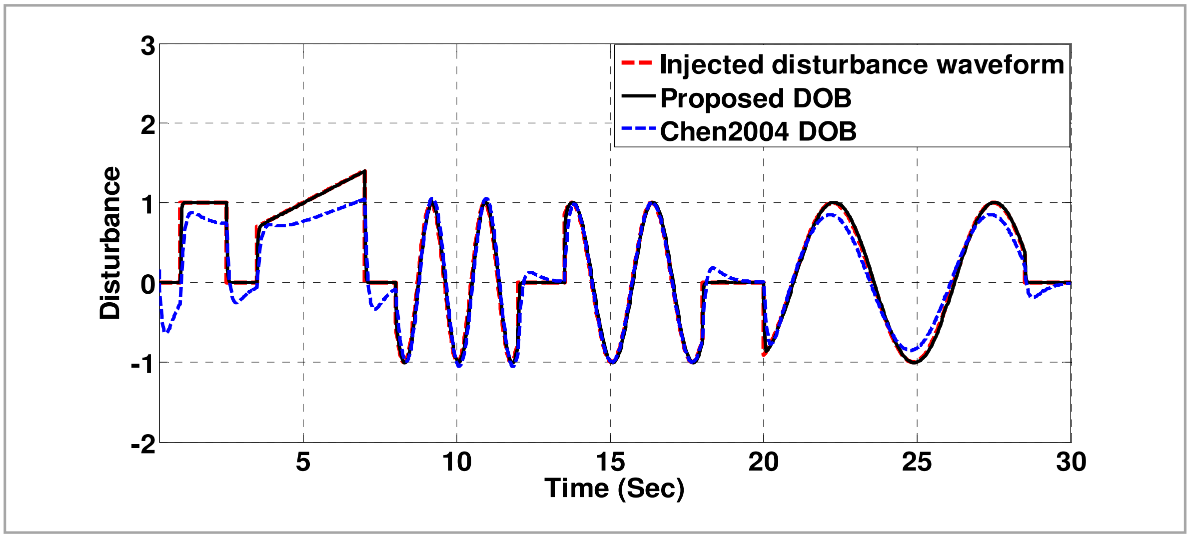


(B)

FIG.-7.4.4 FOR CSTR IN CASE (III) (A) INJECTED DISTURBANCE AND ITS OBSERVED VALUE BY THE PROPOSED DOB (B) OBSERVATION ERROR OF DOB



(A)



(B)

FIG.-7.4.5: COMPOSITE WAVEFORM DISTURBANCE COMPARISON (A) IN FULL SCALE (B) ZOOMED

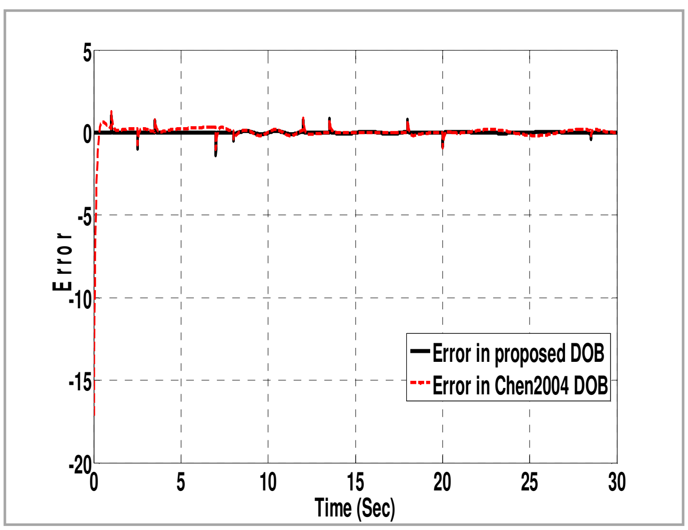
It may be noted that high frequency tracking error for the proposed DOB is attributable to the low pass filters which define the bandwidth of the DOB. When the disturbance signal is well within the bandwidth, the phase shift due to the filters would be negligible, and consequently the tracking error would also be negligible after the transients have decayed.

Case (IV): The performance of the proposed DOB has been compared with that proposed in [Chen2004], the primary features of which were discussed in the introduction section. Output of the DOB and injected disturbance have been superimposed on Figure-7.4.5-7.4.6. It can be inferred that the DOB tracks the disturbance quite acceptably except for the high frequency portion of the waveform as evident from Figure-7.4.5-7.4.6. The error in the high frequency sine wave can be seen to be contributed mostly by the phase shift between the actual and the estimated disturbance. This phase shift is contributed primarily by the low pass filter which can be tuned to increase or decrease the bandwidth of the observer.

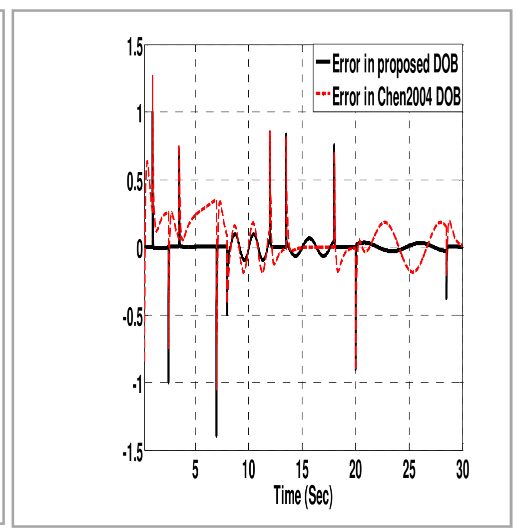
In this case, performance of the proposed DOB with that proposed in [Chen2004] has been compared. It may be noted that [Chen2004] provides some freedom to choose observer parameters as long as the P matrix therein satisfies the concerned Lyapunov equation (eqn. no. 20 in [Chen2004]). However, all such solutions may not provide satisfactory estimation of disturbance even for sine wave disturbance at frequencies other than the tuned frequency. The present workers have chosen a solution which is near optimal in the sense that the designed DOB can track frequencies other than the tuned frequency and also other waveforms in a reasonable manner. The tuning frequency used is 2.4 rad/sec and the chosen P matrix is $P = \begin{bmatrix} 0.1 & -0.12 \\ -0.12 & 0.2 \end{bmatrix}$.

The proposed DOB and the DOB designed as per [Chen2004] have been subjected to a composite waveform as shown in Figure-7.4.5-7.4.6 which consists of a square pulse, a ramp and three packets of sine waves at 1.2 rad/sec, 2.4 rad/sec and 3.6 rad/sec. The first and third sine waves respectively being 50% and 150% of the tuned frequency of [Chen2004] DOB. From the figure, it may be seen that while the DOB proposed in this paper tracks the disturbance very well, the DOB designed as per [Chen2004] exhibits (i) high initial transient, (ii) reasonable tracking at 3.6 rad/sec (iii) severe waveform distortions for both pulse and ramp portions of the signal and (iv) noticeable tracking error at 1.2 rad/sec and 3.6 rad/sec. It has also been shown that at the tuned frequency of 2.4 rad/sec, the error for [Chen2004] DOB is negligible.

In Figure 7.4.6(A), a large initial error may be noted for the DOB described in [Chen2004]. This is apparently due to mismatch in initial condition.



(A)



(B)

FIG.- 7.4.6: OBSERVATION ERROR FOR COMPOSITE WAVEFORM (A) FULL SCALE (B) ZOOMED

In Figure-7.4.5 and Figure-7.4.6, large initial error may be noted for the DOB described in [Chen2004]. This is apparently due to mismatch in initial condition.

7.5 Chapter Conclusion

A new method of designing disturbance observer for nonlinear systems has been presented in this chapter using direct utilization of state variables. This method, based on Hirschorn Inverse, has been illustrated by industrial processes, which are highly nonlinear. In all the cases, the plants have been subjected to pulse, truncated ramp and periodic disturbances and it was shown that the disturbances have been estimated satisfactorily. As both Lie derivative and Hirschorn Inverse exist for many nonlinear chemical processes, it is conjectured that these methods may be applicable for a non-trivial class of nonlinear problems. Additionally the performances are compared with that for a well-known DOB which demonstrates the superiority of the proposed DOB.

Chapter 8: Disturbance Observer for Nonlinear SISO Systems where state variables are not directly accessible

8.1 Chapter Introduction

Disturbance Observers (DOB) are increasingly suggested as a component in Active Anti-Disturbance Control (AADC). Whereas the structure and design pragmatics of DOBs for linear systems are well-known, very few publications deal with DOB for nonlinear systems. A new method for designing Disturbance Observers for nonlinear systems has been proposed in this chapter employing special state observers where state variables are not directly accessible [Dasgupta2017]. Instead of the usual observer gain based approach, the proposed approach employs Lie Derivative and Hirschorn Inverse as shown in the description of the design methodology. Performance of the proposed DOB has been evaluated using highly nonlinear chemical processes. Additionally the performance is compared with that for a well-known DOB which demonstrates the superiority of the proposed DOB. Previous works on Disturbance Observer (DOB) are already depicted in Section 7.1 of Chapter-7, which shows the importance of designing such nonlinear DOB's. The basic difference between the DOB proposed in Chapter 7 and the current DOB is that the DOB depicted in Chapter-7 requires direct utilization of state variables; whereas DOB design proposed in this current chapter employs special state observers where state variables are not directly accessible.

8.2 Proposed DOB design method

A general form of SISO nonlinear system (plant) in control affine form has been considered as:

$$\begin{aligned} \dot{x} &= \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})v \\ y &= h(\mathbf{x}) \end{aligned} \qquad (8.2.1),$$

where $\mathbf{x}$ is an n dimensional state vector, y is a scalar controlled output and v is a scalar manipulated input.

It is assumed that $\mathbf{f}$, $\mathbf{g}$ and h are sufficiently smooth in a domain $\Xi \subset \mathbf{R}^n$. The mappings

$\mathbf{f}:\Xi \rightarrow \mathbf{R}^n$ and $\mathbf{g}:\Xi \rightarrow \mathbf{R}^n$ are called vector fields on Ξ. Let us now consider the case when the plant is globally asymptotically stable, though this restriction may be relaxed. Additionally, boundedness of the input and disturbance signals and BIBO (Bounded Input Bounded Output) stability (with respect to the input and disturbance) are assumed to make the disturbance observation problem meaningful in the context of feed-forward compensation, mentioned earlier.

The equivalent disturbance at the input of the plant is denoted by *d*. The duty of the disturbance observer is to estimate the disturbance ($\hat{d}$) as closely as possible. The estimation error $\varepsilon = \hat{d} - d$ and its time derivative would be of interest.

The proposed DOB for nonlinear systems requires the concept of relative degree [Li2014], (which is somewhat analogous to a similar concept in linear systems) for choosing an appropriate low-pass filter. The relative degree (*r*) for a nonlinear system is determined [Li2014, Henson1997] as follows.

From (8.2.1),

$$\dot{y} = \frac{\partial h}{\partial \mathbf{x}}[\mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})v] = L_{\mathbf{f}}h(\mathbf{x}) + L_{\mathbf{g}}h(\mathbf{x})v \qquad (8.2.2),$$

where, $L_{\mathbf{f}}h(\mathbf{x}) = \frac{\partial h}{\partial \mathbf{x}} f(\mathbf{x})$, $L_{\mathbf{g}}h(\mathbf{x}) = \frac{\partial h}{\partial \mathbf{x}} \mathbf{g}(\mathbf{x})$.

Here, $L_{\mathbf{f}}h(\mathbf{x})$ is called the Lie Derivative [Slotine1991] or Directional Derivative of h with respect to $\mathbf{f}$ or along $\mathbf{f}$.

If the right hand side of equation (8.2.2) contains a term involving the input v, by definition, the relative degree is 1. In case the right hand side does not contain any term involving the input v, i.e., $\dot{y} = L_{\mathbf{f}}h(\mathbf{x})$, successive differentiation is to be carried out till the term $L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h(\mathbf{x})$ becomes non-zero. When this is obtained, by definition, the relative degree is r.

At such a step, equation of $y^{(r)}$ with non zero coefficient of v becomes

$$y^{(r)} = L_{\mathbf{f}}^{r}h(\mathbf{x}) + L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h(\mathbf{x})v \qquad (8.2.3),$$

where, r is relative degree.

From (8.2.3),

$$v = \frac{1}{L_{\mathbf{g}} L_{\mathbf{f}}^{r-1} h(\mathbf{x})} [-L_{\mathbf{f}}^{r} h(\mathbf{x}) + y^{(r)}] \tag{8.2.4}$$

The above is an expression for left Hirschorn inverse, which reconstructs the input from the plant output and its derivatives. An alternative explanation of Hirschorn inverse may be obtained from [Henson1997].

The proposed DOB is structurally different from the conventional time-domain based nonlinear DOB approach as reported in literature, but superficially resembles the structure of a frequency domain DOB as had been used for linear systems. However, the detailed implementation of the proposed DOB as explained later differs from both these previous approaches.

The proposed DOB may be applicable for any smooth, stable and observable process model expressed in state variable form and with a well-defined relative degree. Although Hirschorn Inverse has reportedly been used in designing controllers for nonlinear systems [Henson1997] with or without employing feedback linearization, its application to DOB has not appeared in previous work.

In the proposed DOB, use of low pass filter is required for proper implementation. Such filters additionally ensure that high frequency noise from sensors and other exogenous sources are attenuated.

In this section, Disturbance Observer has been designed using Hirschorn Inverse where some of the state variables are not accessible. A common issue with all observers and state estimators is the mismatch of initial conditions between the actual plant and the estimator. Stability of the error dynamics in the observer is required so that transients due to such mismatch eventually decay. This aspect, which is more complex in nonlinear observers compared to the linear observers, has been explored here with the help of a case study.

The structure and formulations are depicted in the subsequent sections.

8.2.1 Structure and Formulation

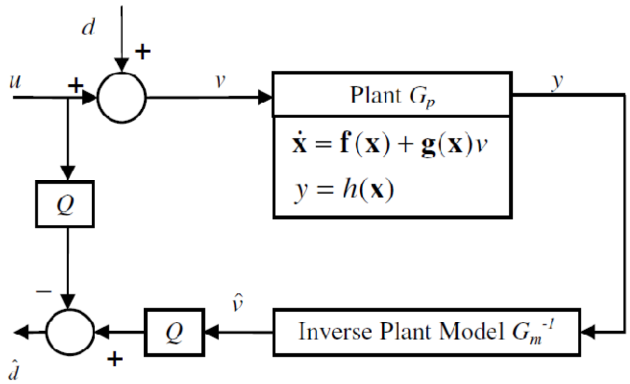


FIG.-8.2.1: BLOCK DIAGRAM OF NONLINEAR DISTURBANCE OBSERVER

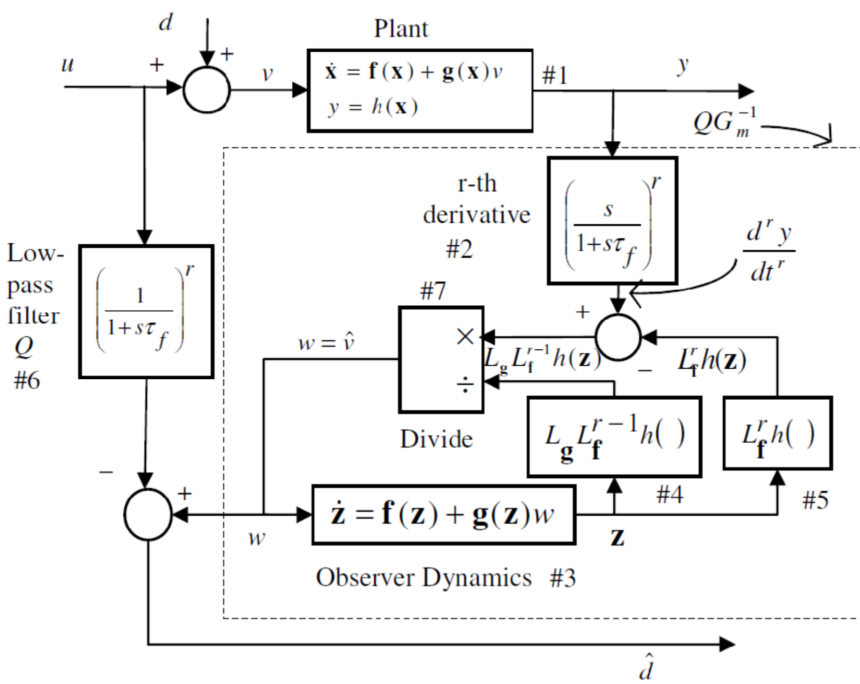


FIG.-8.2.2: IMPLEMENTATION OF THE DISTURBANCE OBSERVER

The conceptual structure of the proposed disturbance observer is shown in Figure-8.2.1. In this block diagram, u is the manipulated variable, which generally comes from the controller (not shown), d is the equivalent process disturbance, $\hat{d}$ is the estimated disturbance and G_m^{-1} is the

Hirschorn inverse of the nonlinear model (to be described in the next section). Note that the plant is excited by the composite input, v, defined as $v = u + d$.

The similarity of this structure with that described in [Chen2009] may be noted. However, the referred earlier work describes a frequency domain approach to construct the DOB for linear systems whereas the proposed method is defined in the time domain with a state variable representation of the nonlinear plant model. The structure presented in Figure-8.2.1 is hybrid because it also embodies two frequency domain filters. This unconventional approach has been taken to show the structural simplicity and also to contrast the proposed DOB structure with that of other time-domain DOB structures [e.g., fig 2.6 in Li2014]. In Figure-8.2.1, G_p symbolically represents the nonlinear SISO plant. The block G_m^{-1} represents the Hirschorn inverse of its nonlinear model, which is followed by a low-pass filter symbolized by $Q(s)$ of appropriate degree as explained later. Note that Figure-8.2.1 describes the conceptual structure of the proposed DOB. Implementation details of QG_m^{-1} (i.e., one of the low pass filters along with the Hirschorn inverse) is shown in Figure-8.2.2.

The expression in (8.2.4) for left Hirschorn inverse, which reconstructs the input from the plant output and its derivatives. (An alternative explanation of Hirschorn inverse may be obtained from [Henson1997].) However, to obtain the true Hirschorn inverse, the expression in (8.2.4) requires state variable $\mathbf{x}$, which may not be available in general. We, therefore, have to construct a state estimator with a new variable $\mathbf{z}$ which should emulate the dynamics of the original state variable, $\mathbf{x}$. The dynamics of the observer is as follows.

$$\dot{\mathbf{z}} = \mathbf{f}(\mathbf{z}) + \mathbf{g}(\mathbf{z})\hat{v}$$

The observed composite input $(\hat{v})$ is to be used because the actual input (v) is not available due to the unknown disturbance component. The observed composite input $(\hat{v})$ may, however, be computed using (8.2.4) and the fact that $v = u + d$. The observed value of the disturbance signal $(\hat{d})$ is given by

$$\hat{d} = \frac{\dfrac{d^r y}{dt^r} - L_{\mathbf{f}}^r h(\mathbf{z})}{L_{\mathbf{g}} L_{\mathbf{f}}^{r-1} h(\mathbf{z})} - u \tag{8.2.5}$$

Note that the denominator in (8.2.5) is a scalar.

From the above one can derive

$$\hat{d} = \frac{[L_{\mathbf{f}}^{r}h(\mathbf{x}) - L_{\mathbf{f}}^{r}h(\mathbf{z})]}{L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h(\mathbf{z})} + \left[\frac{L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h(\mathbf{x})}{L_{\mathbf{g}}L_{\mathbf{f}}^{r-1}h(\mathbf{z})}\right]d \tag{8.2.6}$$

Now, it is straightforward to show that $\hat{d} = d$ is a solution to the above equation after the transients due to initial condition mismatch (between the plant and the observer) have decayed. The argument proceeds as follows. For simplicity, it is assumed that $u = 0$. Note that $\dot{\mathbf{z}} = \mathbf{f}(\mathbf{z}) + \mathbf{g}(\mathbf{z})\hat{v}$ is globally asymptotically stable because it is an emulation of the original plant. When both the plant and the observer dynamics have individually reached equilibrium and the excitations are the same ($\hat{d} = d$), trajectories of both the state vectors, namely $\mathbf{x}$ and $\mathbf{z}$ would be identical. This will force the first term of (8.2.6) to be zero and the second coefficient to be unity, satisfying the condition $\hat{d} = d$. The above argument, however, does not take into account the effects of low-pass filters. In a practical scenario, the estimation error $\varepsilon = \hat{d} - d$ would become negligible once the transients due to initial conditions decay down and the disturbance signal remains well within the bandwidth of the filters.

Implementation of the above proposed disturbance observer is shown in Figure-8.2.2, where the block #1 represents the plant dynamics and block #3 represents the observer dynamics. Noting that obtaining derivatives of signals worsens the signal to noise ratio, an approximate differentiator of *r*-th degree is shown in block #2. This corresponds to the filter applied to the inverse model in Figure-8.2.1. Here, τ_f is the filter time constant, which has to be chosen appropriately [Chen2009]. The corresponding low pass filter for the control input u is shown in block #6. In (8.2.5), the numerator has two components of which the subtrahend is performed in block #5. The concerned denominator is computed in block #4. The purpose of the summer and that of the divide block #7 are self explanatory.

Note that the theory developed above and the implementation diagram are applicable to nonlinear single-input-single-output (SISO) systems. The requirement of global asymptotic stability of the plant has already been mentioned. Also required is the condition that the system description is sufficiently smooth to permit computation of the corresponding Lie derivatives. Further implied requirements are that (i) the plant model is observable, and (ii) the relative order of the system as defined above should be independent of the operating point [Slotine1991]. Fortunately, for many chemical process models, the above conditions are satisfactorily met.

An additional requirement for all inversion based observers, like the present one, is that the inverse must be stable. This requires the "zero dynamics" [Henson1997] to be stable and this must be investigated for implementing the proposed DOB.

8.3 Case Study and Comparison

A test problem [Goodwin2009], has been considered first to show the efficacy of this proposed method. Some industrially relevant case studies have been reported to demonstrate the functioning and efficacy of the proposed disturbance observer. One case study involves a Continuous Stirred Tank Reactor (CSTR) whereas the other one involves a fermentation process. The Disturbance Observers for both these plants have been excited with similar composite disturbance signals to characterize the corresponding DOB performance.

8.3.1 Test Problem-C

8.3.1.1 Problem Statement

To illustrate the performance of the proposed DOB, a nonlinear second order system [Goodwin2009] has been considered as a Test Problem-C which is in state space form.

$$\begin{aligned} \dot{x}_1 &= x_2 + x_2^{\,3} \\ \dot{x}_2 &= -2x_1 - 3x_2 + u + 0.1x_1^{\,2}u \\ y &= x_2 \end{aligned} \tag{8.3.1}$$

8.3.1.2 Design of DOB

From (8.3.1),

$$\begin{aligned} \dot{x}_1 &= x_2 + x_2^{\,3} \\ \dot{x}_2 &= -2x_1 - 3x_2 + u + 0.1x_1^{\,2}u \\ y &= x_2 \end{aligned}$$

Comparing with (8.2.1),

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} x_2 + x_2^{\,3} \\ -2x_1 - 3x_2 \end{bmatrix}}_{f(x)} + \underbrace{\begin{bmatrix} 0 \\ 1 + 0.1x_1^2 \end{bmatrix}}_{g(x)} u$$

$$y = h(x) = x_2$$

Since, $L_g h(x) \neq 0$

$$\therefore L_g L_f^{\,1-1} h(x) \neq 0$$

So, relative degree is 1.

Now using Hirschorn's inverse, the inverse system becomes

$$\dot{z} = f(z) + g(z) \frac{\frac{dy}{dt} - L_f^1 h(z)}{L_g L_f^{\,1-1} h(z)}$$

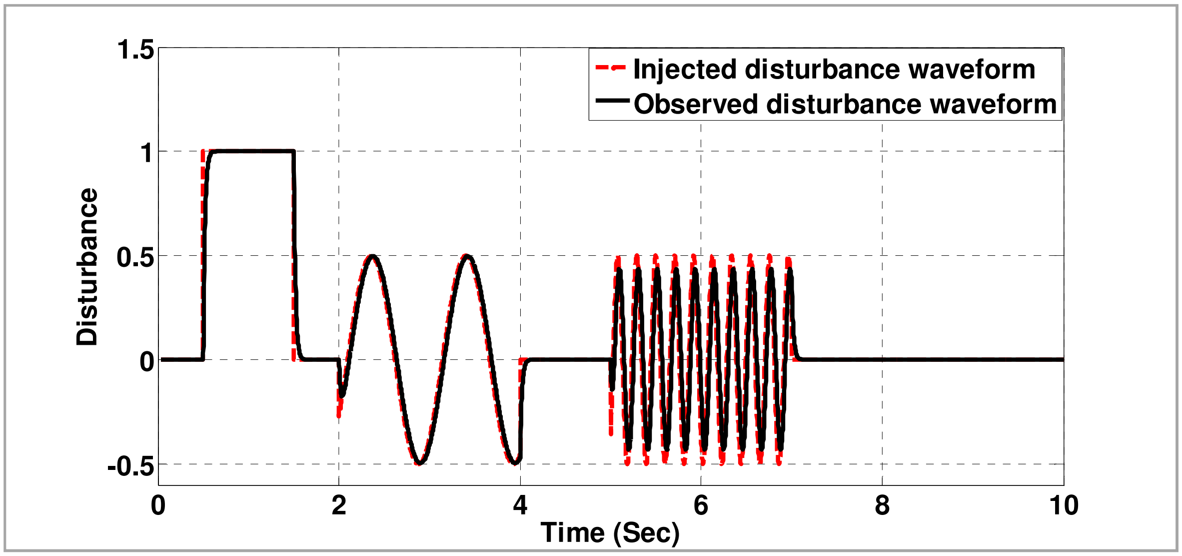
$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} z_2 + z_2^3 \\ -2z_1 - 3z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 + 0.1z_1^2 \end{bmatrix} \frac{\frac{dy}{dt} + 2z_1 + 3z_2}{1 + 0.1z_1^2}$$

Here, input $u + d$ has been reconstructed as $\dfrac{\frac{dy}{dt} - L_f^1 h(z)}{L_g L_f^{\,1-1} h(z)} = \dfrac{\frac{dy}{dt} + 2z_1 + 3z_2}{1 + 0.1z_1^2}$

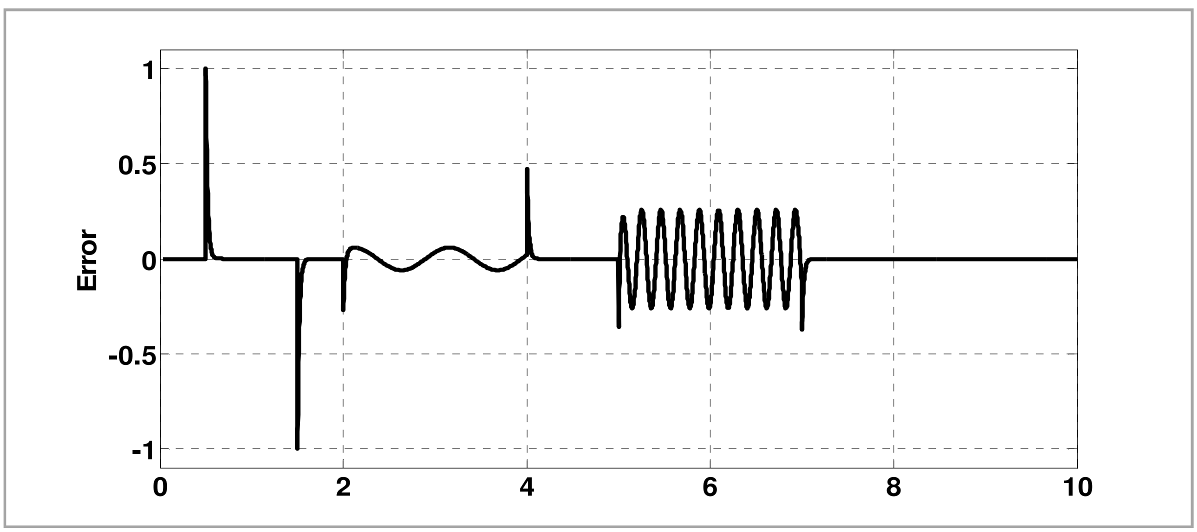
8.3.1.3 Simulation Results

We have introduced a composite disturbance signal d (shown in Fig. 8.3.1(A)) consisting of a pulse followed by two sine wave pulses. This composite disturbance waveform is used to demonstrate the versatility of the proposed DOB as well as the effect of finite bandwidth dictated by the low pass filter. The specification of the composite waveform is stated below:

Step Pulse height=1, Step Pulse width=1 sec, beginning at 0.5 sec; Sine wave height=1, frequency =6 rad/s, Sine wave Pulse width=2 sec, beginning at 2sec; Sine wave height=1, frequency =30 rad/s, Sine wave Pulse width=2 sec, beginning at 5 sec.



(A)



(B)

FIG.-8.3.1: FOR TEST PROBLEM-C (A) INJECTED DISTURBANCE AND ITS OBSERVED VALUE BY THE PROPOSED DOB (B) OBSERVATION ERROR OF DOB

In Figure-8.3.1, it has been shown that satisfactory disturbance estimation has been obtained. Superimposed on the Figure-8.3.1(A*)* is the output of the DOB from which it may be inferred that the DOB tracks the disturbance quite acceptably except for the high frequency portion of the waveform as evident from Figure-8.3.1(B*)*. The error in the high frequency sine wave can be seen to be contributed mostly by the phase shift between the actual and the estimated disturbance. This phase shift is contributed primarily by the low pass filter which can be tuned to increase or decrease the bandwidth of the observer.

8.3.2 Continuous fermentor process

Another example with different process dynamics is included to demonstrate that the performance of the proposed DOB algorithm is not dependent on plant model. As an aside, we also demonstrate the decay of errors in case of mismatch of initial conditions.

8.3.2.1 Problem Statement

A nonlinear continuous fermentation process [Szederke´nyi2002] has been considered as shown in (8.3.2).

$$\begin{aligned}\frac{dX}{dt} &= \mu(S)X - \frac{XF}{V} \\ \frac{dS}{dt} &= -\frac{\mu(S)X}{Y} + \frac{(S_F - S)F}{V}\end{aligned} \qquad (8.3.2),$$

Where X is biomass concentration, S is substrate concentration, F is feed flow rate, V is volume, S_F is substrate feed concentration, Y is yield coefficient, $\mu_{\max}$ is maximal growth rate, K_1 is saturation parameter and K_2 is inhibition parameter.

Nonlinear growth rate function is $\mu(S)$, where $\mu(S) = \mu_{\max} \dfrac{S}{K_2 S^2 + S + K_1}$.

In [Szederke´nyi2002], (8.3.2) has been considered as standard control affine form with the centered state vector $x = \begin{bmatrix}\overline{X} & \overline{S}\end{bmatrix}^T = \begin{bmatrix}x_1 & x_2\end{bmatrix}^T = \begin{bmatrix}X - X_0 & S - S_0\end{bmatrix}^T$ i.e. centered biomass and substrate concentration. The centered input flow rate is the manipulated input variable, $u = \overline{F} = F - F_0$. ($X_0$, S_0, F_0) is steady state operating point; values are S_0=0.2187, X_0 =4.8907 and F_0=3.2089.

Now state model becomes,

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})u \qquad (8.3.3)$$

where $\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mu(x_2 + S_0)(x_1 + X_0) - \dfrac{(x_1 + X_0)F_0}{V} \\ -\dfrac{\mu(x_2 + S_0)(x_1 + X_0)}{Y} + \dfrac{(S_F - (x_2 + S_0))F_0}{V} \end{bmatrix} = \begin{bmatrix} f_1(\mathbf{x}) \\ f_2(\mathbf{x}) \end{bmatrix}$;

$$\mathbf{g}(\mathbf{x}) = \begin{bmatrix} -\dfrac{(x_1 + X_0)}{V} \\ \dfrac{(S_F - (x_2 + S_0))}{V} \end{bmatrix} = \begin{bmatrix} g_1(\mathbf{x}) \\ g_2(\mathbf{x}) \end{bmatrix}$$

It has been shown in [Szederke´nyi2002] that the best choice of output to be controlled is the substrate concentration, i.e. $y = x_2$, or, $h(\mathbf{x}) = x_2$

The coefficients have been taken as $V = 4, S_F = 10, Y = 0.5, \mu_{\max} = 1, K_1 = 0.03, K_2 = 0.5$.

8.3.2.2 Design of DOB

Now, to derive the DOB, we follow the procedure outlined in section 8.2.

$$L_{\mathbf{f}}^1 h(\mathbf{x}) = f_2(\mathbf{x}), L_{\mathbf{g}} h(\mathbf{x}) = g_2(\mathbf{x})$$

The relative degree of the fermentation process (8.3.3) is 1 as

$$L_{\mathbf{g}} L_{\mathbf{f}}^{1-1} h(\mathbf{x}) = L_{\mathbf{g}} L_{\mathbf{f}}^0 h(\mathbf{x}) = L_{\mathbf{g}} h(\mathbf{x}) = g_2(\mathbf{x}) = \frac{(9.78 - x_2)}{4} \neq 0$$

Now, the Hirschorn Inverse model of fermentation process (from (8.2.4)):

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} f_1(\mathbf{z}) \\ f_2(\mathbf{z}) \end{bmatrix} + \begin{bmatrix} g_1(\mathbf{z}) \\ g_2(\mathbf{z}) \end{bmatrix} \frac{\dfrac{dy}{dt} - f_2(\mathbf{z})}{g_2(\mathbf{z})}$$

Observed value of disturbance, $\hat{d} = \dfrac{\dfrac{dy}{dt} - f_2(\mathbf{z})}{g_2(\mathbf{z})} - u$

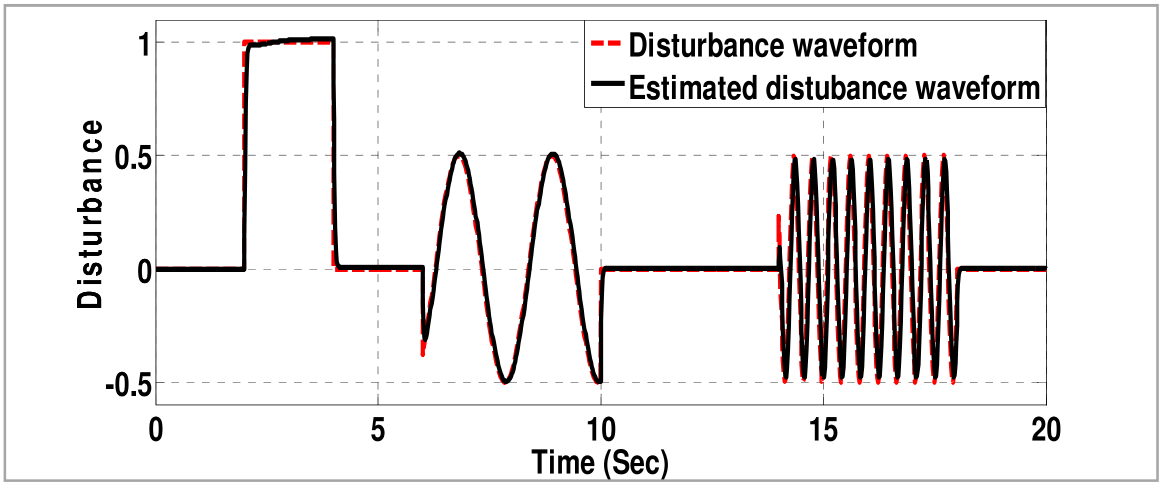
As this nonlinear model has well defined relative degree 1, while implementing the DOB for simulation studies, the filter time constant has been taken as 0.02 with relative degree 1.

Zero dynamics of this fermentation process has been shown in [Szederke´nyi2002]. By selecting substrate concentration x_2 as output, zero dynamics is found globally stable.

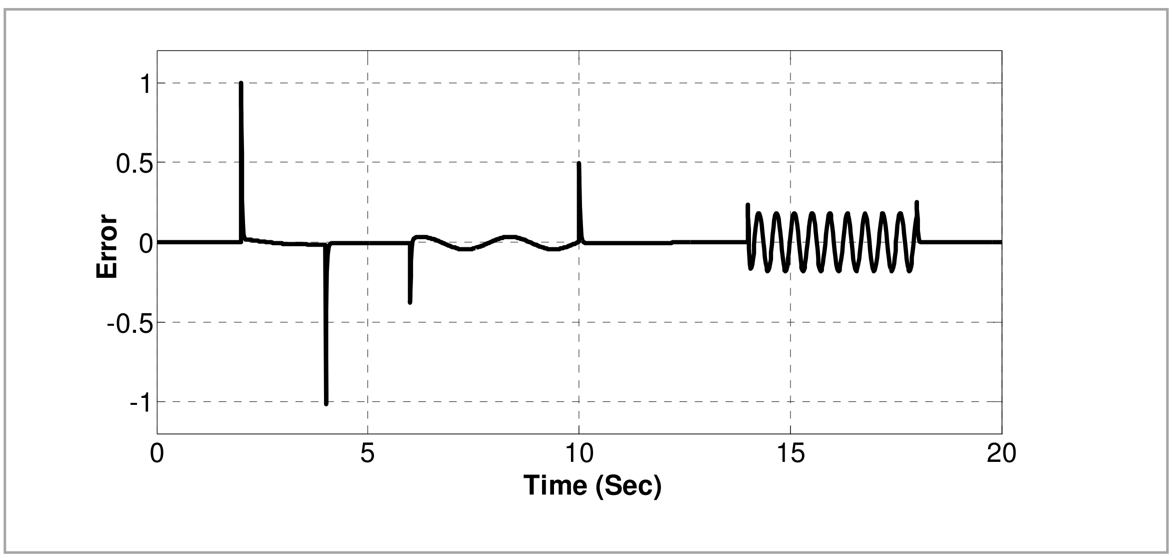
8.3.2.3 Simulation Results

A composite disturbance signal d has been considered which consists of a pulse followed by two sine wave pulses. The specification of the composite waveform is stated below:

Step Pulse height=1, Step Pulse width=2 sec, beginning at 2 sec; Sine wave height=1, frequency =3 rad/s, Sine wave Pulse width=4 sec, beginning at 6 sec; Sine wave height=1, frequency =15 rad/s, Sine wave Pulse width=4 sec, beginning at 14 sec.



(A)



(B)

FIG. 8.3.2. FOR FERMENTATION PROCESS (A) INJECTED DISTURBANCE AND ESTIMATED DISTURBANCE (B) OBSERVATION ERROR OF THE PROPOSED DOB

The equilibrium point of the process equation (8.3.3) is (0, 0), which has been used for the purpose of initializing the model. Injected disturbance and observed disturbance have been superimposed on Figure-8.3.2(A*)*, which shows successful disturbance estimating property of

proposed nonlinear DOB. Corresponding estimation error is also shown in Figure-8.3.2(B*)*. It may be seen that the low frequency sine wave component as well as the pulse are tracked very well. The noticeable error in the higher frequency is due to the phase shift as explained before.

The problem of initial condition arises generically in all state estimators. As a result, most observers operate with an initial error due to mismatch in the initial condition. As long as the error dynamics is stable and errors decay acceptably fast, the role of an observer is deemed to be fulfilled. Initial condition mismatching case also has been considered for the above process. Considering substantial initial condition mismatch, observation error has been shown in Figure-8.3.3. In that case, observer states have been initialized as 0.5 and 0 respectively. It may be inferred that the decay of initial transient is rather sluggish. However

it would only occur when this DOB is engaged for the first time. After this initial transient period is over, the DOB would continue to track time varying disturbance inputs successfully as shown in the previous diagrams.

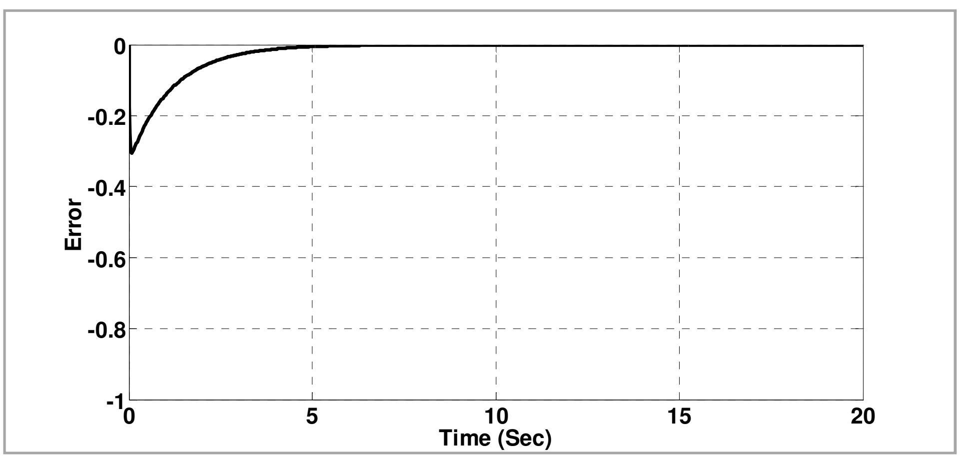


FIG.- 8.3.3: OBSERVATION ERROR WITH INITIAL CONDITION MISMATCH

It may be added here that the error dynamics of any nonlinear observer, including the one proposed, has to be verified for each nonlinear plant.

8.3.3 Continuous Stirred Tank Reactor (CSTR)

8.3.3.1 Problem Statement

A nonlinear CSTR state variable model [Henson1997, Ghaffari2013, Wu2001] has been used as plant to illustrate the performance of the proposed DOB. For generalized analysis, dimensionless form of CSTR (described in Section 7.4.2.1) has been chosen and dimensionless parameters and process variables have been considered as listed in Table-7.4.1. Zero dynamics of the CSTR system has been calculated in Section 7.4.2.3.

$$\begin{aligned}\dot{x}_1 &= -\alpha x_1 + D_\alpha (1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} \\ \dot{x}_2 &= -\alpha x_2 + D_\alpha (1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} + \beta(u-x_2) + \alpha d(t)\end{aligned} \tag{8.3.4}$$

The control objective is to regulate the reactor temperature i.e. $y = x_2$.

The coefficients are taken as $D_\alpha = 1$, $\alpha = 1$, $\beta = 0.3$ and $\gamma = 20$. Also, the plant model has been initialized at its equilibrium point i.e. $x_1(0)$=0.625 and $x_2(0)$=0.48.

8.3.3.2 Design of DOB

From (8.3.4),

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} -\alpha x_1 + D_\alpha (1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} \\ -\alpha x_2 + D_\alpha (1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} - \beta x_2 \end{bmatrix}; \mathbf{g}(\mathbf{x}) = \begin{bmatrix} 0 \\ \beta \end{bmatrix}; y = h(\mathbf{x}) = x_2$$

Now, to derive the DOB, we follow the procedure outlined above.

$$L_{\mathbf{g}} h(\mathbf{x}) = \beta \quad ; \quad L_{\mathbf{f}} h(\mathbf{x}) = -\alpha x_2 + D_\alpha (1-x_1)e^{\frac{x_2}{1+x_2/\gamma}} - \beta x_2$$

Since, $L_{\mathbf{g}} L_{\mathbf{f}}^{1-1} h(\mathbf{x}) = L_{\mathbf{g}} L_{\mathbf{f}}^{0} h(\mathbf{x}) = L_{\mathbf{g}} h(\mathbf{x}) = \beta \neq 0$, the relative degree of this CSTR model is 1, i.e. $r = 1$.

Now, the Hirschorn Inverse model of CSTR [Henson1997] (from (8.2.4)):

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} -\alpha z_1 + D_\alpha (1-z_1)e^{\frac{z_2}{1+z_2/\gamma}} \\ -\alpha z_2 + D_\alpha (1-z_1)e^{\frac{z_2}{1+z_2/\gamma}} - \beta z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \beta \end{bmatrix} \frac{\frac{dy}{dt} + \alpha z_2 - D_\alpha (1-z_1)e^{\frac{z_2}{1+z_2/\gamma}} + \beta z_2}{\beta} \tag{8.3.5}$$

Observed value of disturbance, $\hat{d} = \dfrac{\dfrac{dy}{dt} + \alpha z_2 - D_\alpha (1 - z_1) e^{\frac{z_2}{1+z_2/\gamma}} + \beta z_2}{\beta} - u$

As the nonlinear model has well defined relative degree 1, while implementing the DOB for simulation studies, the filter time constant has been taken as 0.02 with relative degree 1.

8.3.3.3 Simulation Results

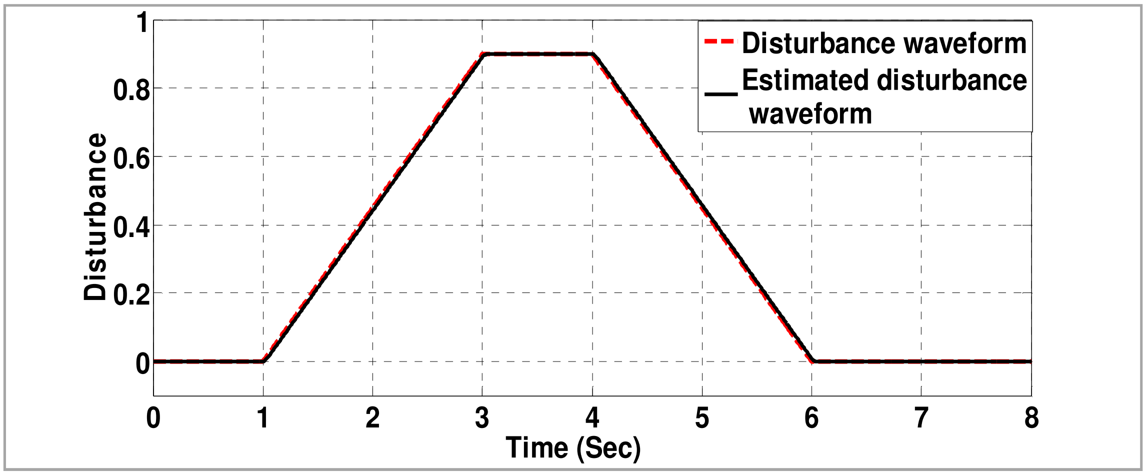
For analysing the performance of the proposed DOB, different cases have been considered to show the effectiveness of our proposed nonlinear DOB method. To focus on the disturbance tracking property, the plant model has been initialized at its equilibrium point and the observer is initialized to eliminate the starting transient.

Case (I): A composite disturbance signal d (shown in Figure-8.3.4) has been considered, which consists of ramp and step signals as stated below:

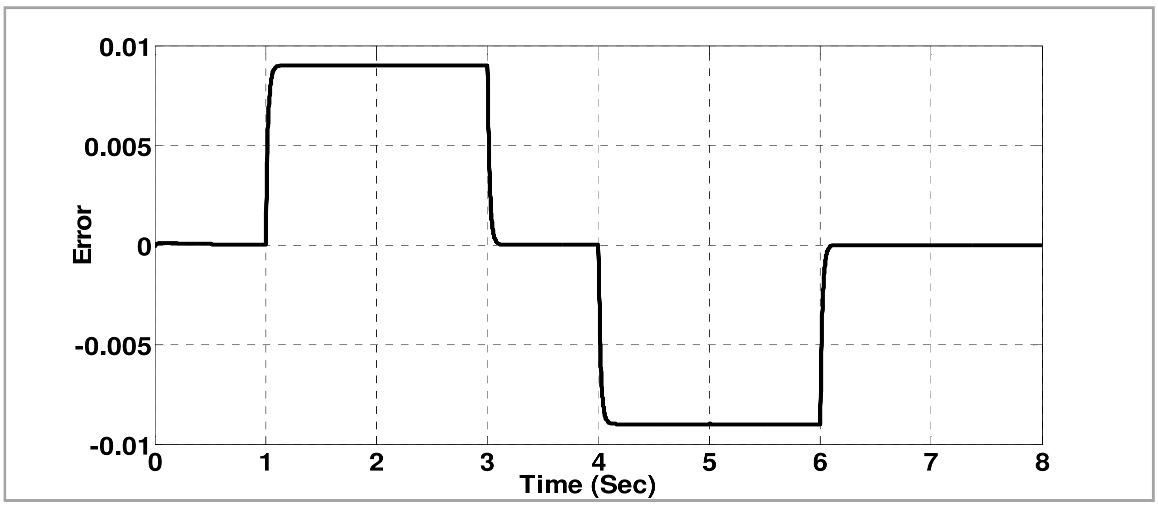
$$d = \begin{cases} 0 & 0 \le t < 1 \\ 0.9 + \dfrac{9(t-3)}{20} & 1 \le t < 3 \\ 0.9 & 3 \le t < 4 \\ 0.9 - \dfrac{9(t-4)}{20} & 4 \le t < 6 \\ 0 & 6 \le t \end{cases}$$

We prefer this waveform as a prototype disturbance test signal as (i) one can get good idea about the behaviour of the DOB for ramping/sawtooth disturbance signal and steady disturbance signal, (ii) it can be modified to create a wide range of disturbance signal waveforms.

The observed signal has also been shown in Figure-8.3.4(A*).* and it is evident that acceptable disturbance estimation has been achieved. Corresponding observation error is presented in Figure-8.3.4(*B)*, wherefrom it may be seen that the estimation errors are negligible for this case.



(A)



(B)

FIG.- 8.3.4: FOR CSTR IN CASE (I)- (A) INJECTED DISTURBANCE AND ITS OBSERVED VALUE BY THE PROPOSED DOB (B) OBSERVATION ERROR OF DOB

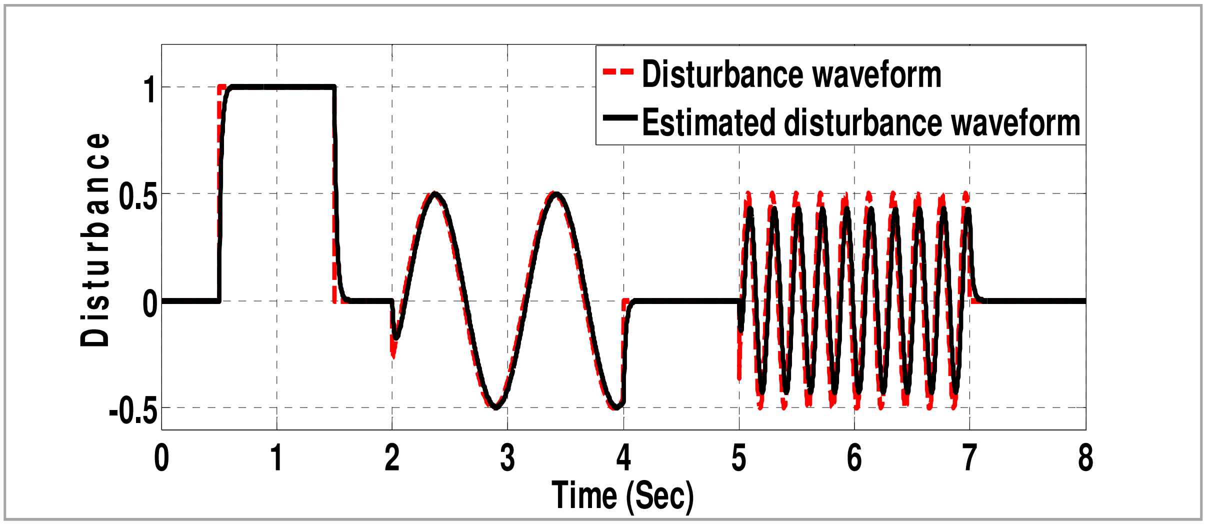
Case (II): We have introduced a composite disturbance signal d (shown in Fig. 8.3.5(A)) consisting of a pulse followed by two sine wave pulses. This composite disturbance waveform is used to demonstrate the versatility of the proposed DOB as well as the effect of finite bandwidth dictated by the low pass filter. The specification of the composite waveform is stated below:

Step Pulse height=1, Step Pulse width=1 sec, beginning at 0.5 sec; Sine wave height=1, frequency =6 rad/s, Sine wave Pulse width=2 sec, beginning at 2sec; Sine wave height=1, frequency =30 rad/s, Sine wave Pulse width=2 sec, beginning at 5 sec.

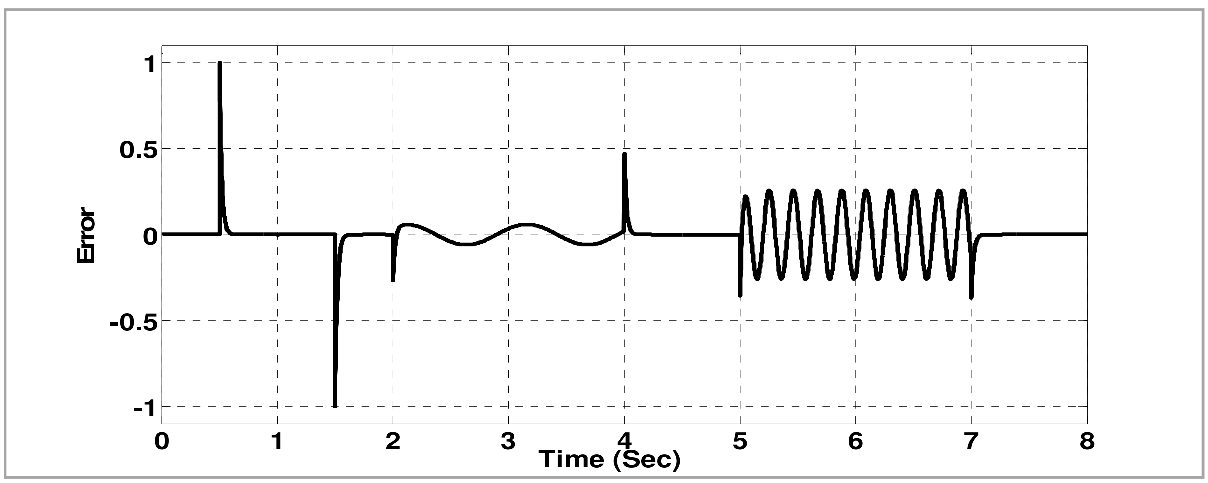
Superimposed on the Figure-8.3.5(A) is the output of the DOB from which it may be inferred that the DOB tracks the disturbance quite acceptably except for the high frequency portion of the waveform as evident from Fig. Figure-8.3.5(B). The error in the high frequency sine wave can be seen to be contributed mostly by the phase shift between the actual and the estimated disturbance. This phase shift is contributed primarily by the low pass filter which can be tuned to increase or decrease the bandwidth of the observer.

It may be seen that low frequency disturbances are tracked well but at higher frequency, there is non-trivial error. For the sine wave disturbance, the error occurs mostly due to phase shift. The high frequency error also introduces error spikes at the beginning and end of the pulses.

Case (III): At this stage it would be worthwhile to compare the performance of the proposed DOB with that proposed in [Chen2004], the primary features of which were discussed in the introduction section. It may be noted that [Chen2004] provides some freedom to choose observer parameters as long as the P matrix therein satisfies the concerned Lyapunov equation (eqn. no. 20 in [Chen2004]). However, all such solutions may not provide satisfactory estimation of disturbance even for sine wave disturbance at frequencies other than the tuned frequency. The present workers have chosen a solution which is near optimal in the sense that the designed DOB can track frequencies other than the tuned frequency and also other waveforms in a reasonable manner. The tuning frequency used is 2.4 rad/sec and the chosen P matrix is $P = \begin{bmatrix} 0.1 & -0.12 \\ -0.12 & 0.2 \end{bmatrix}$. The proposed DOB and the DOB designed as per [Chen2004] have been subjected by a composite waveform as shown in Figure- 8.3.6 which consists of a square pulse, a ramp and two packets of sine waves at 1.2 rad/sec and 3.6 rad/sec respectively being 50% and 150% of the tuned frequency of [Chen2004] DOB. From the figure, it may be seen that while the DOB proposed in this paper tracks the disturbance very well, the DOB designed as per [Chen2004] exhibits (i) high initial transient, (ii) reasonable tracking at 3.6 rad/sec (iii) severe waveform distortions for both pulse and ramp portions of the signal and (iv) noticeable tracking error at 1.2 rad/sec. It may be shown that at the tuned frequency of 2.4 rad/sec, the error for [Chen2004] DOB is negligible.

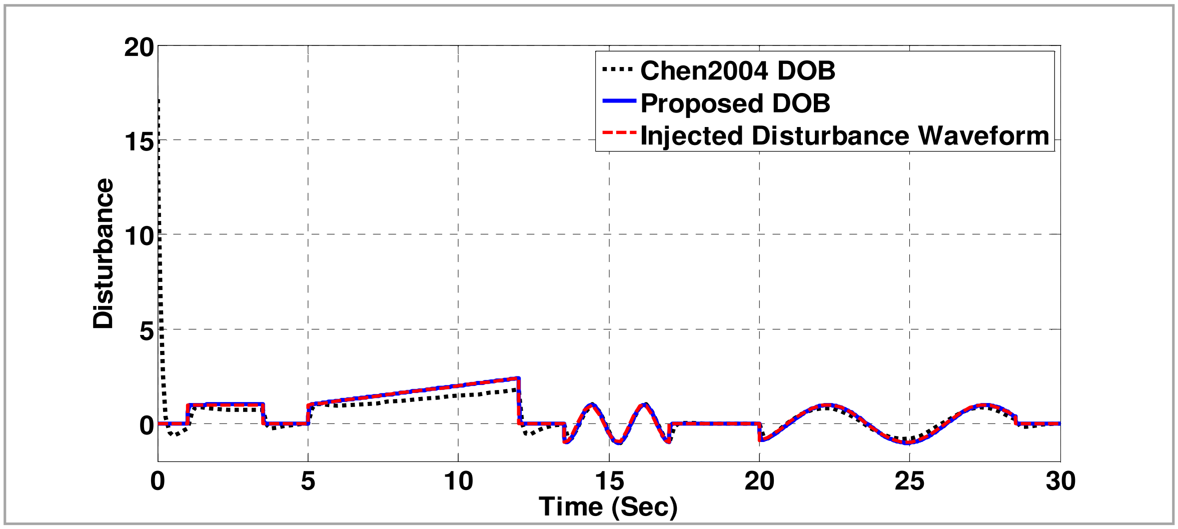


(A)

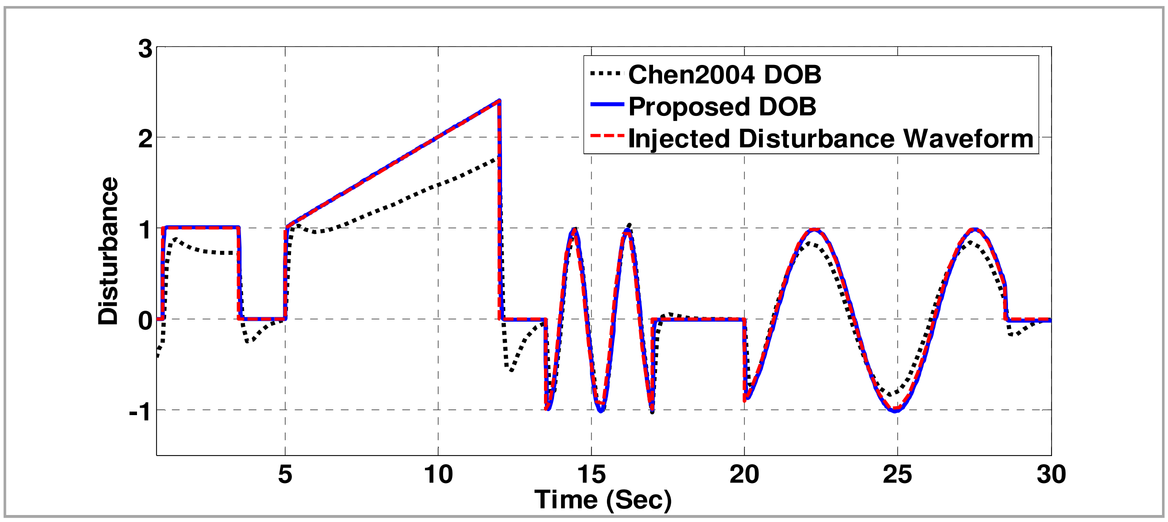


(B)

FIG.- 8.3.5: FOR CSTR IN CASE (II)- (A) INJECTED DISTURBANCE AND ITS OBSERVED VALUE BY THE PROPOSED DOB (B) OBSERVATION ERROR OF THE DOB



(A)



(B)

FIG.-8.3.6: COMPOSITE WAVEFORM DISTURBANCE COMPARISON FOR CSTR IN CASE (III) (A) IN FULL SCALE (B) ZOOMED

8.4 Discussions

In this section, we discuss a few points regarding the strengths and weaknesses of the proposed DOB vis-à-vis those of [Chen2004].

- The proposed DOB does not need access to the state variables or their derivatives, unlike [Chen2004] and several other DOB's mentioned in [Li2014] which require the same. This is, possibly, one of the strongest points in favour of that proposed DOB as accessibility of the state variables cannot be taken for granted.

- In the derivation of the proposed DOB, asymptotic stability of the plant was assumed. However, this restriction can be relaxed fairly easily by using a stabilising feedback as has been proposed in [Li2014, (in section 5.2)]. It should be noted that the purpose of the DOB is to add feed-forward to such feedback control scheme so that the existence of such a stabilising feedback may be assumed. Though the assumption about stability of the plant is not an explicit requirement of the DOB in [Chen2004], but for the application of the same, existence of a feedback for performance improvement and/or stabilisation would be required in any case.
- It may be noted that high-frequency tracking error for the proposed DOB is attributable to the low-pass filters which define the bandwidth of the DOB. When the disturbance signal is well within the bandwidth, the phase shift due to the filters would be negligible, and consequently the tracking error would also be negligible after the transients have decayed.
- With appropriate choice of parameters, convergence of the DOB in [Chen2004] may be provably assured for a specified waveform of disturbance though for other waveforms, the question of convergence remains open. For the proposed DOB, such convergence has been demonstrated empirically with different simple and composite waveforms. Additionally, it has been shown for the proposed DOB that the observed disturbance signal equalling the actual disturbance signal is a solution in the ideal condition, i.e. when the effects of the filters are negligible and the transients due to initial condition mismatch have decayed.
- With a composite waveform, it has been found that the tracking error of a DOB constructed as per [Chen2004] is more than that obtained in the proposed DOB. However, as there are possible alternative solutions to the DOB of [Chen2004], the above comment may not be generalised.
- Trading-off of noise rejection versus tracking error is performed in the proposed DOB by appropriate choice of filter time constants. In the DOB of [Chen2004], a degree of design freedom is obtainable by choice of appropriate filter parameters. However, the trade-off mechanism in [Chen2004] is not explicitly described.
- In Figure-8.3.6, large initial error may be noted for the DOB described in [Chen2004]. This is apparently due to mismatch in initial condition.

- It would be worthwhile to conjecture about the applicability of the proposed DOB for MIMO cases. As Hirschorn inverse is applicable to MIMO non-linear systems as well, under certain restrictions, these non-linear SISO DOB approaches can potentially be extended to MIMO systems. The extension to multi-output systems is fairly straightforward. However, in some cases, it may result in multiple solutions. This may be understood from the following. Let, a system be observable by either of its two outputs. A DOB can then be constructed following the process described above. Alternatively, one can take a linear combination of the two outputs and generate a DOB. Extension to multiple outputs is possible but for the case of multiple inputs, and/or multiple disturbances, the theoretical development becomes involved.

8.5 Chapter Conclusion

New method of designing disturbance observers for nonlinear systems have been presented in this chapter. This method, based on Hirschorn Inverse, has been illustrated by industrial processes, which are highly nonlinear. In all the cases, the plants have been subjected to pulse, truncated ramp and periodic disturbances and it was shown that the disturbances have been estimated satisfactorily. As both Lie derivative and Hirschorn Inverse exist for many nonlinear chemical processes, it is conjectured that these methods may be applicable for a non-trivial class of nonlinear problems. Additionally the performances are compared with that for a well-known DOB which demonstrates the superiority of the proposed DOB.

Chapter 9: Active Anti-Disturbance Control for Nonlinear SISO Systems

9.1 Chapter Introduction and previous work

Active Anti-Disturbance Control, which so far had reportedly been applied to linear plant models, has been extended in this chapter to cover control of nonlinear plant models. To accommodate nonlinear plants, an Internal Model Controller (IMC) and a Disturbance Observer (DOB) for nonlinear systems have been used innovatively in the design architecture. It is conjectured that the IMC approach would mitigate plant parameter perturbations whereas the DOB would take care of external disturbances together to compositely produce a more robust closed loop plant. To illustrate the proposed algorithm, viz., Modified Active Anti-Disturbance Control (MAADC), the proposed technique has been employed to control a nonlinear Continuous Stirred Tank Reactor (CSTR) system. It is shown that strong external disturbances and some times, model uncertainties have been actively mitigated by using the proposed MAADC, indicating superior robustness compared to ordinary nonlinear IMC based control. Different set-point and disturbance conditions have been considered to characterize the algorithm.

Internal Model Control (IMC) [Garcia1982, Morari1989] is one of the model based controls, which is well accepted in process control industry due to its simplicity, robustness and good control performance like setpoint tracking and disturbance rejection. The IMC approach has also been considered as one of the Passive Anti-Disturbance Control (PADC) methods. Though IMC can reject disturbances to a considerable extent, their performance sometimes is inadequate in the presence of strong disturbances [Li2014, Chen2011]. To overcome the limitations of PADC methods in disturbance handling, Active Anti-Disturbnace Control (AADC) approach has been used [Li2014]. The idea behind AADC, elaborated in a subsequent section, is to counteract the disturbances directly by feedforward control. Disturbance Observer (DOB), a popular disturbance estimation technique, is of current interest [Ali2015]. Not only external disturbance, but unmodeled dynamics and uncertainties can also be estimated using appropriate forms of DOB [Li2014] and may be employed in so named Disturbance Observer Based Control (DOBC).

Such controllers can achieve a good disturbance-rejection performance without sacrificing the nominal performance. In a survey paper [Chen2016], Disturbance Observer Based Control (DOBC) and related methods have been reviewed.

Literature [Guo2014, Guo2014a] reported several Anti-Disturbance Control strategies for multiple disturbances. In [Yang2010, Liu2012, Wei2009, Wei2010, Chen2010] Model Predictive Control (MPC), PID, H_∞, adaptive control and variable structure control have been compositely used with DOBC. However, DOB based IMC control was not included there. In [Chen2011, Qi-bing2015, Zhang2016], IMC and DOB have been combined. For all these previous works using IMC and DOB, improved disturbance attenuation ability has been demonstrated for linear systems. In [Chen2011], they have used only external measurement disturbance. In case of [Qi-bing2015], external measurement disturbance and internal disturbance as process model mismatch have been considered. In [Zhang2016], external process disturbance as well as process-model mismatch have been considered again for linear systems whereas in our case, IMC plus DOB have been considered for nonlinear system where external process disturbance, measurement disturbance as well as process-model mismatch have been considered.

Out of the previous work, [Chen2011, Qi-bing2015, Zhang2016, Chen2009, Yang2011] specifically deal with process control applications. Both frequency domain and time domain approaches to DOB design have been reported in the literature [Li2014], of which, for nonlinear plants, only the time domain approach is applicable. For most of the DOBs for nonlinear systems reported in literature, the so-named gain based nonlinear observers approach had been employed. Such nonlinear DOB design approaches have been used in applications such as robotic manipulator [Chen2000, Chen2004], missile systems [Yang2011], magnetic bearing system [Chen2004a], permanent magnet synchronous motor [Yang2012] etc.

In the present work, a novel method of designing a Modified Active Anti-Disturbance Control (MAADC) has been presented. For that purpose, a nonlinear DOBC has been made by combining IMC and DOB for nonlinear systems. Using the concept of Lie Derivative (a differential geometry approach), Hirschorn Inverse has been obtained to get the inverse model. Additionally, using this model inverse, not only the Internal Model Controller for nonlinear systems has been designed [Economou1986, Henson1991], but a DOB for nonlinear system also has been designed [Dasgupta2017]. Unlike other IMC based controllers for nonlinear systems [Brosilow2002], the proposed controller is expected to mitigate modeling error, process disturbance and measurement disturbance. A case study has been used to test the above. A nonlinear CSTR process has been considered as the plant for the case study. Zero dynamics analysis has been done for the model because stability of the zero dynamics is the necessary condition for closed loop internal stability of the considered system. Time varying set-point tracking with sinusoidal external disturbance as well as internal disturbance due to model uncertainty have been considered. Root Mean Square Errors have been shown. Robustness of the MAADC controller and that for conventional nonlinear IMC has been compared. Several set-point and disturbance cases (process disturbance, measurement disturbance, uncertainty due to process-model mismatch) have been considered to compare the performance of this proposed nonlinear AADC over nonlinear IMC using simulation.

9.2 Proposed Disturbance Rejection Approach using IMC and DOB for nonlinear systems

In this section, a disturbance rejection approach has been proposed for nonlinear system using IMC and DOB. For that purpose DOB employing embedded state observers as depicted in Chapter-8, has been used.

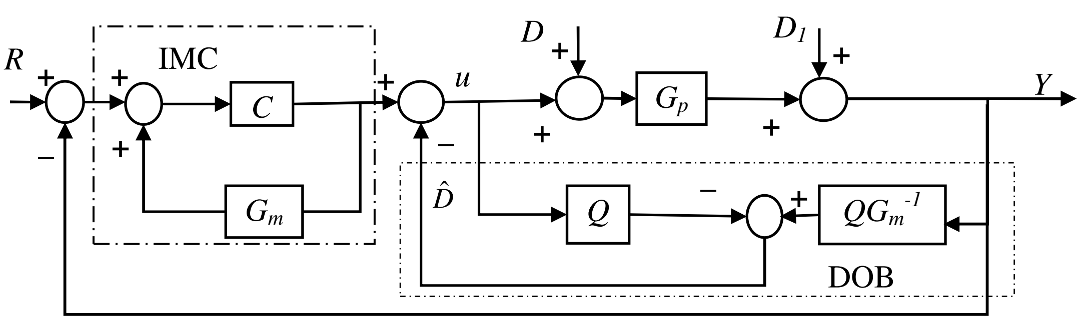


FIG.- 9.2.1: MAADC STRUCTURE

As, IMC has been known as one of the Passive Anti-Disturbance Control (PADC) which can mitigate process disturbance as well as measurement disturbance, combined use of IMC and

DOB give superior disturbance rejection in all respect. The MAADC architecture has been shown in Figure- 9.2.1.

9.3 IMC for SISO Nonlinear Systems

IMC for nonlinear systems has been designed as depicted in [Economou1986, Henson1991], where Hirschorn Inverse has been used while designing the controller. Hirschorn Inverse has been described before in Section 7.2. By constructing inverse of the nonlinear system model and multiplying low pass filter with suitable relative degree, Internal Model Controller has been designed. Here, basic structure of IMC has been considered which has been shown in Figure-3.2.2 of Chapter-3.

9.3.1 Stability of the Inverted system

For a linear system, locations of zeros are responsible for stability of the internal dynamics. Though extension of concept of zero is possible in nonlinear systems, the stability of internal dynamics may depend on particular control input. To overcome these difficulties in nonlinear system, zero-dynamics can be used. Zero-dynamics is defined to be the internal dynamics of the system when the system output is kept at zero by the input. Zero dynamics is an intrinsic feature of nonlinear systems, which is independent of the choice of control law or the desired trajectories [Slotine1991]. A nonlinear system is called an asymptotically minimum phase system if its zero dynamics is asymptotically stable.

To determine stability of the inverse system, the unforced inverse dynamics or zero dynamics is analyzed. As inverse of the process model is required in designing the internal model controller, evaluation of zero dynamics is important provided that relative degree of the nonlinear system is not equal with the order of the system.

We are considering a SISO nonlinear system of the form

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})u \\ y &= h(\mathbf{x}) \end{aligned} \tag{9.3.1}$$

When the relative degree r is defined, the nonlinear system can be transformed into a normal form [Henson1997].

Coordinate transformation becomes:

$$\begin{pmatrix} \boldsymbol{\xi} \\ \boldsymbol{\eta} \end{pmatrix} = \boldsymbol{\varphi}(\mathbf{x}) = \begin{pmatrix} h(\mathbf{x}) \\ L_{\mathbf{f}} h(\mathbf{x}) \\ \vdots \\ L_{\mathbf{f}}^{r-1} h(\mathbf{x}) \\ t_1(\mathbf{x}) \\ \vdots \\ t_{n-r}(\mathbf{x}) \end{pmatrix}. \tag{9.3.2}$$

Where n, r are order and relative degree of the system respectively, $\boldsymbol{\xi}$ is a r dimensional normal state vector and $\boldsymbol{\eta}$ is a (n-r) dimensional normal state vector.

$t_i(\mathbf{x})$ functions are basically solution to the partial differential equation

$$L_{\mathbf{g}} t(\mathbf{x}) = 0 \tag{9.3.3}$$

Now, Byrnes-Isidori normal form:

$$\begin{aligned} \dot{\xi}_1 &= \xi_2 \\ \dot{\xi}_2 &= \xi_3 \\ &\vdots \\ \dot{\xi}_{r-1} &= \xi_r \\ \dot{\xi}_r &= \alpha(\boldsymbol{\xi}, \boldsymbol{\eta}) + \beta(\boldsymbol{\xi}, \boldsymbol{\eta}) u \\ \dot{\eta}_1 &= q_1(\boldsymbol{\xi}, \boldsymbol{\eta}) \\ &\vdots \\ \dot{\eta}_{n-r} &= q_{n-r}(\boldsymbol{\xi}, \boldsymbol{\eta}) \\ y &= \xi_1 \end{aligned} \tag{9.3.4}$$

Where, $\alpha = \left[L_{\mathbf{f}}^{r} h(\mathbf{x})\right]_{\mathbf{x}=\boldsymbol{\Phi}^{-1}(\xi,\eta)}$, $\beta = \left[L_{\mathbf{g}} L_{\mathbf{f}}^{r-1} h(\mathbf{x})\right]_{\mathbf{x}=\boldsymbol{\Phi}^{-1}(\xi,\eta)}$ and $q_i = \left[L_{\mathbf{f}} \boldsymbol{\Phi}_i(\mathbf{x})\right]_{\mathbf{x}=\boldsymbol{\Phi}^{-1}(\xi,\eta)}$

Now, zero dynamics can be obtained by setting the state variables $\boldsymbol{\xi}(t) = 0$ for all $t \geq 0$:

$$\dot{\boldsymbol{\eta}} = \mathbf{q}(0, \boldsymbol{\eta}) . \tag{9.3.5}$$

When system output is constrained to a constant value or setpoint (can be assumed as zero), the stability of the closed loop system in which the inverse is employed as the controller is completely determined by the stability of these internal dynamics [Henson1997].

9.4 Case Study -- CSTR System

A nonlinear CSTR state variable model [Henson1997, Ghaffari2013, Wu2001] has been used as plant to illustrate the performance of the proposed AADC applicable for nonlinear systems using DOB employing special state observer. For generalized analysis, dimensionless form of CSTR (described in Section 7.4.2.1) has been chosen and dimensionless parameters and process variables have been considered as listed in Table-7.4.1. Zero dynamics of the CSTR system has been deduced in Section 7.4.2.3.

$$\begin{aligned}\dot{x}_1 &= -\alpha x_1 + D_\alpha (1-x_1) e^{\frac{x_2}{1+x_2/\gamma}} \\ \dot{x}_2 &= -\alpha x_2 + D_\alpha (1-x_1) e^{\frac{x_2}{1+x_2/\gamma}} + \beta(u-x_2) + \alpha d(t)\end{aligned} \tag{9.4.1}$$

The control objective is to regulate the reactor temperature i.e. $y = x_2$.

The coefficients are taken as $D_\alpha = 1$, $\alpha = 1$, $\beta = 0.3$ and $\gamma = 20$. Also, the plant model has been initialized at its equilibrium point i.e. $x_1(0)$=0.625 and $x_2(0)$=0.48.

9.4.1 MAADC Design

DOB employing special state observers for CSTR system has been designed in Section 8.3.3.

While designing nonlinear IMC, model inversion has been done as in the case of nonlinear DOB. Here, dimensionless model of CSTR in (9.4.1) has been compared with (9.3.1).

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} -\alpha x_1 + D_\alpha (1-x_1)\exp\left(\dfrac{x_2}{1+x_2/\gamma}\right) \\ -\alpha x_2 + D_\alpha (1-x_1)\exp\left(\dfrac{x_2}{1+x_2/\gamma}\right) - \beta x_2 \end{bmatrix}; \mathbf{g}(\mathbf{x}) = \begin{bmatrix} 0 \\ \beta \end{bmatrix}; y = h(\mathbf{x}) = x_2 \tag{9.4.2}$$

Now, $L_{\mathbf{g}} h(\mathbf{x}) = \beta$; $L_{\mathbf{f}} h(\mathbf{x}) = -\alpha x_2 + D_\alpha (1-x_1)\exp\left(\dfrac{x_2}{1+x_2/\gamma}\right) - \beta x_2$

Since, $L_{\mathbf{g}} L_{\mathbf{f}}^{1-1} h(\mathbf{x}) = L_{\mathbf{g}} L_{\mathbf{f}}^{0} h(\mathbf{x}) = L_{\mathbf{g}} h(\mathbf{x}) = \beta \neq 0$, the relative degree of this CSTR model is 1 i.e. r = 1.

Now, Hirschorn Inverse Model of CSTR :

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} -\alpha z_1 + D_\alpha (1-z_1) e^{\frac{z_2}{1+z_2/\gamma}} \\ -\alpha z_2 + D_\alpha (1-z_1) e^{\frac{z_2}{1+z_2/\gamma}} - \beta z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \beta \end{bmatrix} \frac{\frac{dy}{dt} + \alpha z_2 - D_a (1-z_1) e^{\frac{z_2}{1+z_2/\gamma}} + \beta z_2}{\beta}$$

Since,

$$L_{\mathbf{f}}^{1} h(\mathbf{z}) = -\alpha z_2 + D_a (1-z_1) e^{\frac{z_2}{1+z_2/\gamma}} - \beta z_2$$

$$L_{\mathbf{g}} L_{\mathbf{f}}^{1-1} h(\mathbf{z}) = L_{\mathbf{g}} h(\mathbf{z}) = \beta$$

A model inversion using Hirschorn Inverse has been computed, which has been used in designing nonlinear Internal Model Controller. Low pass filters with suitable relative degree have been used with inverse model. Using framework illustrated in Figure- 9.2.1., MAADC has been designed.

9.4.2 Results and performance analysis

Different set-point and disturbance conditions have been considered; comparison has been done between the proposed MAADC method over nonlinear IMC and effectiveness of the proposed MAADC method has been shown. Additionally, robustness study has been performed. Low pass filter time constants have been taken as 0.02 for DOB and 0.7 for IMC for all the cases. As a measure of controlled system performance, Integral Absolute Errors (IAE) have been compared (shown in Table 9.4.1) between MAADC and nonlinear IMC for all the cases.

Case (i): Zero set-point, measurement disturbance D_1 as a composite signal (which is illustrated below), and plant parametric uncertainty (plant perturbation +50% in D_α and β and -50% in B and γ) have been assumed. The specification of the composite waveform is stated as: Step Pulse height=1, Step Pulse width=20 sec, beginning at 10 sec; Sine wave peak to peak amplitude=1, frequency =6 rad/s, Sine wave Pulse width=15 sec, beginning at 35sec; Sine wave peak to peak amplitude=1, frequency =30 rad/s, Sine wave Pulse width=10 sec, beginning at 60 sec.

It is eminent in the Figure- 9.4.1, that performance in terms of tracking and disturbance rejection (both external measurement disturbance and internal disturbance due to parametric uncertainty) of MAADC is superior to nonlinear IMC.

Case (ii): Setpoint change control $R=\begin{cases} 0.5 & 0\le t<30 \\ ramp & 30\le t<60 \\ 0.9 & t\ge 60 \end{cases}$ and an external process disturbance D=0.5 for $70\le t<75$ have been considered with parametric uncertainty (plant perturbation +50% in D_α and β and -50% in B and γ).

It has been shown in Figure- 9.4.2 that set-point change control has been achieved efficiently. Additionally, both external process disturbance rejection and internal disturbance (due to process-model mismatch) rejection have been taken care of. Overall performance of the proposed MAADC has evidently enhanced from the nonlinear IMC.

Case (iii): Set point as $R=\frac{2\pi}{15}\sin\left(\frac{\pi}{25}t\right)$ has been considered with an external process disturbance D=10 for $20\le t<25$ with no plant-model mismatch.

Performance of MAADC and nonlinear IMC for set-point tracking of a sinusoidal signal and external process disturbance rejection have been shown in Figure-9.4.3. It has been eminent that MAADC possesses superior disturbance rejection even in the presence of sinusoidal set-point.

Case (iv): Zero setpoint and measurement disturbance as $D_1=\begin{cases} 1 & 0\le t<3 \\ 1-\frac{t-3}{2} & 3\le t<7 \\ -1 & t\ge 7 \end{cases}$ were considered with parametric uncertainty (plant perturbation +50% in D_α and β and -50% in B and γ).

In Figure 9.4.4, a time varying disturbance has been rejected much faster by MAADC than by nonlinear IMC.

Case (v): Zero setpoint and process disturbance as $D=t;10<t<15$ were considered with parametric uncertainty (plant perturbation +50% in D_α and β and -50% in B and γ).

In Figure 9.4.5, external time varying process disturbance and internal disturbance as plant parametric uncertainty have been mitigated. It has been shown that performance of MAADC is advanced than nonlinear IMC.

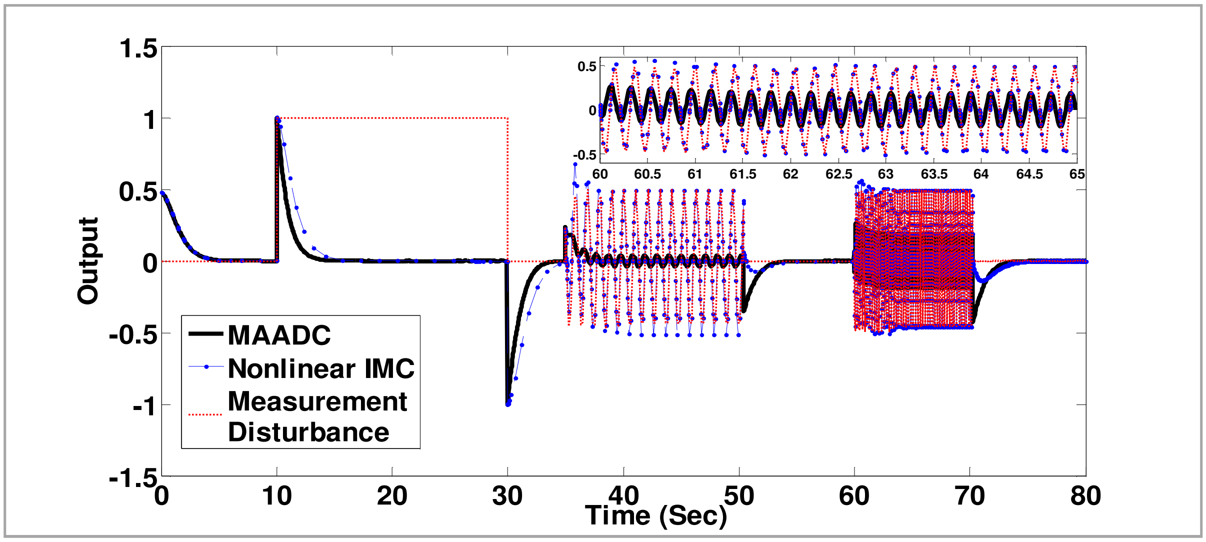


FIG.-9.4.1: OUTPUT RESPONSE FOR A ZERO SETPOINT, EXTERNAL MEASUREMENT DISTURBANCE AND INTERNAL DISTURBANCE CAUSED BY PARAMETRIC UNCERTAINTY

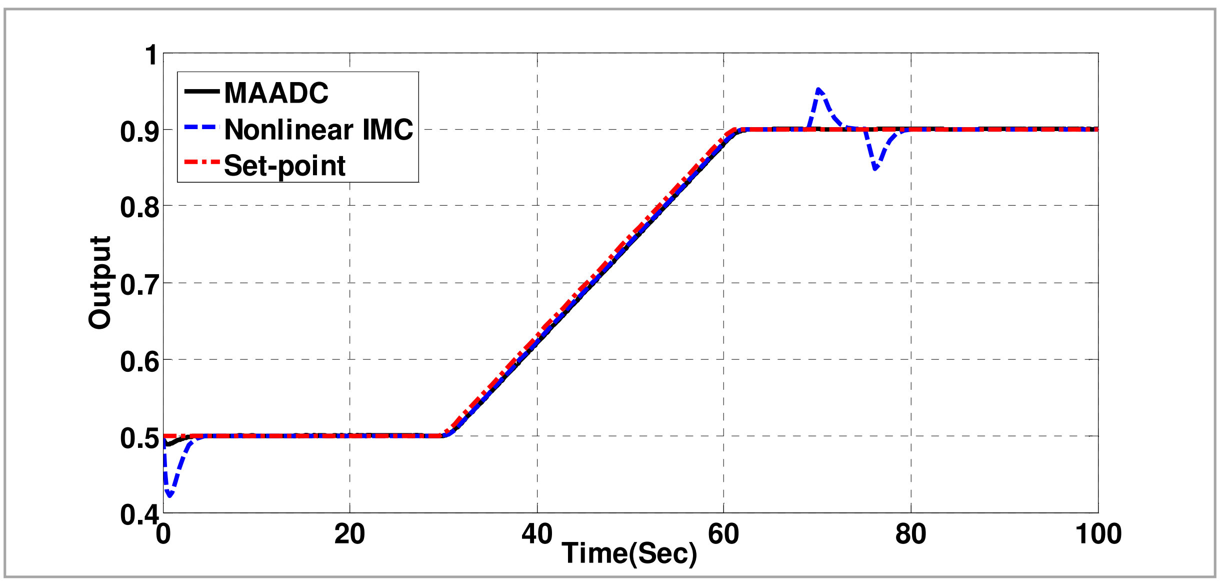
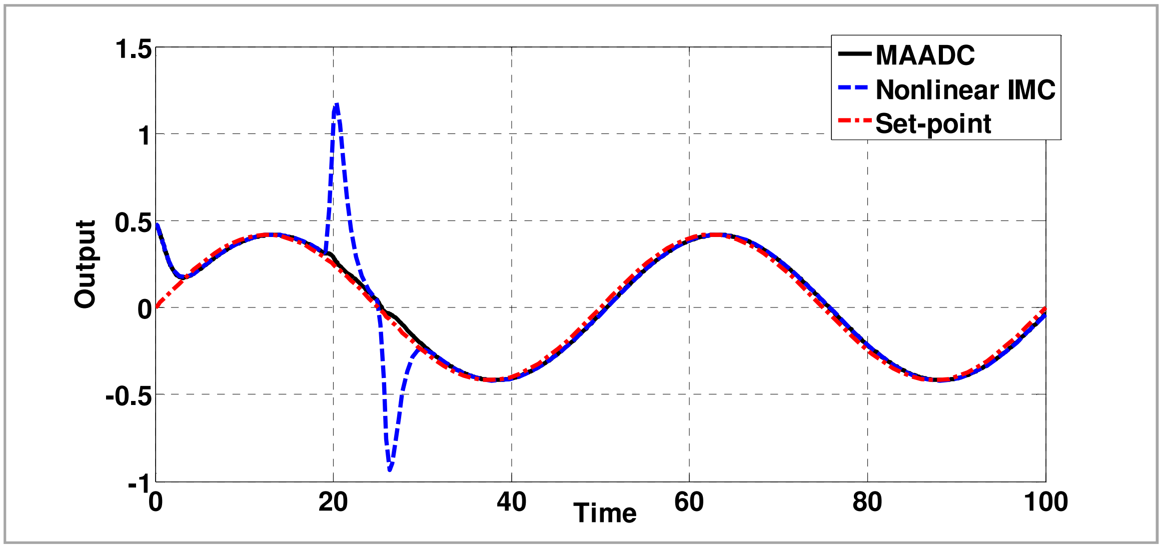
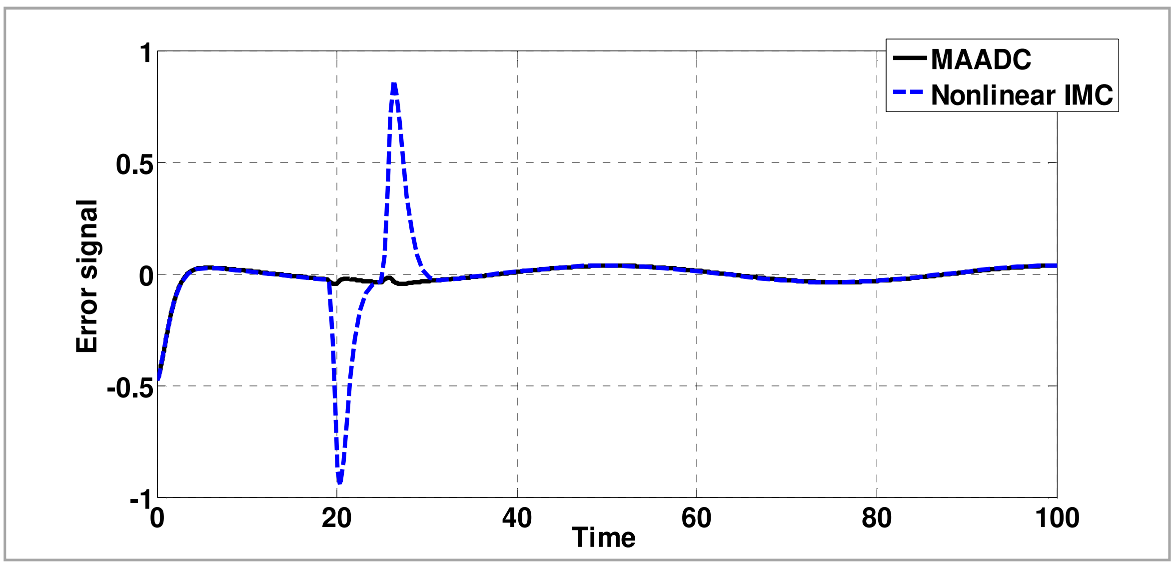


FIG.- 9.4.2: OUTPUT RESPONSE FOR A SETPOINT CHANGE CONTROL, A CONSTANT EXTERNAL PROCESS DISTURBANCE APPLIED FOR $70 \le t < 75$ *AND INTERNAL DISTURBANCE CAUSED BY PARAMETRIC UNCERTAINTY*



(A)



(B)

FIG.-9.4.3: FOR A SINUSOIDAL SETPOINT, A CONSTANT EXTERNAL PROCESS DISTURBANCE APPLIED FOR $20 \le t < 25$ ***(A) OUTPUT RESPONSE (B) ERROR SIGNAL***

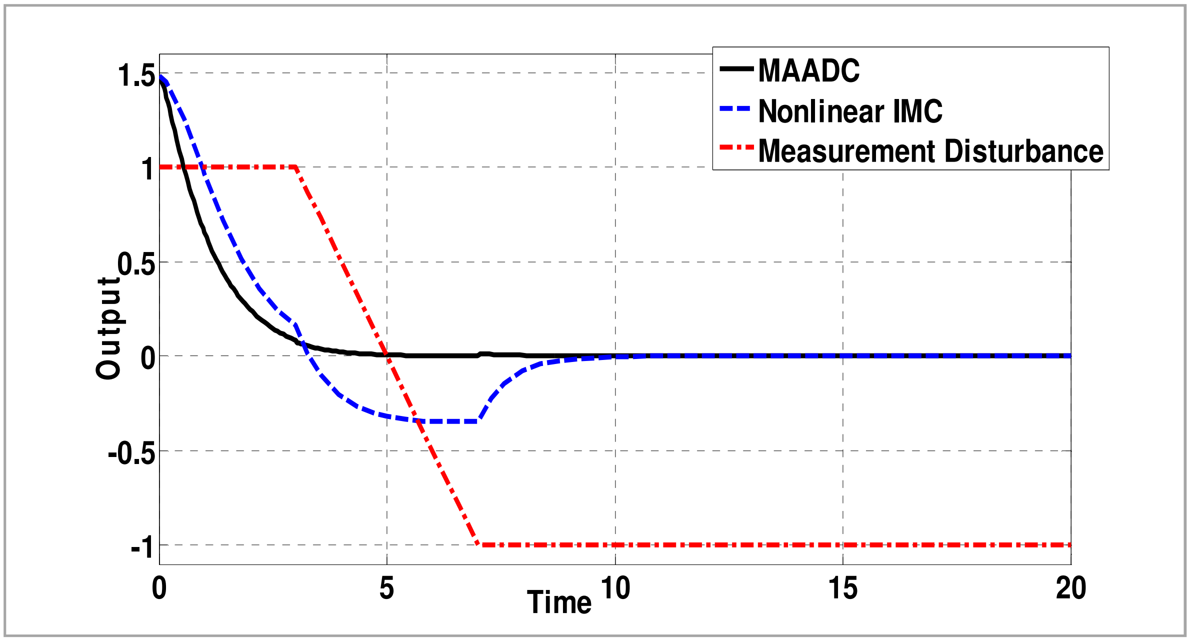


FIG.-9.4.4:OUTPUT RESPONSE FOR A ZERO SET-POINT, TIME VARYING MEASUREMENT DISTURBANCE AND PLANT PARAMETRIC UNCERTAINTY

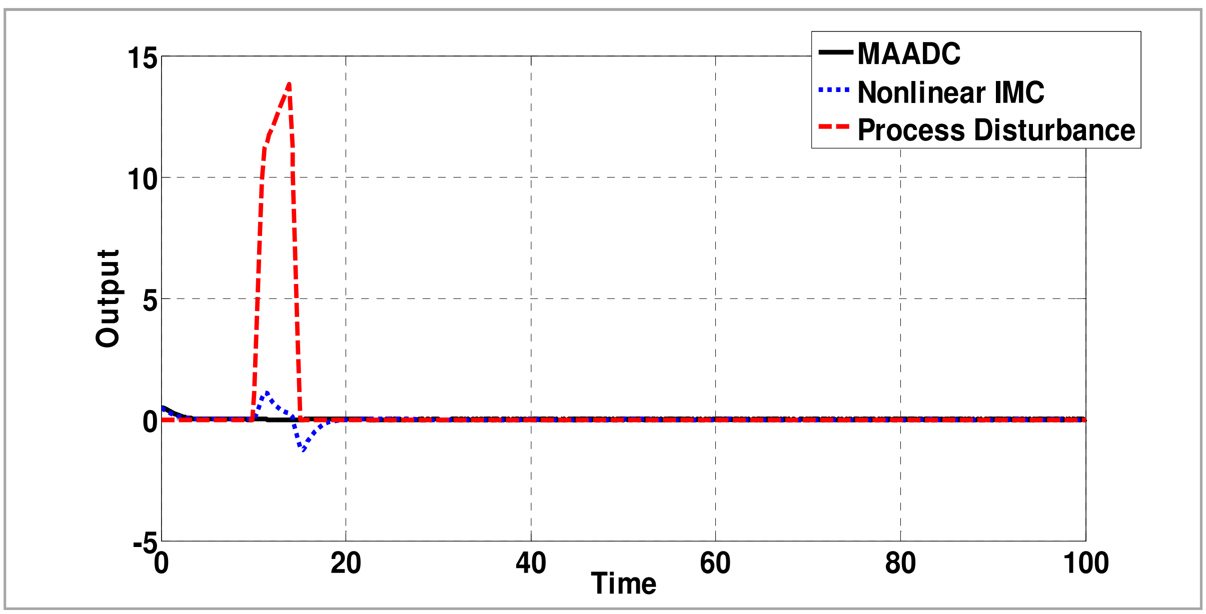


FIG.- 9.4.5: OUTPUT RESPONSE FOR A ZERO SET-POINT WITH TIME VARYING PROCESS DISTURBANCE AND PLANT PARAMETRIC UNCERTAINTY

Case (vi): Robustness Study

Set-point as $R=\begin{cases}0.3 & t=0\\ 0.5 & 0<t<50\\ 0.1 & 50\le t<100\\ 0.3 & t\ge 100\end{cases}$ and sinusoidal measurement disturbance as D_I=0.5*Sin(wt) have been considered with parametric uncertainty (plant perturbation +50% in D_α and β and -50% in B and γ).

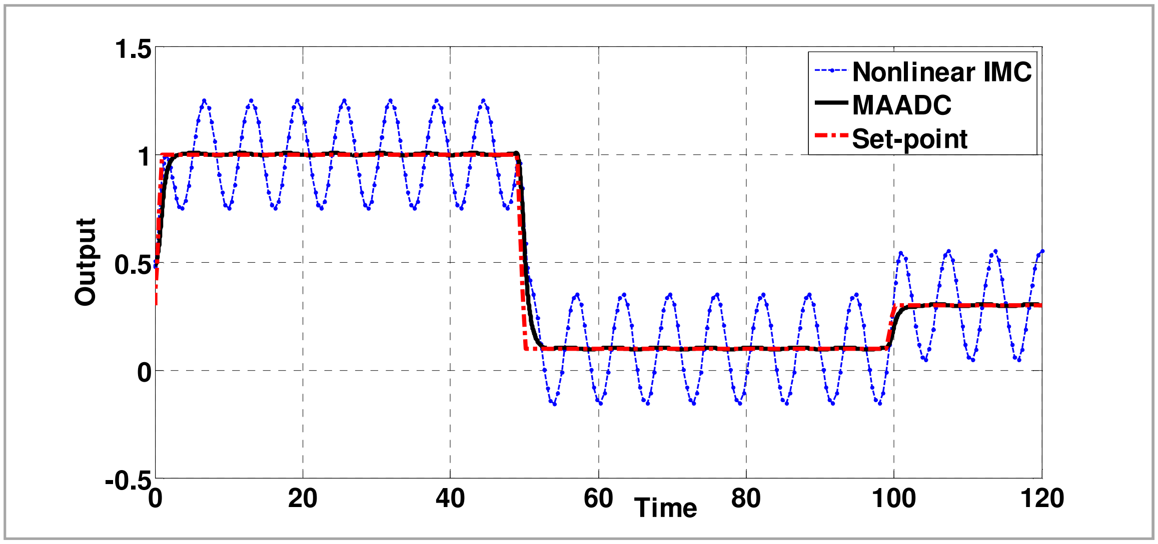
D_I= Sinusoidal signal of amplitude 0.5 has been considered and by varying the frequency, Root Mean Square Error (RMSE) of output has been plotted in frequency response.

RMSE $=\sqrt{\dfrac{\sum_{i=1}^{n}(Y_i-R_i)^2}{n}}$, where i is number of observed instant, Y_i is the output at i^{th} observed instant, R_i is the set-point at i^{th} observed instant and n is the number of observations. In this work, for different frequencies (w) of external sinusoidal disturbance signal, RMSEs have been calculated. RMSE of output has been shown by varying frequency of sinusoidal disturbance; the considered frequencies were w = 0.1, 0.3, 0.5, 0.7, 1, 3, 5, 10, 15 and 20 rad/sec.

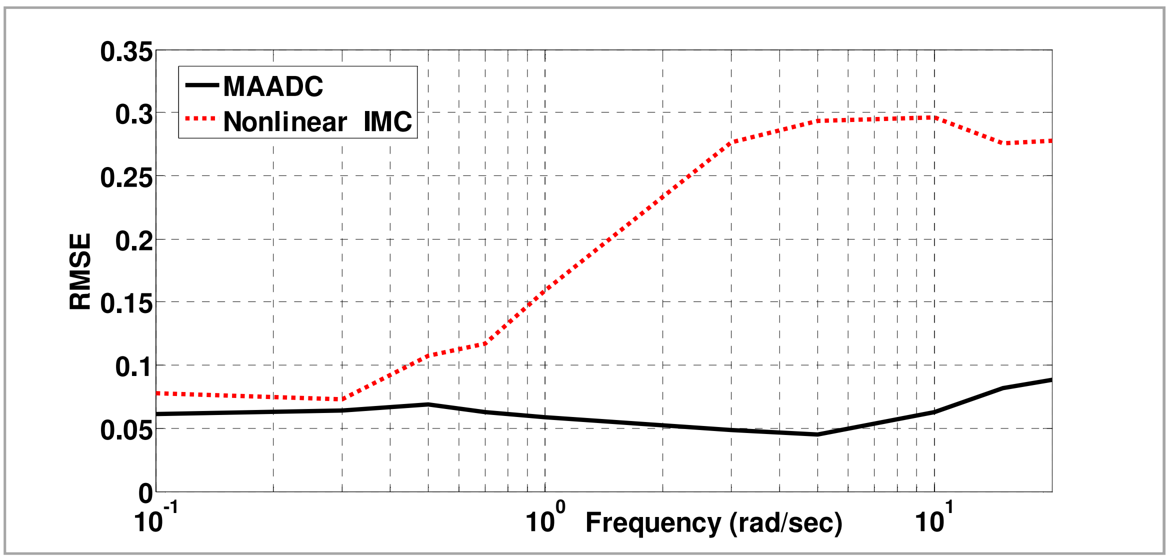
In Figure- 9.4.6, it has been shown that sinusoidal disturbance has been attenuated in a much better manner in case of nonlinear AADC than in nonlinear IMC. At w = 1 rad/sec, the response is shown in Figure- 9.4.6(A) and IAE value has been computed. In Figure- 9.4.6(B), it has been shown that for the above time varying set-point, sinusoidal external disturbance and internal disturbance due to plant-model mismatch, RMSE of output (using frequency response) for MAADC is much less than nonlinear IMC. So, it can be concluded that superior robustness has been achieved for MAADC.

Additionally, plant parametric uncertainty has been considered for most cases; set-point tracking and disturbance rejection have been obtained successfully, which are shown in their corresponding figures. These also testify robustness of the proposed MAADC strategy.

In Table-9.4.1, IAE values have been compared between MAADC and Nonlinear IMC for all the cases considered. It has been observed in Table-9.4.1 that performance of MAADC is superior than nonlinear IMC for all the cases.



(A)



(B)

FIG.-9.4.6:FOR A TIME VARYING SETPOINT, SINUSOIDAL EXTERNAL MEASUREMENT DISTURBANCE AND INTERNAL DISTURBANCE CAUSED BY PARAMETRIC UNCERTAINTY
(A) OUTPUT RESPONSE (B) ROOT MEAN SQUARE ERROR (RMSE) USING FREQUENCY RESPONSE

Table-9.4.1 IAE Values

IAE	Case(i)	Case(ii)	Case(iii)	Case(iv)	Case(v)	Case(vi)
MAADC	7.028	0.3028	2.837	1.7	0.8878	1.332
Nonlinear IMC	17.6	0.5694	6.124	3.022	5.291	19.47

9.5 Chapter Conclusion

A novel method for designing Modified Active Anti-Disturbance Control using the Internal Model Controller and Disturbance Observer compositely has been proposed for nonlinear systems and its application illustrated. The proposed control law provides the designer the freedom to choose two tuning parameters, one for the Internal Model Controller and the other for the Disturbance Observer. A comparison in the performances of the proposed MAADC controller and the existing nonlinear IMC controller, when applied to the nonlinear systems, shows that the proposed MAADC controller exhibits noticeably better tracking and regulatory performance even in the presence of externally injected disturbances and plant parameter perturbations. Considering the improved set-point tracking performance, disturbance rejection and demonstrable robustness, application of the proposed method, (though marginally more computationally intensive in digital implementation), to other real life problems is advocated.

Chapter 10: Disturbance Observer for Nonlinear MIMO Systems

10.1 Chapter Introduction and previous work

For many process plants, the feedback control has to be augmented with feed-forward schemes to take care of loads and disturbances. Whereas it is fairly easy to measure loads, special arrangements like Disturbance Observers (DOB) [Chen2016] have to be employed to estimate the disturbance. Disturbance Observer Based Control (DOBC) where Disturbance Observers (DOB) are specifically used as feed-forward compensation is of current interest [Chen2016, Yang2017]. There are several advantages of DOBC because such feed-forward scheme can improve set point tracking accuracy without sacrificing stability margins, speed of response and other nominal control performance [Back2008]. A recent review [Ali2015] shows a growing interest in Disturbance Observers for chemical processes. The present paper proposes a novel approach for designing DOB's for MIMO nonlinear process plants and exemplifies the proposed approach with an example for the benchmark Quadruple Tank level control process which has two inputs and two outputs.

Frequency domain design strategy for DOB where the process plant is linear is well documented in [Chen2009, Li2014]. Robustness and performance constraints of such (linear) DOBC have been dealt in [Sariyildiz2014]. A predictive DOB based filtered PI control has been applied to FOPDT plants in [Huba2013]; Fractional order DOB with Bode Ideal Cut-Off (BICO) filter has been documented in [Olivier2012]. Comparatively, the literature about design methods for DOB's and DOBC's for nonlinear processes is rather not so well populated. Most of the contribution on disturbance estimation of nonlinear plants are essentially in time domain [Li2014] and employ the so-named gain based nonlinear observer approach [Chen2000, Chen2003, Chen2004, Mohammadi2013, Yang2011, Chen2004a, Yang2012, Guo2005, Liu2012, Wang2016]. In contrast to the gain based DOB design approach employed in the literature mentioned above, a Hirschorn inverse based approach for designing DOB's for nonlinear SISO process plants has been reported in [Dasgupta2017]. DOB's for nonlinear systems reported in literature had been demonstrated to estimate constant [Chen2000a], harmonic [Chen2003], and general time varying [Chen2004, Kim2010, Dasgupta2017] disturbances. Such nonlinear DOB design approaches have been exemplified for applications such as robotic manipulator [Chen2000, Chen2004, Mohammadi2013], fermentation process [Dasgupta2017], missile systems [Yang2011a], magnetic bearing system [Chen2004a], permanent magnet synchronous motor [Yang2012], flight control systems [Guo2005], small scale helicopters [Liu2012], Reusable Launch Vehicle (RLV) [Wang2016], etc.

Among the references cited above, only a limited number of references discuss design of DOB's for nonlinear MIMO systems.

In [Guo2005], the DOBC approaches for a class of multiple-input-multiple-output (MIMO) nonlinear systems have been presented, where design schemes for full order and reduced order DOB's have been presented using Linear Matrix Inequality (LMI) approach. Motivated by Variable Structure System (VSS) method and adaptive algorithms, [Chen2004a] proposed a new nonlinear DOB for multivariable minimum-phase systems with arbitrary relative degrees, where the model uncertainties and the system nonlinearities were treated as disturbances. In [Yang2012], a DOB has been designed for MIMO nonlinear system with arbitrary disturbance relative degree, where the Lie derivative concept has been used in calculating observer gain. In [Liu2012], MIMO nonlinear DOB design method proposed by [Chen2004] has been used. An active disturbance rejection control scheme involving a DOB and sliding mode controller for MIMO nonlinear systems has been described in [Wei2009a]. However, it restricts the disturbance types to be norm bounded and having harmonic components which is essentially an improvement and extension to [Chen2004].

This current approach in this Chapter is structurally different from conventional (time-domain based) nonlinear DOB approach as explained later. Unlike other existing nonlinear MIMO DOB approaches, the current work innovatively employs Hirschorn nonlinear inversion [Hirschorn1979, Daoutidis1991, Boutat2015], for designing DOB's for nonlinear MIMO systems. Though Hirschorn nonlinear inversion has been used in [Dasgupta2017], the present Chapter utilizes the more straight forward state variable driven approach and is comparatively more suited for MIMO processes. The present work avoids the use of auxiliary variables and associated additional dynamics in the DOB as is required for the scheme in [Dasgupta2017]. Further, the DOB formulation section would provide additional consideration necessary to extend a SISO DOB using Hirschorn inverse to the case of a MIMO DOB. It may be noted that application of Hirschorn inverse for DOB of MIMO nonlinear processes has not appeared in previous work.

For proper implementation of the proposed DOB, arrays of low pass filters are required. These filters may be also tuned for attenuating high frequency noise from sensors and other exogenous sources.

10.2 Proposed Nonlinear MIMO DOB using Hirschorn Inverse and state variables

This DOB architecture deals with disturbance (which satisfies the matching condition) estimation problem for a general form of affine MIMO nonlinear square system. Matching condition means that the disturbances appear in the same channels as the control inputs.

A general form of affine MIMO nonlinear square systems have been considered as

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}) + \sum_{j=1}^{m} \mathbf{g}_j(\mathbf{x})\mathbf{v}_j \\ y_i &= h_i(x),\ i = 1,2,\cdots,m \end{aligned} \qquad (10.2.1),$$

where $\mathbf{f}$ and $\mathbf{g}_j$ are smooth vector fields on $\Re^{\mathbf{n}}$; h_i are smooth scalar field on $\Re^{\mathbf{m}}$.

$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \in \Re^{\mathbf{n}}$, $\mathbf{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_m \end{bmatrix} \in \Re^{\mathbf{m}}$, $\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} \in \Re^{\mathbf{m}}$ are vectors of states, manipulated inputs and outputs respectively.

It has been assumed that the plant is square and globally asymptotic stable i.e. $i = j = 1,2,\cdots,m$.

It has also been assumed that system is with finite relative orders $r_1, r_2, \cdots, r_m$ and non-singular characteristic matrix $\mathbf{C}(\mathbf{x})$.

r_i = relative order of output y_i, with respect to manipulated input vector $\mathbf{v}_i$, $i = 1,\cdots,m$.

Here, $\mathbf{C}(\mathbf{x}) = \begin{bmatrix} L_{\mathbf{g}_1} L_{\mathbf{f}}^{r_1-1} h_1(\mathbf{x}) & \cdots & L_{\mathbf{g}_m} L_{\mathbf{f}}^{r_1-1} h_1(\mathbf{x}) \\ \vdots & & \vdots \\ L_{\mathbf{g}_1} L_{\mathbf{f}}^{r_m-1} h_m(\mathbf{x}) & \cdots & L_{\mathbf{g}_m} L_{\mathbf{f}}^{r_m-1} h_m(\mathbf{x}) \end{bmatrix}$

The equivalent disturbance at the input of the plant is denoted by $\mathbf{D}$, where $\mathbf{D} = [D_1 \quad D_2 \quad \cdots \quad D_m]^T$. It is assumed that $\mathbf{D}$ also contains effects of in-plant disturbance as well as output disturbance. The plant is excited by not only the nominal input *u*, but also the disturbance $\mathbf{D}$. The duty of the disturbance observer is to estimate $\hat{\mathbf{D}} = \begin{bmatrix}\hat{D}_1 & \hat{D}_2 & \cdots & \hat{D}_m\end{bmatrix}^T$, of the disturbance as faithfully as possible. Both time-domain and frequency domain characters of $\mathbf{\Xi} = \hat{\mathbf{D}} - \mathbf{D}$ are of interest.

It may be noted that application of the proposed method assumes finite relative orders and non-singular characteristic matrix.

The structure of the conventional linear DOB was described in [Chen2009]. The similarity of the proposed structure with that described in [Chen2009] may be noted. However, the referred earlier work describes a frequency domain approach to construct the DOB for linear SISO systems whereas the proposed method is defined in the time domain with a state variable representation of the nonlinear MIMO plant model. The proposed structure is hybrid i.e., because it also embodies frequency domain filter. This unconventional approach has been taken to retain the simplicity and also to contrast the proposed DOB structure with that of other time-domain DOB structures [Li2014]. In our proposed structure, G_p symbolically represents the nonlinear MIMO plant. G_m^{-1} represents its Hirschorn inverse of the nonlinear MIMO model, which is followed by low-pass filter transfer function matrix symbolized by $\mathbf{K}(s)$ of appropriate degree in their diagonal elements,

where $\mathbf{K}(s) = \begin{bmatrix} K_1 & \cdots & \cdots & \cdots & 0 \\ \vdots & \ddots & & & \vdots \\ \vdots & & K_i & & \vdots \\ \vdots & & & \ddots & \vdots \\ 0 & \cdots & \cdots & \cdots & K_m \end{bmatrix}$; $\mathrm{K}_i = \left[\dfrac{1}{1+s\tau_i}\right]^{r_i}, i = 1,2,\cdots,m$.

The proposed DOB for nonlinear MIMO system requires the concept of relative degree [Li2014] (also known as relative order), which is somewhat analogous to a similar concept in linear systems and is required to implement a low-pass filter for realizability of the inverse. Relative degree for a nonlinear system is derived as follows (from (10.2.1)).

It is to be noted that square system has been assumed and so $i = j = 1,2,\cdots,m$.

At i th input (or output) from (10.2.1),

$$\dot{y}_i = \frac{\partial h_i}{\partial \mathbf{x}}[\mathbf{f}(\mathbf{x}) + \mathbf{g}_i(\mathbf{x})v_i] = L_{\mathbf{f}} h_i(\mathbf{x}) + L_{\mathbf{g}_i} h_i(\mathbf{x})v_i \tag{10.2.2),}$$

where, $L_{\mathbf{f}} h_i(\mathbf{x}) = \frac{\partial h_i}{\partial \mathbf{x}}\mathbf{f}(\mathbf{x})$, $L_{\mathbf{g}} h_i(x) = \frac{\partial h_i}{\partial \mathbf{x}}\mathbf{g}_i(\mathbf{x})$.

Here, $L_{\mathbf{f}} h_i(\mathbf{x})$ is called the Lie Derivative [Slotine1991] or Directional Derivative of h_i with respect to $\mathbf{f}$ or along $\mathbf{f}$.

If the right hand side of equation (10.2.2) contains a term involving the manipulated input v_i, by definition, the relative degree is 1. In case the right hand side does not contain any term involving the manipulated input v_i, i.e., $\dot{y}_i = L_{\mathbf{f}} h_i(\mathbf{x})$, successive differentiation is to be carried out till the term $L_{\mathbf{g}} L_{\mathbf{f}}^{r-1} h_i(\mathbf{x})$ becomes non-zero. When this is obtained, by definition, the relative degree is *r*.

After proceeding in this way, equation of $y_i^{(r)}$ with non zero coefficient of v_i becomes

$$y_i^{(r)} = L_{\mathbf{f}}^r h_i(\mathbf{x}) + L_{\mathbf{g}_i} L_{\mathbf{f}}^{r-1} h(\mathbf{x}) v_i \tag{10.2.3),}$$

where, *r* is relative degree (or relative order).

From (10.2.3),

$$v_i = \frac{1}{L_{\mathbf{g}_i} L_{\mathbf{f}}^{r-1} h_i(\mathbf{x})}[-L_{\mathbf{f}}^r h_i(\mathbf{x}) + y_i^{(r)}] \tag{10.2.4}$$

The above is an expression for left Hirschorn inverse, which reconstructs the input from the plant output and its derivatives. (An alternative explanation of Hirschorn inverse may be obtained from [Slotine1991].) However, to obtain the true Hirschorn inverse, the above expression requires state variable $\mathbf{x}$. It is to be noted that denominator of (10.2.4) is scalar for *i* th input (or output).

The observed composite input $(\hat{v}_i)$ is to be used because the actual input (v_i) is not available due to the unknown disturbance component.

The Hirschorn inverse realization [Daoutidis1991] for MIMO nonlinear system of the form of (10.2.1) with finite relative orders r_i, where $i=1,\cdots,m$ and non-singular characteristic matrix has been appreciated in this work.

The observed composite input $(\hat{v}_i)$ may, however, be computed using (10.2.4) and the fact that $v_i = u_i + D_i$. The observed value of the disturbance signal is $\hat{D}_i$.

For the proposed methodology applicable for nonlinear MIMO square system, the plant is excited by not only the nominal input u_i but also the disturbance D_i. As $i=1,\cdots,m$, thus, observed value of disturbance signal $\hat{D}$ is represented as (from (10.2.4))

$$\hat{\mathbf{D}} = [\det[\mathbf{C}(\mathbf{x})]]^{-1}\left(\begin{bmatrix} \dfrac{d^{r_1} y_1}{dt^{r_1}} \\ \vdots \\ \dfrac{d^{r_m} y_m}{dt^{r_m}} \end{bmatrix} - \begin{bmatrix} L_{\mathbf{f}}^{r_1} h_1(\mathbf{x}) \\ \vdots \\ L_{\mathbf{f}}^{r_m} h_m(\mathbf{x}) \end{bmatrix}\right) - \mathbf{u} \tag{10.2.5}$$,

where $\mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{bmatrix}$; $\hat{\mathbf{D}} = \begin{bmatrix} \hat{D}_1 \\ \hat{D}_2 \\ \vdots \\ \hat{D}_m \end{bmatrix}$; $\mathbf{C}(\mathbf{x}) = \begin{bmatrix} L_{\mathbf{g}_1} L_{\mathbf{f}}^{r_1-1} h_1(\mathbf{x}) & \cdots & L_{\mathbf{g}_m} L_{\mathbf{f}}^{r_1-1} h_1(\mathbf{x}) \\ \vdots & & \vdots \\ L_{\mathbf{g}_1} L_{\mathbf{f}}^{r_m-1} h_m(\mathbf{x}) & \cdots & L_{\mathbf{g}_m} L_{\mathbf{f}}^{r_m-1} h_m(\mathbf{x}) \end{bmatrix}$. For simplicity, it is assumed that $\mathbf{u} = 0$.

It is to be noted that $[\det[\mathbf{C}(\mathbf{x})]]^{-1}$ is scalar . Here, the Hirschorn inverse reconstructs the inputs from the plant outputs, its derivatives and states of the process.

Then suitable low pass filter transfer function matrix $\mathbf{K}(s)$ has been designed. Depending on the relative orders of the MIMO nonlinear system, the relative degrees of the diagonal elements of $\mathbf{K}(s)$ have been chosen; $\mathrm{K}_i = \left[\dfrac{1}{1+s\tau_i}\right]^{r_i}, i=1,2,\cdots,m$ where relative order r_i (relative order of output y_i, with respect to manipulated input vector, $i=1,\cdots,m$). Here, τ_i is the filter time constant corresponding to i th input-output pair. Thus, realizability problem has been avoided while reconstructing the disturbance signal.

The implementation diagram has been shown in Figure-10.2.1.

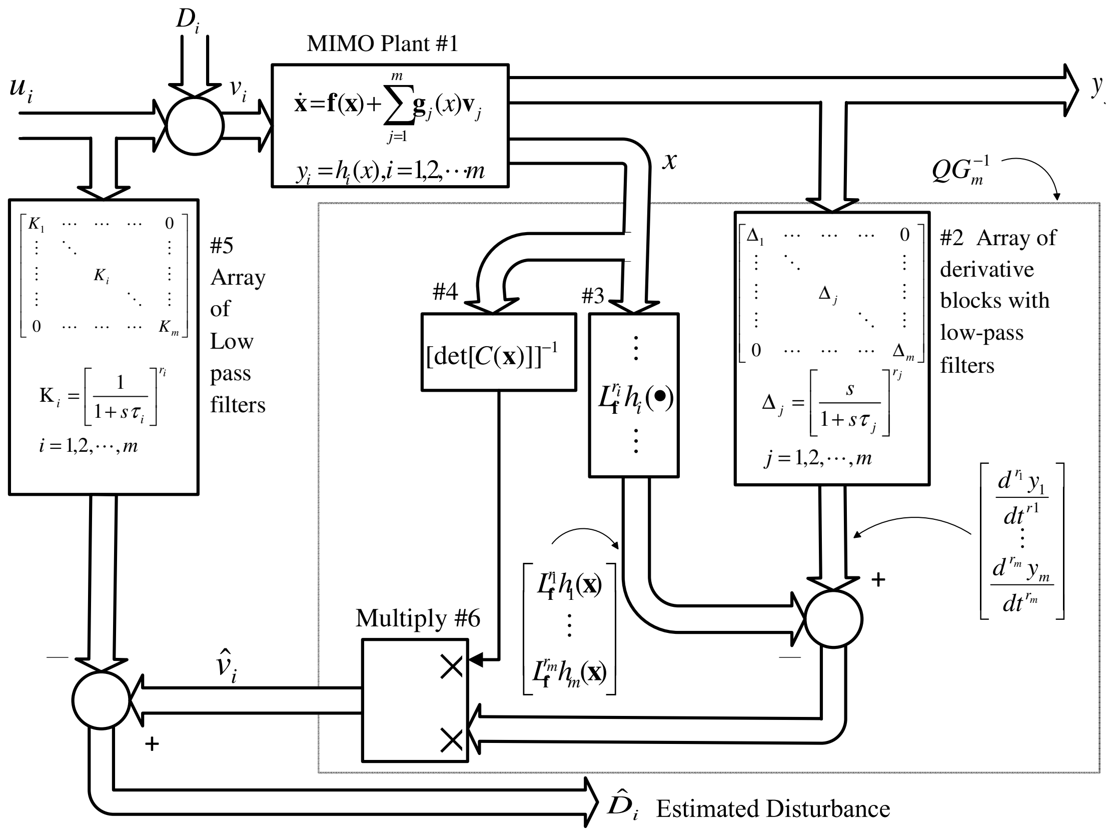


FIG.- 10.2.1*: *IMPLEMENTATION OF THE PROPOSED DOB

In Figure-10.2.1, plant has been denoted by block #1. Here, an array of approximate differentiators with low pass filter of r_j th degree which has been represented by a diagonal matrix whose diagonal elements are denoted by Δ_j (for a square system $i = j = 1,\cdots,m$), has been shown in block #2, where $\Delta_j = \left[\frac{s}{1+s\tau_j}\right]^{r_j}$ $j = 1,2,\cdots,m$. As, square systems has been considered, r_j is the relative degree between j th manipulated input and j th output. Noting that obtaining derivatives of signals worsens the signal to noise ratio, filters have been applied to the inverse model in Figure-10.2.1. Here, τ_j is the filter time constant corresponding to j th element of the diagonal block #2, which has to be chosen appropriately [Chen2009]. The corresponding array of low pass filter block for the control input u_i is shown in block #5. Here, a diagonal matrix with diagonal element K_i has been used where $i = 1,\cdots,m$. In (10.2.5), the numerator has two components of which the subtrahend is performed in block #3. The concerned multiplier is computed in block #4. Lastly, using the multiplier block #6, implementation of (10.2.5) has been completed. The rectangular portion (represented by a fade line) is denoting QG_m^{-1} which is homologous with the linear DOB structure in frequency domain [Chen2009, Li2014]. But, in our case G_m is nonlinear which is represented by state space model and G_m^{-1} is the Hirschorn Inverse of the nonlinear process model; Q is the low pass filter.

The proposed theory and the implementation are applicable for nonlinear Multiple Input Multiple Output (MIMO) systems. The plant has to be globally asymptotically stable. Also the required condition is that the system description is sufficiently smooth to permit computation of the corresponding Lie derivatives. Additionally, the plant model is to be observable. The above conditions are satisfactorily met for many process models.

10.3 Case Study -- Quadruple Tank System

10.3.1 Plant Model

In [Johansson2000], a multivariable laboratory process which consists of four interconnected water tanks has been described. The schematic diagram of the Quadruple Tank Process is shown in Figure- 10.3.1. Control objective of this process is to control the level of the two lower tanks by two pumps. The process inputs are u_1 and u_2, which are input voltages to the pumps. Outputs are y_1 and y_2, which are voltages from level measurement devices.

A mathematical model of quadruple tank process [Johansson2000] is:

$$\begin{aligned}
\frac{dx_1}{dt} &= -\frac{a_1}{A_1}\sqrt{2gx_1} + \frac{a_3}{A_1}\sqrt{2gx_3} + \frac{\gamma_1 k_1}{A_1}u_1 \\
\frac{dx_2}{dt} &= -\frac{a_2}{A_2}\sqrt{2gx_2} + \frac{a_4}{A_2}\sqrt{2gx_4} + \frac{\gamma_2 k_2}{A_2}u_2 \\
\frac{dx_3}{dt} &= -\frac{a_3}{A_3}\sqrt{2gx_3} + \frac{(1-\gamma_2)k_2}{A_3}u_2 \\
\frac{dx_4}{dt} &= -\frac{a_4}{A_4}\sqrt{2gx_4} + \frac{(1-\gamma_1)k_1}{A_4}u_1
\end{aligned} \qquad (10.3.1)$$

Output equations are the measured level signals:

$$y_1 = k_c x_1 \tag{10.3.2}$$

$$y_2 = k_c x_2$$

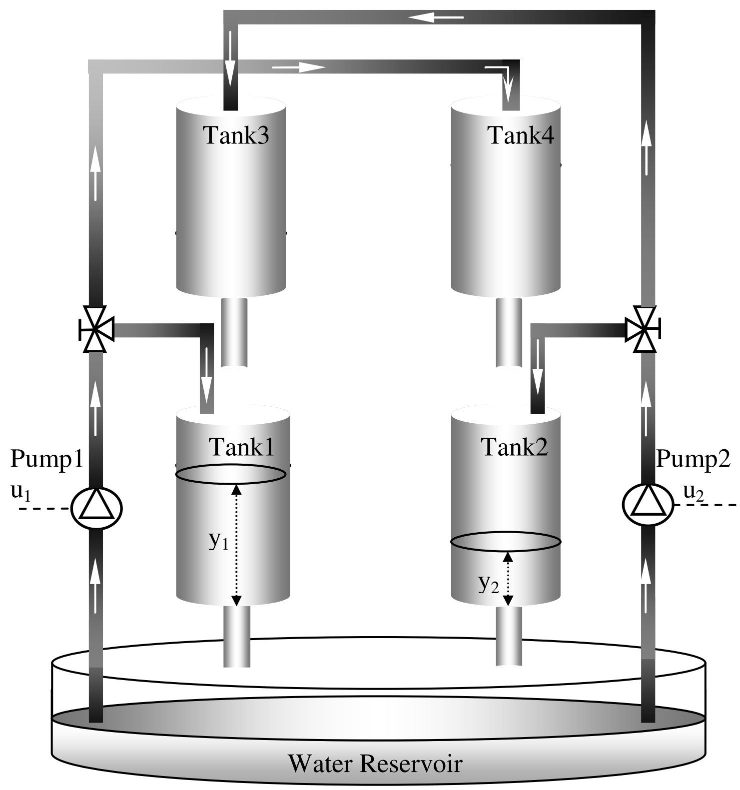


FIG.-10.3.1: SCHEMATIC DIAGRAM OF THE QUADRUPLE-TANK PROCESS

The description of the parameters are listed in Table-10.3.1. The parameter values of the Quadruple tank process as used in [Johansson2000], are shown in Table-10.3.2. Here, Quadruple tank process with minimum phase characteristics has been chosen as in [Johansson2000], with their operating points correspond to the parameter values. The operating points corresponding to the following parameter values are denoted by ($x_1^0, x_2^0, x_3^0, x_4^0$).

Table-10.3.1 The parameters of Quadruple tank process

Parameter	
A_i	Cross-section of Tank i, where $i = 1,\cdots,4$
a_i	Cross-section of the outlet hole of Tank i
h_i	Water level of Tank i
u_i	Voltage applied to Pump i
$k_i u_i$	Flow in Pump i
γ_1, γ_2	These parameters are determined from how the valves are set prior to experiment.
g	Acceleration of gravity

Table-10.3.2 The parameter values of Quadruple tank process

Parameter	Unit	Value
A_1, A_3	cm^2	28
A_2, A_4	cm^2	32
a_1, a_3	cm^2	0.071
a_2, a_4	cm^2	0.057
k_c	V/cm	0.50
g	cm/s^2	981
(x_1^0, x_2^0)	cm	(12.4,12.7)
(x_3^0, x_4^0)	cm	(1.8,1.4)
k_1, k_2	Cm^3/Vs	(3.33,3.35)
γ_1, γ_2		(0.70,0.60)

10.3.2 DOB Design

By comparing (10.2.1) with (10.3.1-10.3.2) and considering the parameter values in Table 10.3.2:

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} -0.1123\sqrt{x_1} + 0.1123\sqrt{x_3} \\ -0.07889\sqrt{x_2} + 0.07889\sqrt{x_4} \\ -0.1123\sqrt{x_3} \\ -0.07889\sqrt{x_4} \end{bmatrix};\ \mathbf{g}_1(\mathbf{x}) = \begin{bmatrix} 0.08325 \\ 0 \\ 0 \\ 0.03122 \end{bmatrix};\ \mathbf{g}_2(\mathbf{x}) = \begin{bmatrix} 0 \\ 0.0628 \\ 0.0478 \\ 0 \end{bmatrix}$$

$h_1(x) = 0.5x_1, h_2(x) = 0.5x_2$

Relative orders are $r_1 = 1, r_2 = 1$.

Characteristic matrix $\mathbf{C}(\mathbf{x})$,

$$\mathbf{C}(\mathbf{x}) = \begin{bmatrix} L_{\mathbf{g}_1} L_{\mathbf{f}}^{r_1 - 1} h_1(\mathbf{x}) & \cdots & L_{\mathbf{g}_m} L_{\mathbf{f}}^{r_1 - 1} h_1(\mathbf{x}) \\ \vdots & & \vdots \\ L_{\mathbf{g}_1} L_{\mathbf{f}}^{r_m - 1} h_m(\mathbf{x}) & \cdots & L_{\mathbf{g}_m} L_{\mathbf{f}}^{r_m - 1} h_m(\mathbf{x}) \end{bmatrix} = \begin{bmatrix} L_{\mathbf{g}1} h_1(\mathbf{x}) & L_{\mathbf{g}2} h_1(\mathbf{x}) \\ L_{\mathbf{g}1} h_2(\mathbf{x}) & L_{\mathbf{g}2} h_2(\mathbf{x}) \end{bmatrix} = \begin{bmatrix} 0.0416 & 0 \\ 0 & 0.0314 \end{bmatrix}$$

In this case, obtained characteristic matrix (since, $\det[\mathbf{C}(\mathbf{x})] = 0.0013$) is non-singular.

So, from (10.2.5),

$$\hat{\mathbf{D}} = [\det[\mathbf{C}(\mathbf{x})]]^{-1} \left(\begin{bmatrix} \dfrac{d^{r_1} y_1}{dt^{r_1}} \\ \vdots \\ \dfrac{d^{r_m} y_m}{dt^{r_m}} \end{bmatrix} - \begin{bmatrix} L_{\mathbf{f}}^{r_1} h_1(\mathbf{x}) \\ \vdots \\ L_{\mathbf{f}}^{r_m} h_m(\mathbf{x}) \end{bmatrix} \right) - \mathbf{u}$$

$$= \frac{1}{0.0013} \begin{bmatrix} \dfrac{dy_1}{dt} + 0.05615\sqrt{x_1} - 0.05615\sqrt{x_3} \\ \dfrac{dy_2}{dt} + 0.0394\sqrt{x_2} - 0.0394\sqrt{x_4} \end{bmatrix} - \mathbf{u}$$

Nonlinear MIMO DOB has been designed, where low pass filter transfer function matrix has been taken as $\mathbf{K}(s) = \begin{bmatrix} \dfrac{1}{(0.2s+1)} & 0 \\ 0 & \dfrac{1}{(0.2s+1)} \end{bmatrix}$.

The plant model has been initialized at its equilibrium point.

10.3.3 Simulation Results

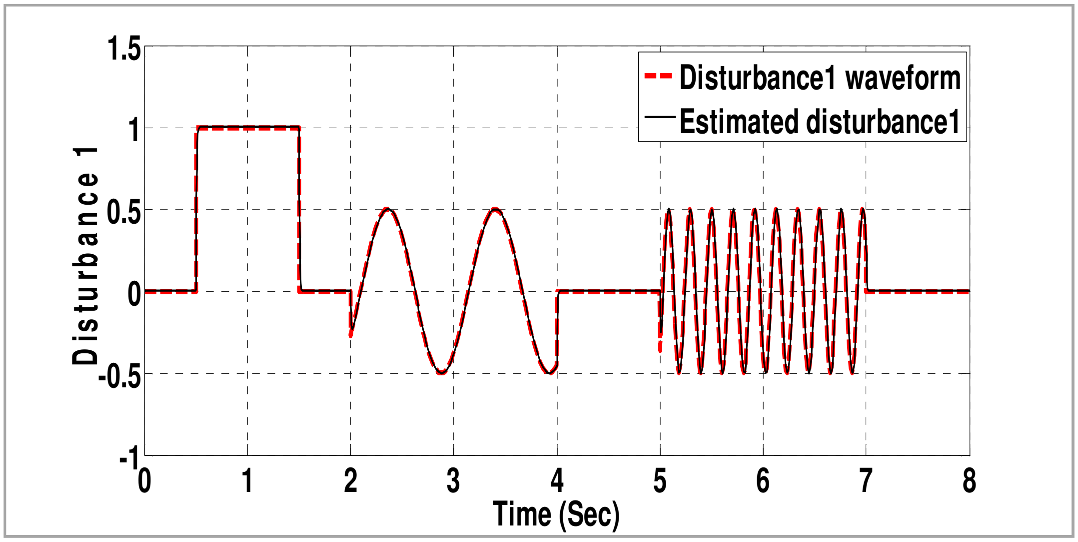
In this case study, input disturbance $\mathbf{D}$ and observed disturbance $\hat{\mathbf{D}}$ both are two input functions, where $\mathbf{D} = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix}$ and $\hat{\mathbf{D}} = \begin{bmatrix} \hat{D}_1 \\ \hat{D}_2 \end{bmatrix}$ respectively. In this work, matched disturbances have been considered. Two disturbance inputs D_1 and D_2 have been considered as various disturbance waveforms and by using the proposed Disturbance Observer (DOB) methodology, those disturbances have been estimated.

Case (i): D_1 and D_2 have been considered as composite and zero signals respectively. The specification of the composite disturbance waveform is stated below:

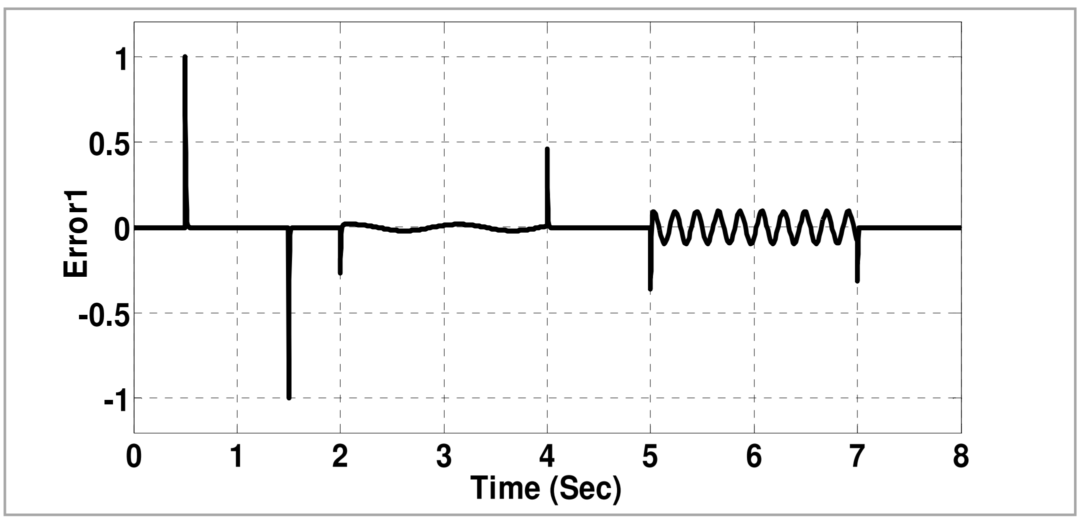
Step Pulse height=1, Step Pulse width=1 sec, beginning at 0.5 sec; Sine wave peak to peak amplitude=1, frequency =6 rad/s, Sine wave Pulse width=2 sec, beginning at 2sec; Sine wave peak to peak amplitude=1, frequency =30 rad/s, Sine wave Pulse width=2 sec, beginning at 5 sec.

The original composite and zero signals are shown as D_1 and D_2 (shown in Figure-10.3.2(A) and Figure- 10.3.3(A) respectively); observed signals are also superimposed on the same figures. Observation errors are shown in Figure-10.3.2(B) and Figure-10.3.3(B) respectively. This can be inferred that the DOB tracks the disturbance quite acceptably except for the high frequency portion of the waveform as evident from Figure- 10.3.2(B). The error in the high frequency sine wave can be seen to be contributed mostly by the phase shift between the actual and the estimated disturbance. This phase shift is contributed primarily by the low pass filter which can be tuned to increase or decrease the bandwidth of the observer.

Now, zero disturbance signal and the above mentioned composite disturbance waveform have been injected to *D1* and *D2* respectively (shown in Figure-10.3.4(A)); estimated disturbances have been superimposed on the same figure. It has been shown in Figure-10.3.4(B) that estimation errors are sufficiently small for both of the disturbance inputs. In Figure-10.3.4(A), original and estimated zero disturbance D_1 has been shown in inset. In Figure-10.3.4(B), corresponding error1 for composite waveform disturbance D_1 has been shown in inset.

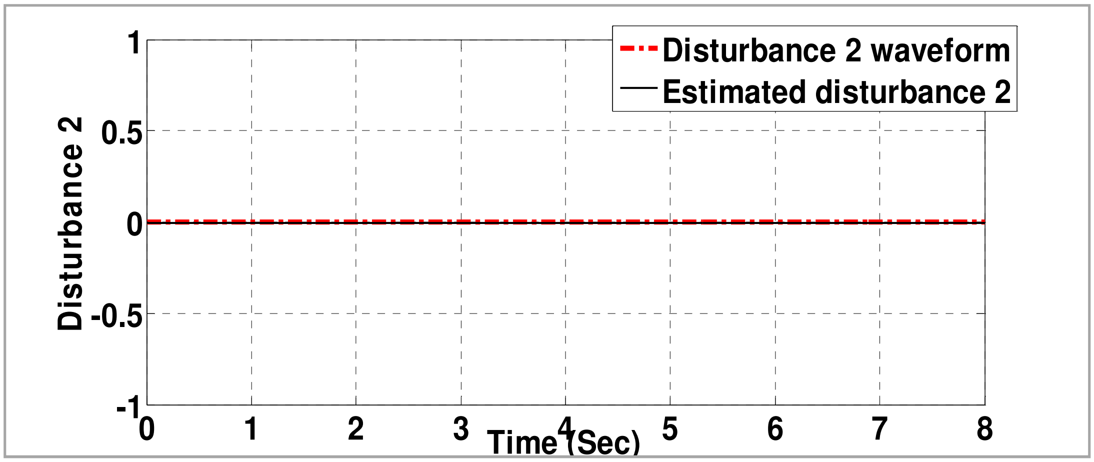


(A)

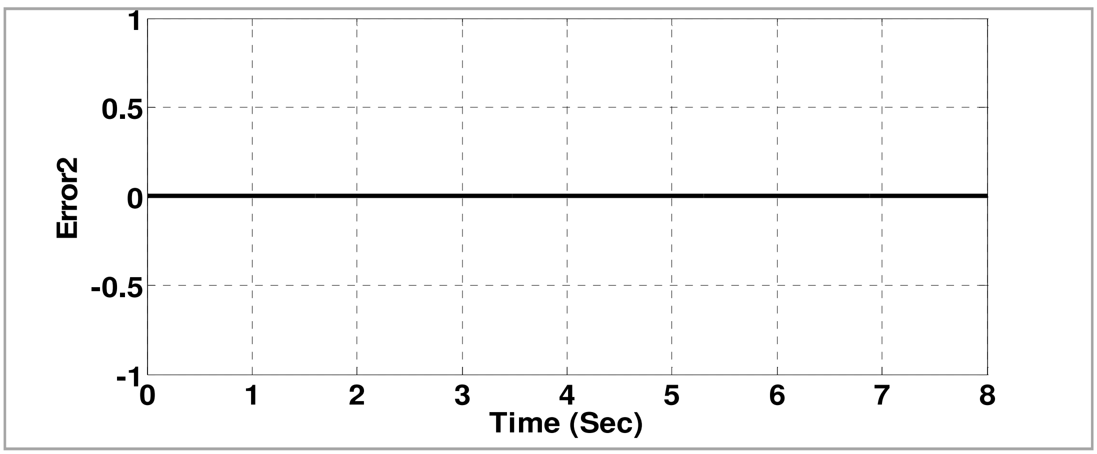


(B)

FIG.-10.3. 2: ***FOR COMPOSITE DISTURBANCE SIGNAL (A) INJECTED DISTURBANCE AND ESTIMATED DISTURBANCE (B) OBSERVATION ERROR OF THE PROPOSED DOB***



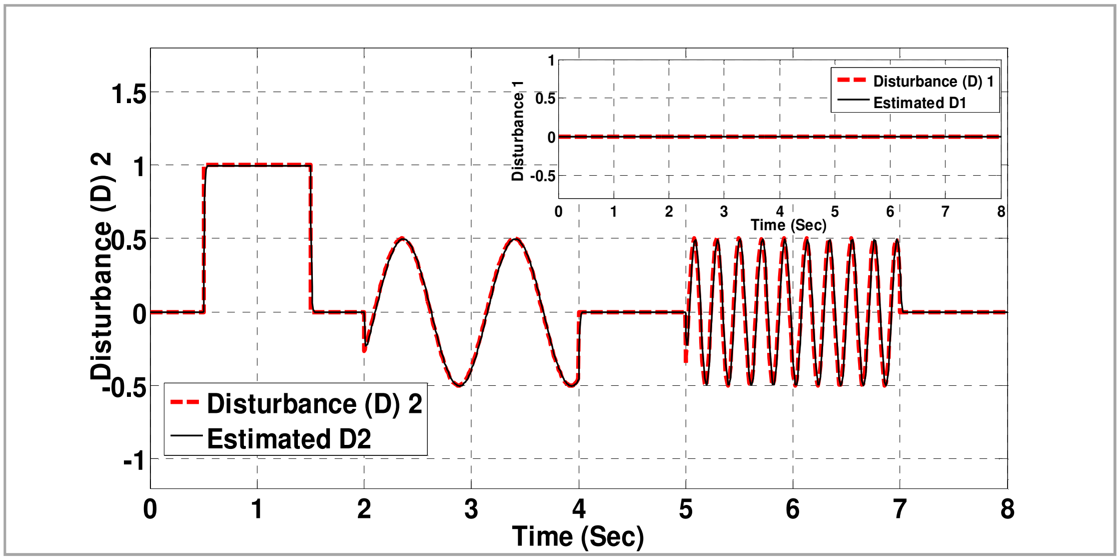
(A)



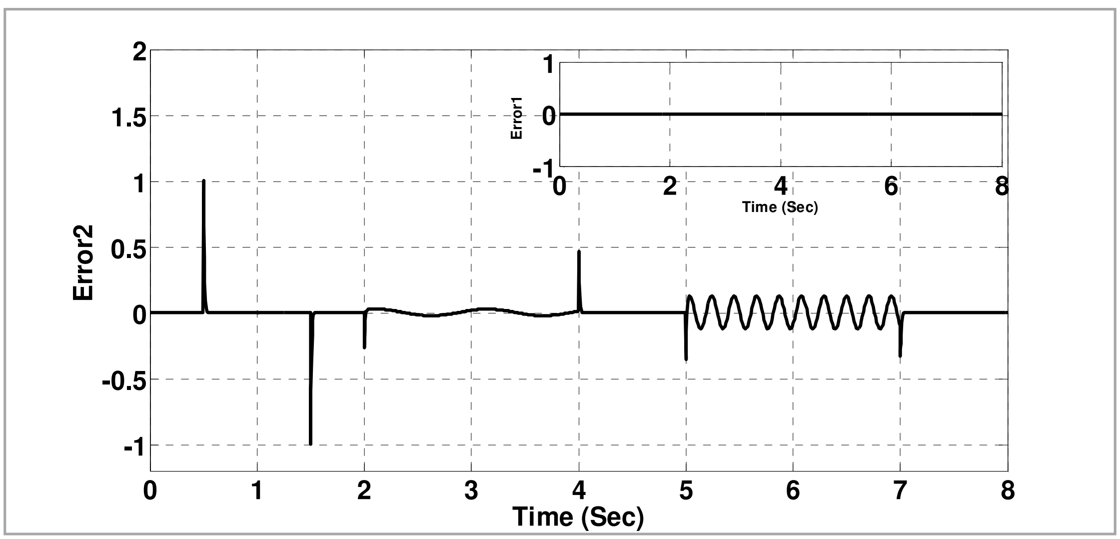
(B)

FIG.-10.3. 3: FOR ZERO DISTURBANCE SIGNAL (A) INJECTED DISTURBANCE AND ESTIMATED DISTURBANCE (B) OBSERVATION ERROR OF THE PROPOSED DOB

It has been evident in Figure-10.3.4, that lower frequency disturbances are observed efficiently but at higher frequency, there exist some non-trivial error. For sinusoidal disturbance, the error occurs mostly due to phase shift; the high frequency error introduces error spikes at the beginning and end of the pulses.



(A)



(B)

FIG.-10.3.4: FOR COMPOSITE DISTURBANCE SIGNAL AS D2 AND ZERO DISTURBANCE SIGNAL D1 IN INSET (A) INJECTED DISTURBANCE AND ESTIMATED DISTURBANCE (B) OBSERVATION ERROR OF THE PROPOSED DOB

Case (ii): D_1 and D_2 have been considered as another composite and zero signals respectively. The specification of the composite disturbance waveform is stated below:

Sine wave Pulse width=2 sec, peak to peak amplitude= 1, beginning at 0 sec, frequency=6.28 rad/sec; Truncated double ramp beginning at 3 sec, amplitude 1, duration 2 sec; Modulated sine wave pulse frequency =30 rad/s, beginning at 6 sec, duration 2 sec.

The original composite disturbance has been shown as D_1 in Figure-10.3.5. Observed signal is also superimposed on the same figure. Observation error Error1 for D_1 is shown in inset. This can be inferred that the DOB tracks the disturbance quite acceptably except for the high frequency portion of the waveform as evident from Figure-10.3.5. The error in the high frequency sine wave can be seen to be contributed mostly by the phase shift between the actual and the estimated disturbance. This phase shift is contributed primarily by the low pass filter which can be tuned to increase or decrease the bandwidth of the observer. The estimated disturbance D_2 has been found to be zero; corresponding error also remains zero. The disturbance D_2 has not been shown in the figure.

Now, D_1 and D_2 have been considered as zero and composite signals respectively.

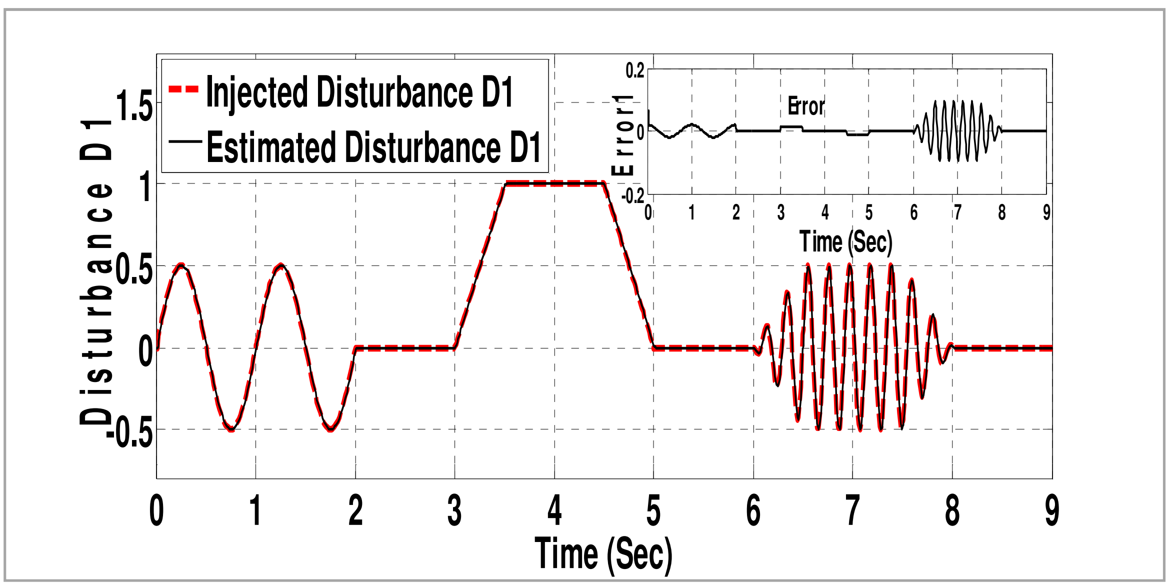


FIG.-10.3.5: INJECTED DISTURBANCE D1 AND ESTIMATED DISTURBANCE OF D1 (CORRESPONDING OBSERVATION ERROR1 AS INSET)

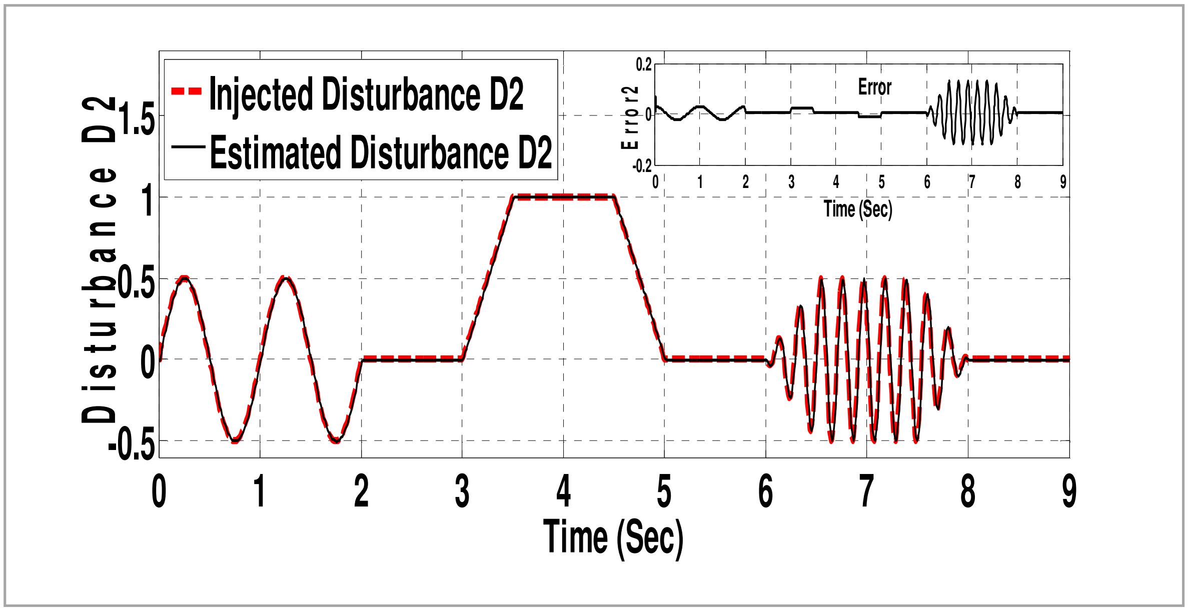


FIG.-10.3.6: INJECTED DISTURBANCE D2 AND ESTIMATED DISTURBANCE OF D2 (CORRESPONDING OBSERVATION ERROR2 AS INSET)

The disturbance D_2 has been taken as composite signal as described above. Injected disturbance D_2 along with estimated disturbance has been superimposed in Figure-10.3.6. Also corresponding error Error2 has been shown in inset. In this case, estimated D_1 and corresponding error has been found to be zero which are not included in figure.

It has been evident in Figure-10.3.6 that lower frequency disturbances are observed efficiently but at higher frequency, there exist some non-trivial error. For sinusoidal disturbance, the error occurs mostly due to phase shift; the high frequency error introduces error spikes at the beginning and end of the pulses.

Case(iii): D_1 and D_2 have been considered as delayed truncated double ramp beginning at 1 sec, amplitude 1, duration 2 sec and delayed modulated sine wave pulse, frequency =30 rad/s, beginning at 4 sec, duration 2 sec respectively. In this case, two non-zero disturbances D_1 and D_2 have been applied simultaneously.

Original disturbance D_1 in the form of delayed truncated double ramp and its estimation as well as original disturbance D_2 in the form of delayed modulated sine wave pulse and its estimation are shown in Figure-10.3.7 and Figure-10.3.8 respectively. Corresponding estimation errors for D_1 and D_2 are shown in insets of Figure-10.3.7 and Figure-10.3.8 respectively; it may be inferred that the DOB tracks the disturbances efficiently.

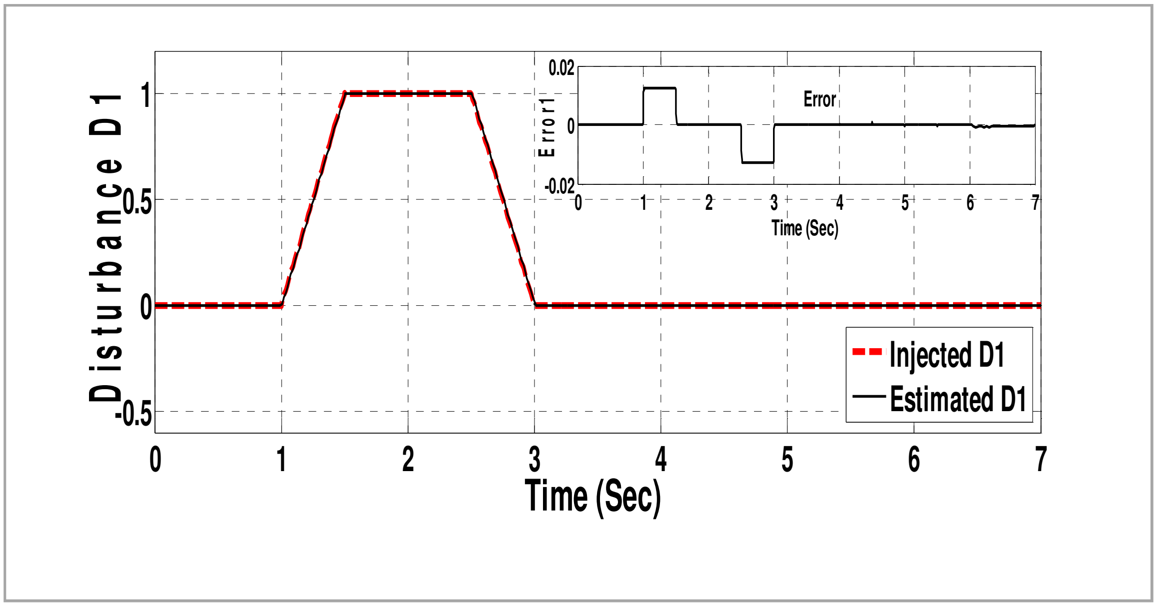


FIG.-10.3.7: INJECTED DISTURBANCE D1 AND ESTIMATED DISTURBANCE OF D1 (CORRESPONDING OBSERVATION ERROR1 AS INSET)

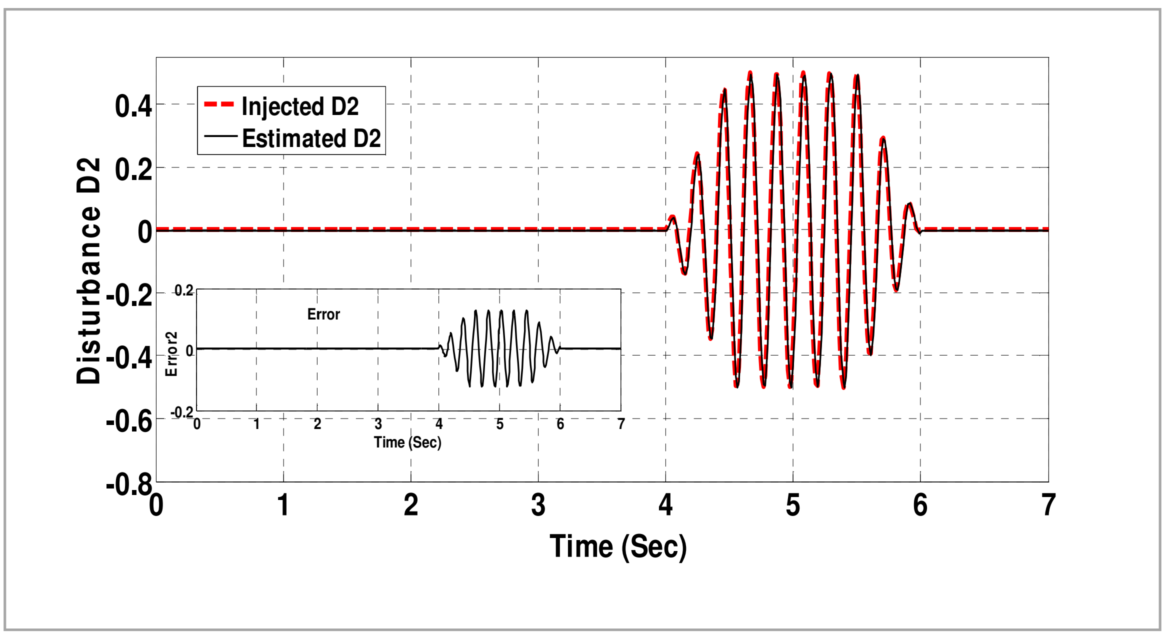


FIG.-10.3.8: INJECTED DISTURBANCE D2 AND ESTIMATED DISTURBANCE OF D2 (CORRESPONDING OBSERVATION ERROR2 AS INSET)

10.4 Chapter Conclusion

A novel method of designing a Disturbance Observer applicable for a class of MIMO nonlinear square process plants has been proposed. The method uses Hirschorn Inverse for inverting nonlinear dynamics relating input and output. To demonstrate the effectiveness of the proposed method, it has been applied to a benchmark Quadruple Tank process where time varying disturbances in the nonlinear system have been estimated effectively over a wide frequency range using various disturbance waveforms. Bandwidth of the proposed DOB is dictated by the filter banks which have to be used. The bandwidth limitation may create waveform distortion and phase shift. However, too large a bandwidth may introduce noise and therefore a trade-off is to be carried out during the design process. Use of this method for active anti disturbance control in process control systems is advocated.

PART-E:

Discussion and Conclusion

Chapter 11: Discussions and Conclusions

11.1 About this Chapter

This chapter contains some discussions about the work done and conclusions obtained from the work. In particular, a summary of the main findings is provided within the conclusion subsection. The scope for future work is also included as a separate subsection.

11.2 Discussions

11.2.1 Objective Revisited

The motivation behind the research work has been to evolve disturbance rejecting controllers for industrial systems using novel techniques for disturbance observation. The industrial plants under consideration would be either linear or nonlinear.

With the above motivation, the current work has been divided into two segments:

- Development of Disturbance Observer techniques
- Development of Decoupling and disturbance rejecting controllers

In the sequel a 2 DOF control structure incorporating IMC based feedback control and DOB Based feed-forward has been developed.

In the present work, we limit our attention to so-named matched disturbances [Yang2011a].

In the subsequent sections, we would examine how the other findings and developments contribute towards the stated objectives.

11.2.2 Summary of Significant Contributions

For the better understanding of the conclusions, significant contributions of this dissertation have been summarized and articulated in the following section:

- Two versions of a nonlinear SISO DOB have been proposed which are applicable to a large class of industrial control systems, namely
    - DOB using state variables of the process model.

    - DOB employing special state observers.

- The above DOB using state variables of the process model has been extended to nonlinear MIMO systems.
- An Active Anti-Disturbance Control (AADC) Architecture for nonlinear process models has been proposed combining IMC and DOB applicable for nonlinear systems.
- Architecture for AADC applicable to linear MIMO time delay systems has been proposed using multivariable decoupling IMC and MIMO DOB and their performance evaluated.
    - Sensitivity analysis has been done for AADC and IMC in the presence of process-model mismatch.
- AADC for linear SISO time delay system has been proposed using IMC and Modified Noise Reduction Disturbance Observer (MNR-DOB) which can attenuate high frequency measurement noise along with other disturbances. Performance of such controllers has been evaluated.
- Some methods of Decoupling Internal Model Controller have been proposed for linear multivariable system with multiple time delay and such methods have been implemented and evaluated. Such schemes include:
    - A controller structure obtained by extending an existing decoupling IMC [Qibing2009].
    - A decoupling IMC controller structure obtained for systems with V-structure.
    - Inverted decoupling controllers obtained using IMC.

11.3 Conclusions

- Findings from a fairly comprehensive literature survey
    - Very few publications deal with nonlinear DOB and rarely used in process control application domain.
    - No significant literature involving combination of nonlinear IMC and nonlinear DOB.

- Findings from SISO DOB with direct use of state variables
  - The process disturbance estimation for proposed SISO DOB method for nonlinear system was found superior to well known nonlinear DOB method by Chen et al. [Chen2004].
- Findings from SISO DOB without using plant states
  - The process disturbance estimation for proposed SISO DOB method applicable for nonlinear system was found superior to well known nonlinear DOB method by Chen et al. [Chen2004].
- Findings from MIMO DOB- using state variable of the process model
  - A case study using an industrial plant exhibited acceptable level of matching disturbances of different waveforms and frequencies with the observed results.
- Findings from Disturbance Rejection Controllers
  - The proposed Active Anti-Disturbance Control (AADC) architecture for nonlinear system provides superior set-point tracking, disturbance rejection (both process and measurement disturbances) and robustness with respect to parametric uncertainty compared to the situation where the nonlinear IMC is used alone.
  - The new MAADC (Modified Active Anti-Disturbance Control) incorporating Noise Reduction Disturbance Observer (NR-MDOB) has been found to be able to mitigate disturbances (including high frequency measurement noise) for linear systems with time delay. The MAADC was seen to perform better than the AADC and the efficacy of this proposed approach has been established.
- Findings from Decoupling Controllers incorporating an extension of an existing decoupling Internal Model Control [Qibing2009]
  - The extended decoupling IMC has been shown to outperform the [Qibing2009] method in the context of set-point tracking, disturbance rejection and robustness.
- Findings from IMC based decoupling controller applied to systems with V structure
  - It has been found that the objectives of IMC (i.e. set-point tracking, disturbance rejection and robustness with respect to parametric uncertainty) have been achieved successfully.

  - By comparing Gershgorin band for uncompensated and compensated systems, it has been found that though some low frequency couplings were present, overall Gershgorin band for compensated system signifies satisfactory decoupling.
- Findings from Inverted decoupling controller
  - Compared to the predecessor approach [Qibing2009], the proposed approach exhibited improved performance for every aspect viz., tracking, disturbance rejection, robustness and decoupling of closed loop system,
  - Further improvements have been obtained with a 2-DOF controller incorporating a command modifier.
- Findings from AADC for MIMO system with multiple time delay
  - By combining IMC and DOB for linear multivariable time delay or non-minimum phase system, it has been found that disturbance rejection is superior to that using IMC alone.
  - In the presence of process-model mismatch, Sensitivity study has been done and it has been found that measurement disturbance rejection of AADC is advanced than IMC.

11.4 Suggestions for further research

- The conditions of applicability of Disturbance Observers can be relaxed.
  - For the case when the nonlinear system do not have *well defined* relative degree
  - For the case when the SISO system do not have smooth functions f, g, h.
- More rigorous proof of Hirschorn-inverse based Disturbance Observer could be done in future.
- The proposed nonlinear DOB can be modified to estimate mismatched disturbances (which can not be equivalently placed at the input point).
- Active Anti-Disturbance Control based on the present work can be modified to reject mismatched disturbances.

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