Project Presentation on

Modified Smith Predictor Based Advanced Control Strategies for Purely Integrating Processes with Large Dead Time

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Instrumentation and Control Engineering

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Motivation

Over 95% processes in industry are controlled by (PID) controller.

Provides reasonable compromise between robustness and performance through correct tuning

Large dead time makes PID tuning difficult

Closed loop performance becomes limited

Thesis presents one such strategy

Predictive control strategy required for high performance

Justifies application over dedicated single controller-based loops or other Smith Predictor based control loops.

Objective

- Study of purely integrating processes with large dead time
- Implementation of Modified Smith Predictor (MSP) based control strategy
- Tuning for satisfactory performance indices and mitigation of model abnormalities

Plan of the Work

Familiarisation	Understanding the problem statement - How and why is dead time a concern to industrial processes ?
Research	Taking account of research that has been done on the topic till date Pinpointing topics relevant to the problem and possible solutions Understanding the individual components involved
Goal Setting	Setting primary goal based on research– Modified Smith Predictor Based Control Setting secondary goals based on experimental results- Improved Tuning and Future Scope
Experimental Evaluation	Validating findings through observations Study of improvements over contemporary works
Future scope	Finding shortcomings - Model Mismatch, Other Process Models Suggesting improvements – Autotuned Modified Smith Predictor

About Dead Time

Definition

Time interval between start of an event at one point in a system and resulting action at another point

Causes

Mainly caused by the time required to transport mass, energy, or information
Processing time or accumulation of time lags in several simple dynamic systems connected in series

Examples

Arise in physical, chemical, biological and economic systems, and measurement and computation
In a conveyer belt delay is determined as ratio of distance to be travelled to the speed of the material

Implications in a Physical Process

Effect of the control action takes some time to affect the controlled variable
Time delay makes the effect of the perturbations felt only after a considerable time
Control action applied is based on a past error value which is not correlated with the present value.
Interpreted in frequency domain as reduction in the system's phase which decreases stability
Controlling the process with conventional tuning methods becomes difficult

Solution

Gain must be reduced to maintain stability
Adaptive control techniques implemented to tackle dynamic plant parameters

Literature Review

Smith Predictor (1957)

The first dead-time compensation algorithm by O.J.M. Smith.

Contained a dynamic model of the dead-time process

Dead Time Compensator for Integrating Processes – by Watanabe (1981)

Pole near origin on left side causes process to be sluggish

Affects rise time and settling time

MSP modification made to tackle this problem

Compensator for Integrating Processes by Astrom (1994)

Improvement over Watanabe

Introduced controller to improve disturbance rejection

Decoupled disturbance from set-point

Compensator by Matausek and Micic (1996)

Compensation technique for higher-order integrating processes with large dead time

Worked with velocity gain, dead-time and closed-loop first order time-constant

Gave good results for set-point tracking and disturbance rejection

Modified Smith Predictor by Kaya and Atherton (1999)

Modification of Matausek

Used for Stable, unstable and integrating processes

Had more than 1 controller

Filtered Smith-Predictor-based Subspace Predictive Controller (2014)

Proposed by P. R. C. Mendes, J. E. Normey-Rico, Jo~ao V. Jr., D. M. Cruz

Based on filtered SP structure to improve performance of SPC when applied to a stable or integrative dead-time process

Simplified Tuning of IMC Based MSP for UFOPDT Processes (2020)

Tuning guideline l (IMC) based MSP technique for unstable lag dominated first-order processes with dead time

For processes like isothermal chemical reactor, bioreactor, dimerization reactor, fluid catalytic cracker ,etc.

Limitations of Conventional Tuning Techniques

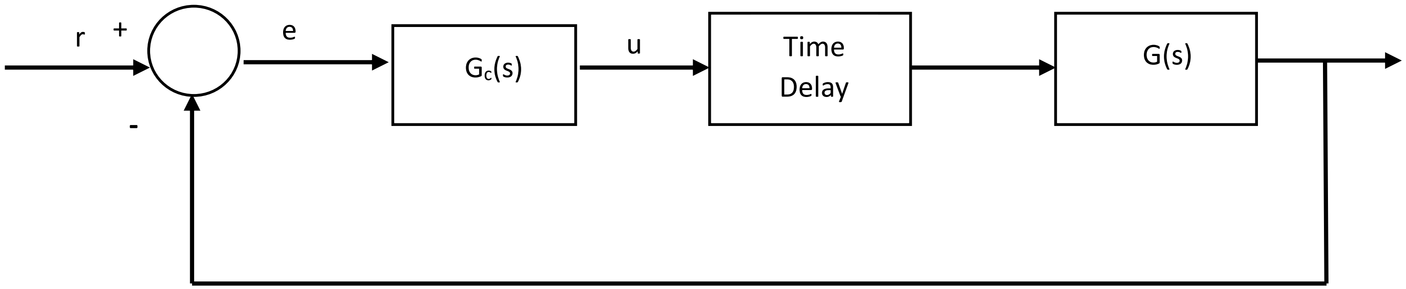


Fig. *Feedback Control Structure for Conventional Tuning Techniques*

$$U(s) = G_c(s)E(s)$$

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right)$$

Model Free Control (Relay Based Tuning)

$$k_c = 0.6 \; x \; Ku$$

$$\tau_I = \mathrm{Pu} / 2$$

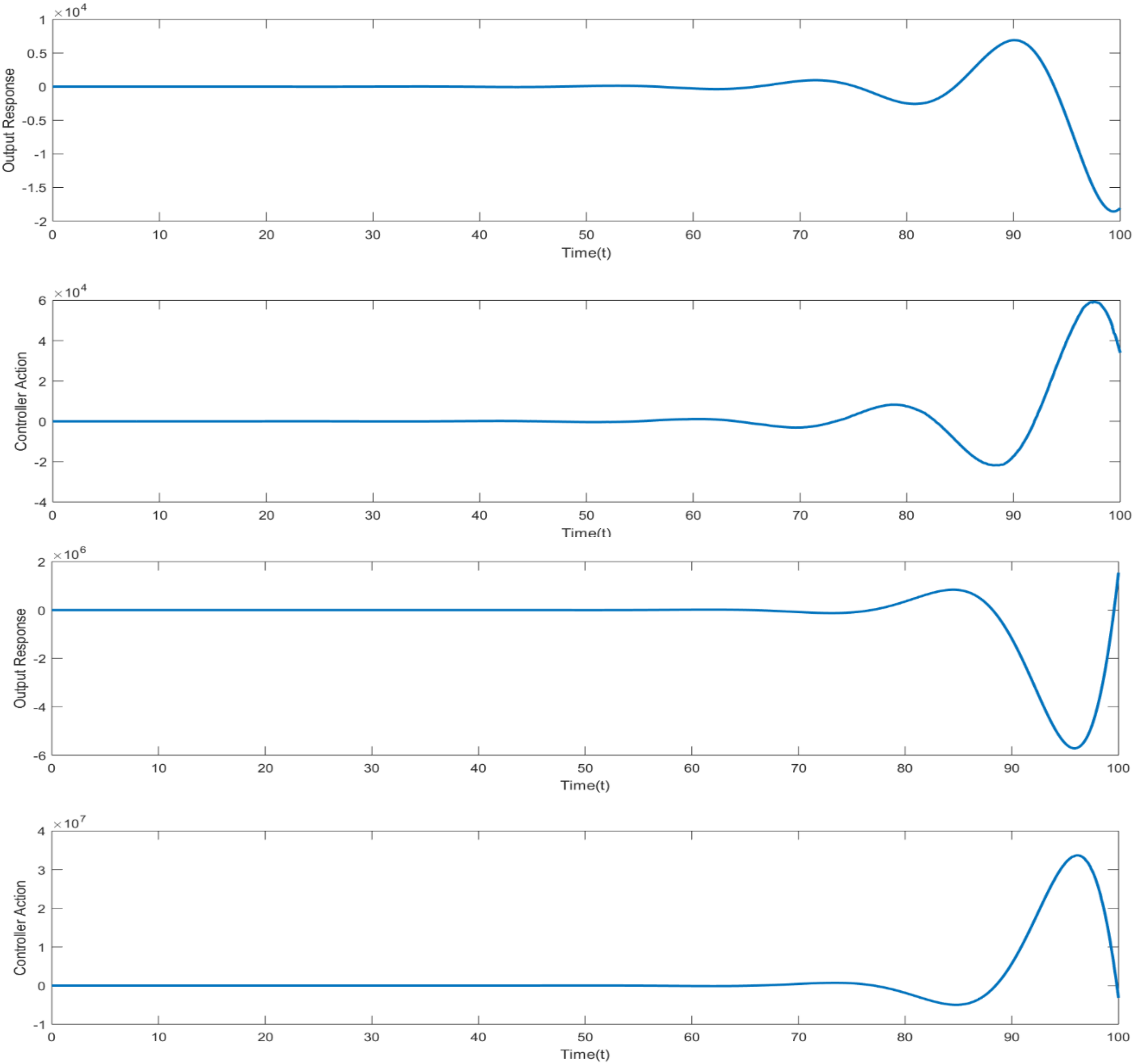
$$\tau_D = Pu / 8$$

Model Based Control (Internal Model Control (IMC))

$$k_c = \frac{(\tau_p + 0.5\theta)}{k_p(\lambda + 0.5\theta)}$$

$$\tau_I = \tau_p + 0.5\theta$$

$$\tau_D = \frac{\tau_p \theta}{2\tau_p + \theta}$$



Process Model $G_{p1} = \frac{0.2}{s} e^{-7.4s}$

Relay-Based Tuning	IMC Based Tuning
Ku = 03.692 Pu=29.50	λ= 1.85
Kc = 2.22	Kc = 4.23
τi = 14.76	τi = 8.40
τd = 3.69	τd = 0.79
Expression of Controller	**Expression of Controller**
(1 + 1/14.76 + 3.96) x2.22e(t)	(1 + 1/8.40 + 0.79) x4.23 e(t)

Fig. *Performance Analysis of Relay based tuning (above) and IMC based tuning (below)*

Smith Predictor (SP -1957)

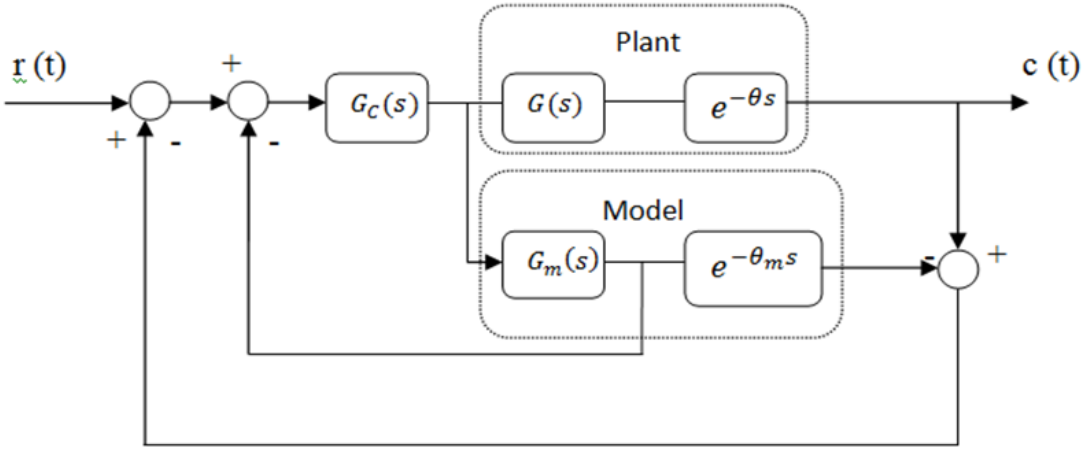


Fig. *SP Configuration as proposed by O. J. M. Smith*

The closed loop transfer function : $T(s) = \frac{C(s)}{R(s)} = \frac{G_C(s)G(s)e^{-\theta s}}{1+G_C(s)[G_m(s)+G_e(s)]}$,Where, $G_e(s) = G(s)e^{-\theta s} - G_m(s)e^{-\theta_m s}$

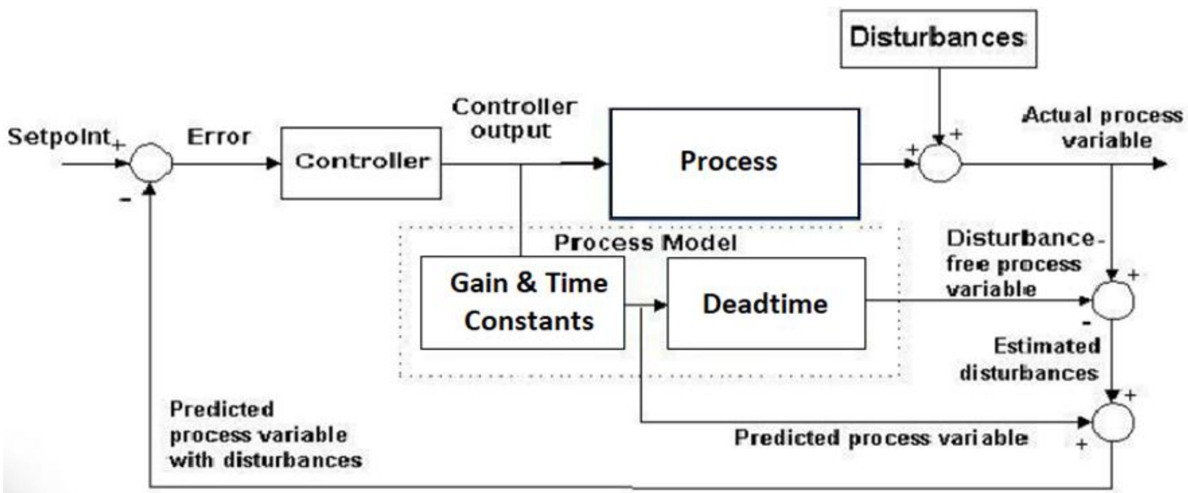


Fig. *Mathematical model of SP*

Modified Smith Predictor

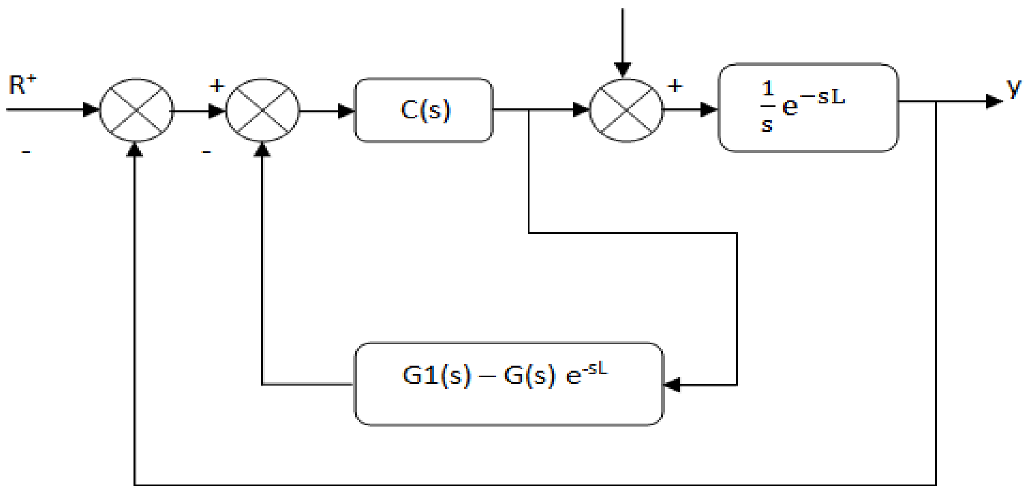


Fig. *MSP Structure by proposed by Watanabe (1981)*

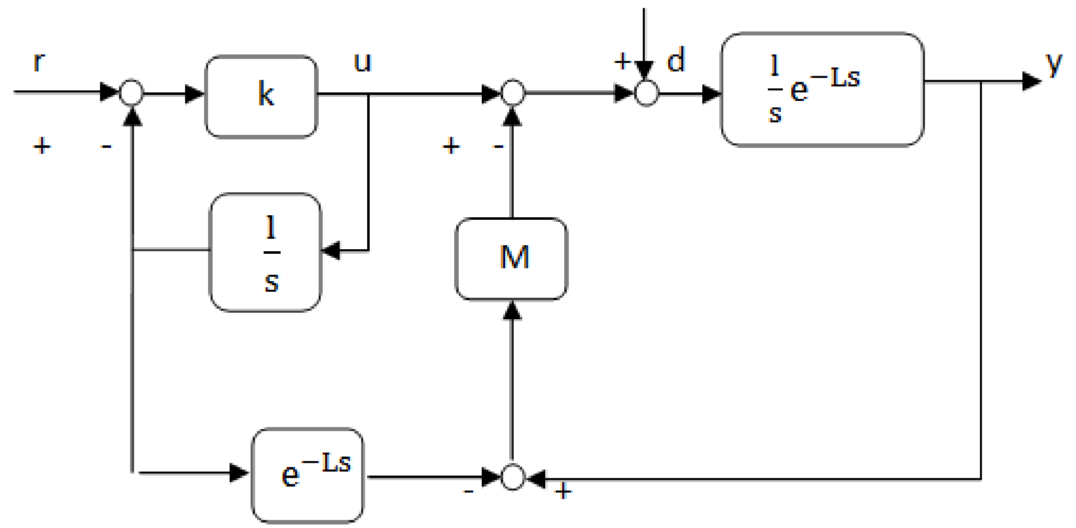


Fig. *Astrom's SP (1984)*

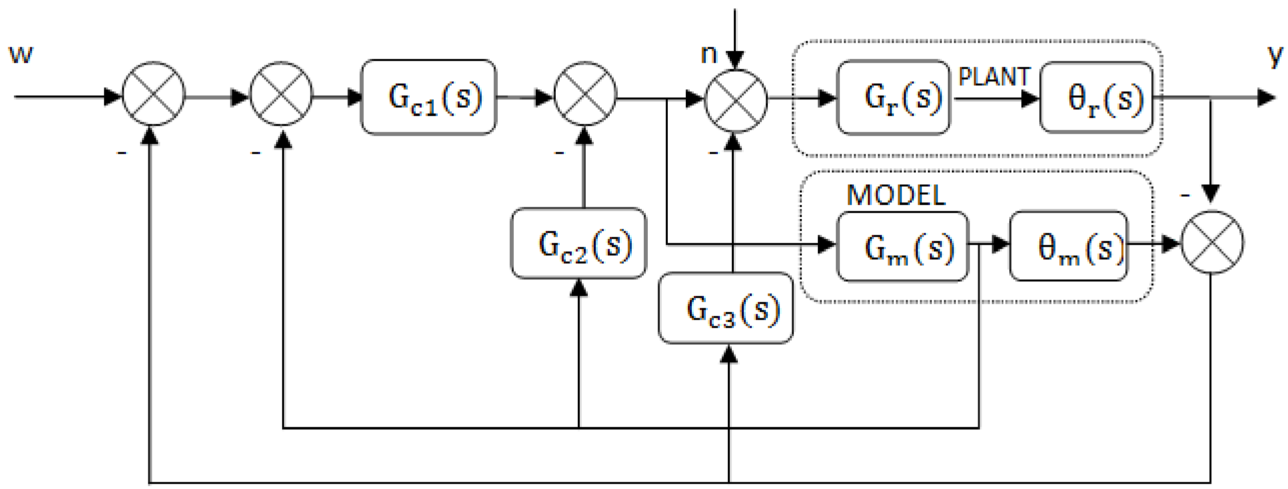


Fig. *MSP control structure of Kaya & Atherton (1999)*

Implemented Modified Smith Predictor

MSP based control scheme is reported by **Karan and Dey (2021)**

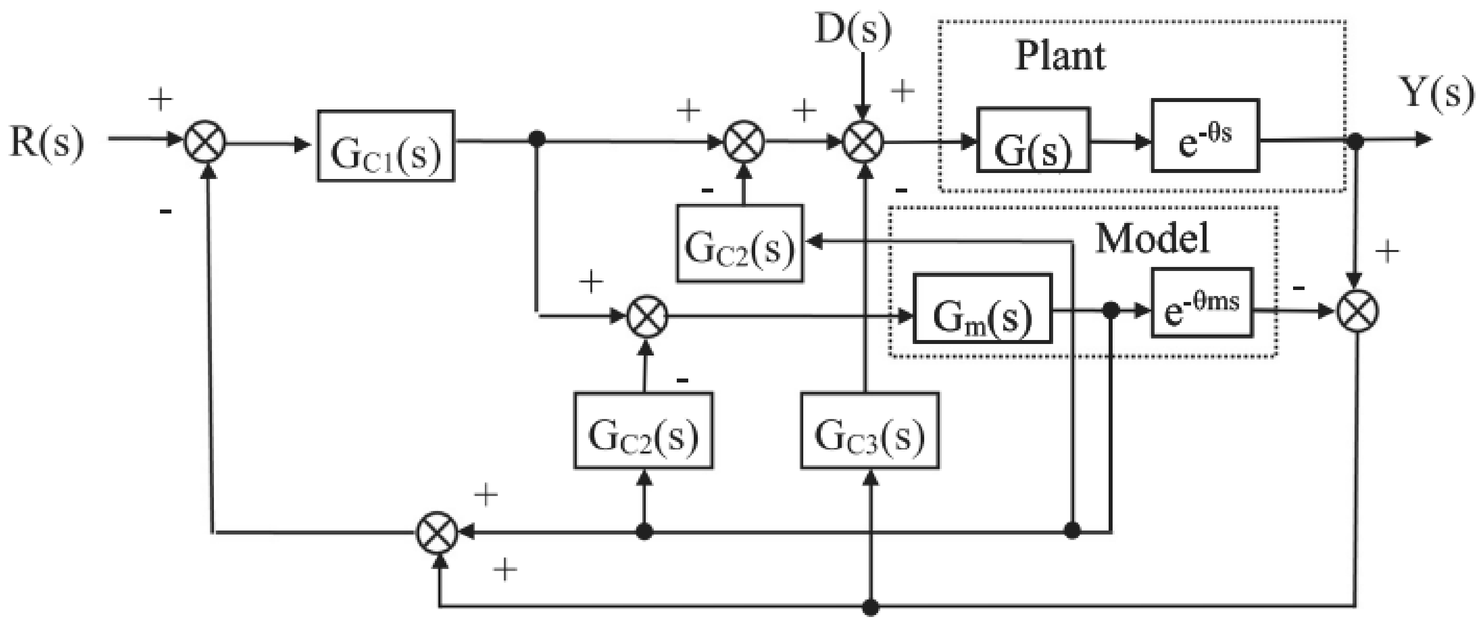


Fig. *Implemented MSP Structure*

$G_{c1}(s) = K_p\left(1 + \frac{1}{T_i}\right)$ Forward path controller for superior set point tracking

$G_{c2}(s) = \beta K_p$ Overshoot Compensation

$G_{c3}(s) = \gamma K_p(1 + T_d s)$ Disturbance Rejection

Performance Evaluation

Model 1

- Popular IPTD model reported by Kumar and Padma Sree and Goud and Rao
- Signifies behaviour of distillation column
- Realized by $G_{p1} = \frac{0.2}{s} e^{-7.4s}$

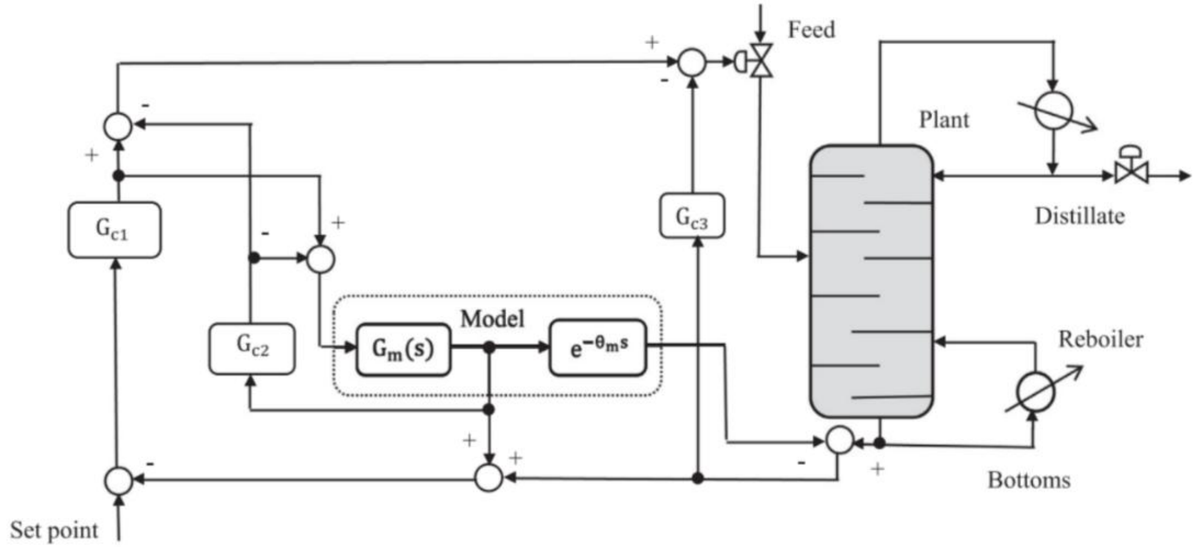


Fig. *Industrial Distillation Column (left), Distillation Column Process Model (right)*

Model 2

- Reported by Goud and Rao
- Obtained through Reduction of the unstable process model $\frac{5}{100s-1} e^{-6s}$
- Realized by $G_{p2} = \frac{0.05}{s} e^{-6s}$

MSP Controller Tuning Parameters

$$G_{c1}(s) = K_p\left(1 + \frac{1}{T_i}\right) \qquad G_{c2}(s) = \beta K_p \qquad G_{c3}(s) = \gamma K_p(1 + T_d s)$$

For the process $\frac{0.2}{s}\, e^{-7.4s}$, the values obtained are

G_{c1}	G_{c2}	G_{c3}
Kc = 5.4 τi = 3.70	Kc= 5.4 β = 0.25	Kc = 5.4 τd = 1.85 γ = 0.06

For the process $\frac{0.05}{s}\, e^{-6s}$, the values obtained are

G_{c1}	G_{c2}	G_{c3}
Kc = 26.67 τi = 3.00	Kc= 26.67 β = 0.25	Kc = 26.67 τd = 1.50 γ = 0.06

Evaluation Process

Evaluation of SP and MSP Performance → Performance Evaluation of MSP and Contemporary Control Techniques under Nominal and Perturbed Conditions → Robustness and Stability Analysis → Observation and Conclusion

Smith Predictor vs Modified Smith Predictor

Process Model $G_{p1} = \frac{0.2}{s} e^{-7.4s}$

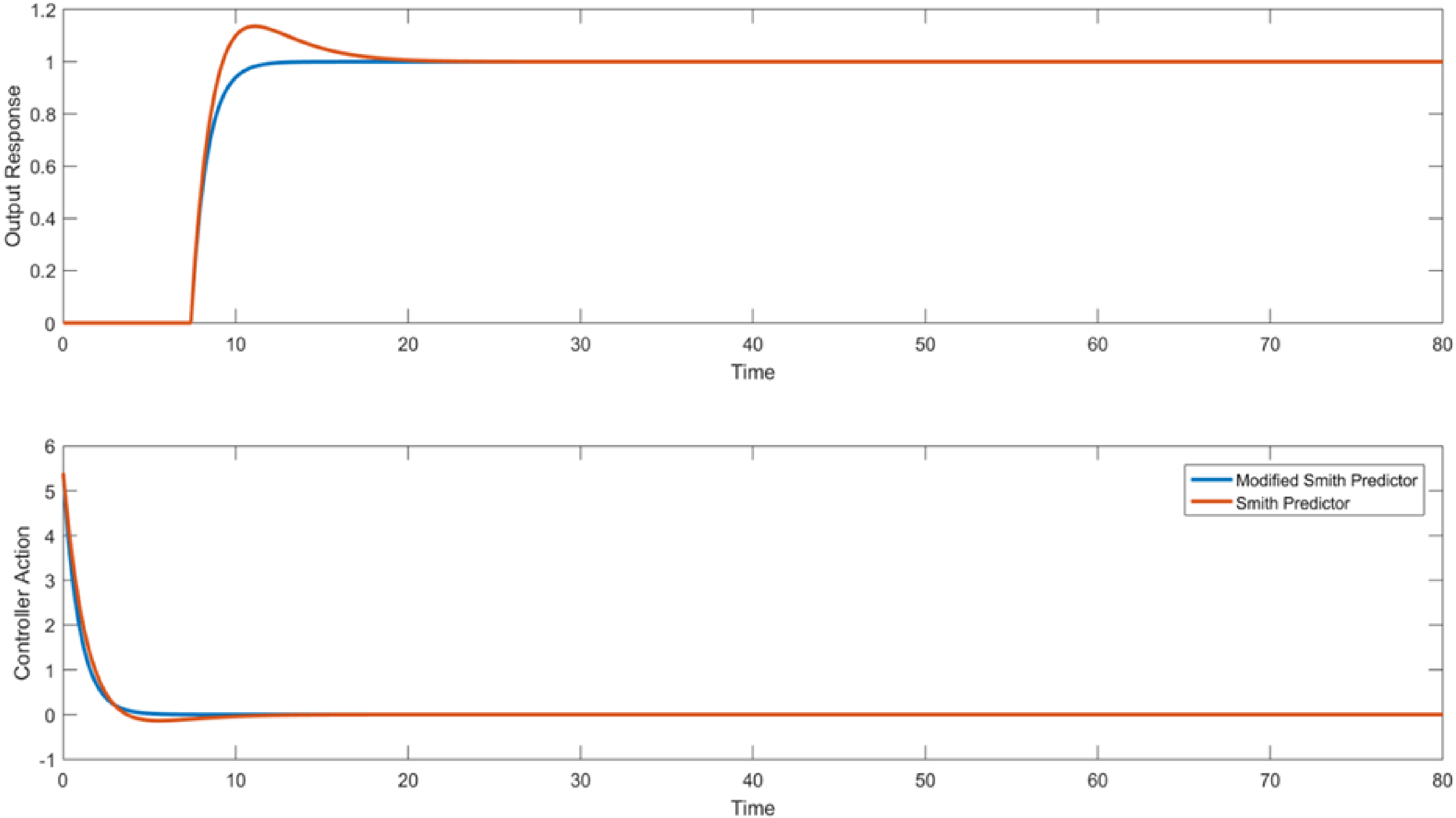


Fig. *Performance Index Analysis of MSP and Conventional SP 1*

***Table** Performance Index Analysis of MSP and Conventional SP*

Parameter	**Modified Smith Predictor**	**Smith Predictor**
Rise Time (Sec)	2.04	1.35
Settling Time (Sec)	11.02	17.39
Settling Min	0.91	0.91
Settling Max	1.00	1.14
Overshoot (%)	0.00	13.53
Undershoot (%)	0.00	0.00
Peak	1.00	1.14
Peak Time (Sec)	40.40	11.10

Performance Index	**Modified Smith Predictor**		**Smith Predictor**	
	Without Load	**With Load**	**Without Load**	**With Load**
ISE	0.46	0.83	0.46	0.53
ITSE	0.21	14.97	0.43	2.67
IAE	0.93	3.78	1.36	2.05
ITAE	0.86	123.30	4.14	28.89
TV	5.00	20.74	6.35	15.12

Observation

- G_{c2} removes output overshoot
- G_{c3} brings down output Magnitude when disturbance is present

Model 1 under Nominal Conditions

Process Model $G_{p1} = \frac{0.2}{s} e^{-7.4s}$

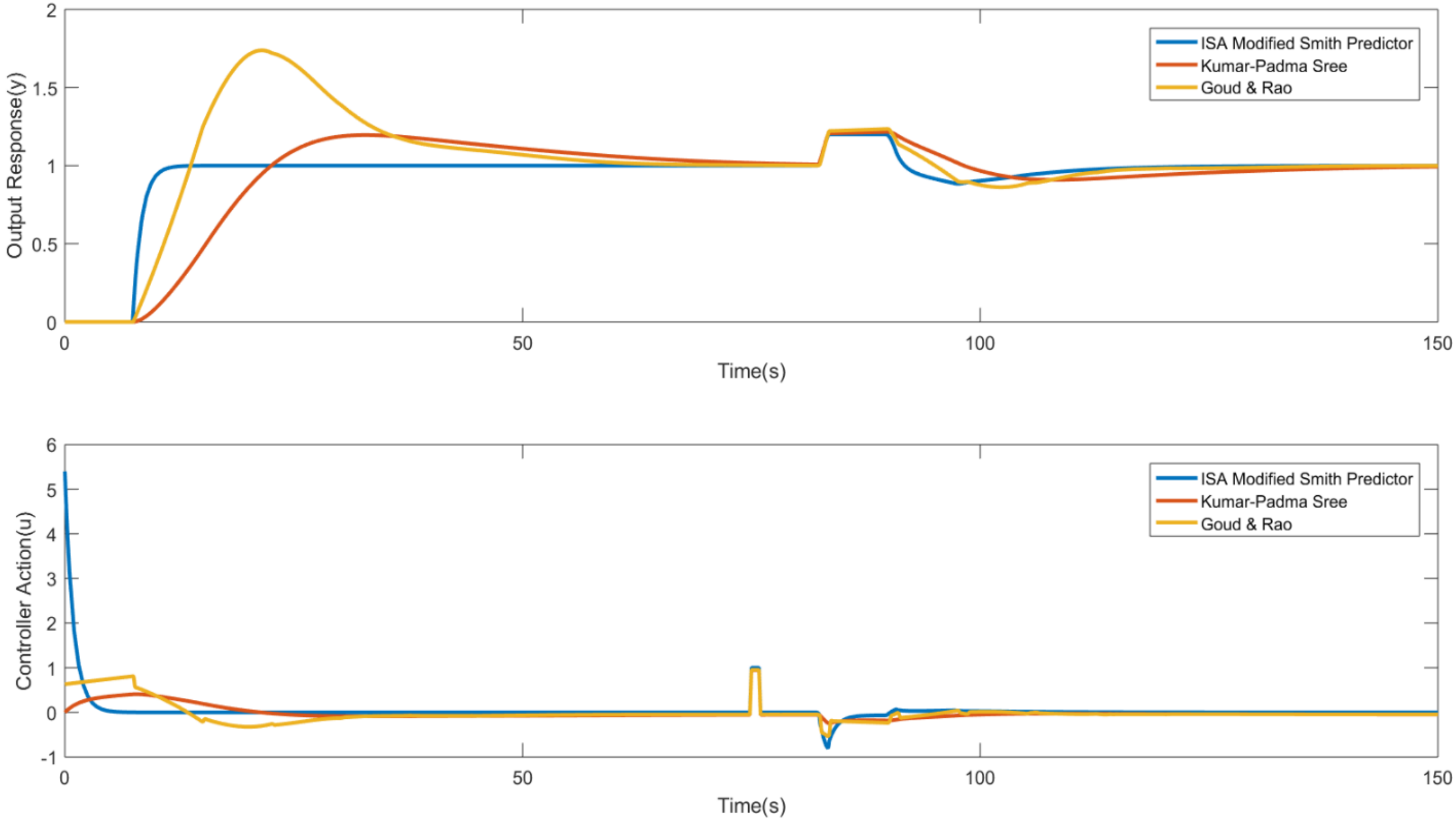


Fig. *Performance Index Analysis of the MSP and Recently Published Works for Model 1 under Nominal Conditions*

***Table** Performance Index Analysis of the MSP and Recently Published Works for Model 1 under Nominal Conditions*

Parameter	Modified Smith Predictor	Kumar - Padma Sree	Goud & Rao
Rise Time (Sec)	2.06	10.58	4.99
Settling Time (Sec)	11.05	73.12	59.80
Settling Min	0.91	0.91	0.92
Settling Max	1.00	1.20	1.74
Overshoot (%)	0.00	19.58	73.79
Undershoot (%)	0.00	0.00	0.00
Peak	1.00	1.20	1.74
Peak Time (Sec)	45.70	32.89	21.50

Performance Index	Modified Smith Predictor		Kumar - Padma Sree		Goud & Rao	
	Without Load	With Load	Without Load	With Load	Without Load	With Load
ISE	0.46	0.48	7.76	8.40	15.85	16.45
ITSE	0.21	1.49	137.93	197.37	194.93	251.03
IAE	0.93	1.30	21.10	24.98	23.53	27.70
ITAE	0.86	34.73	626.03	1013.66	414.04	821.35
TV	5.00	8.16	12.72	14.63	17.27	19.34

Model 2 under Nominal Conditions

Process Model $G_{p2} = \frac{0.05}{s} e^{-6s}$

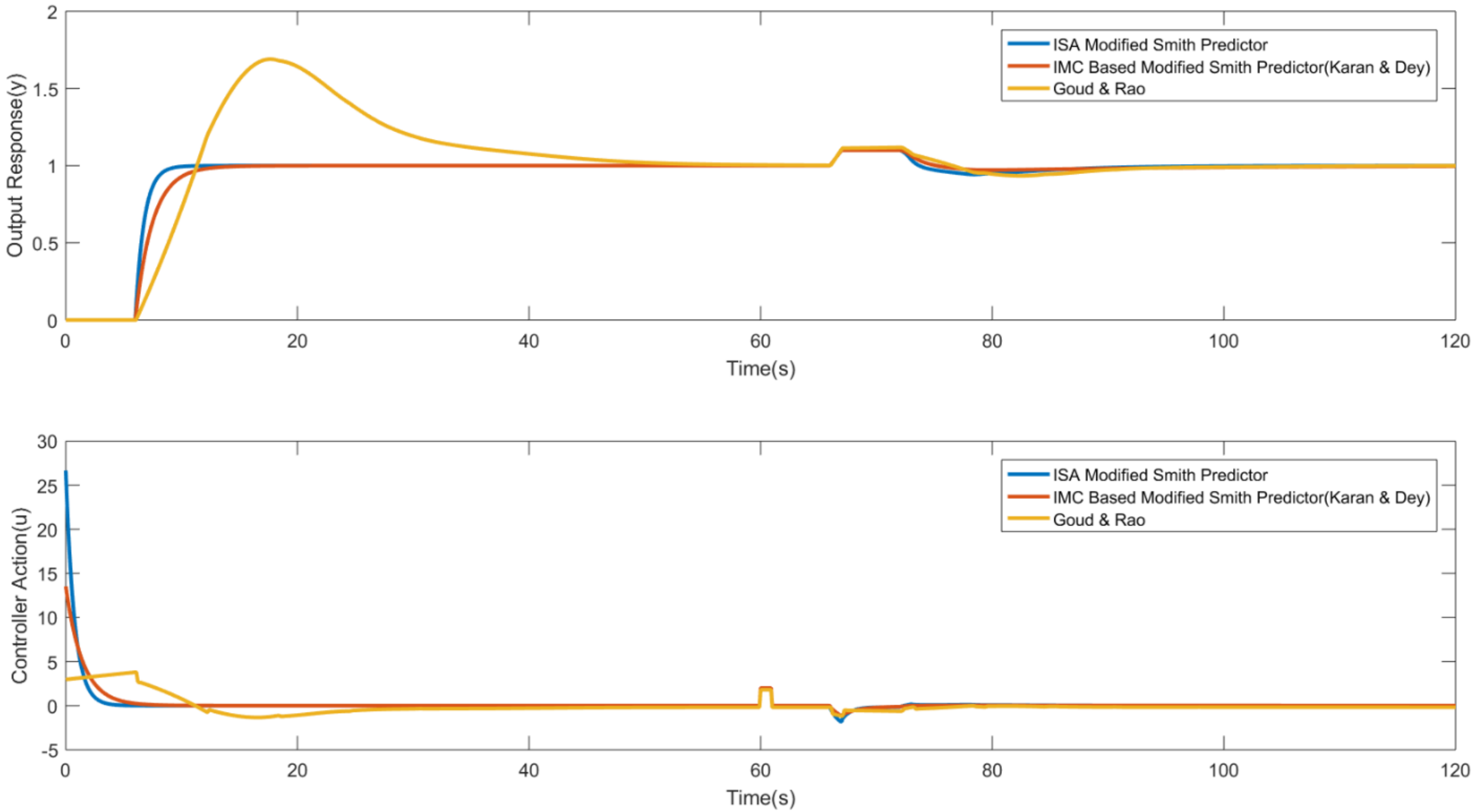


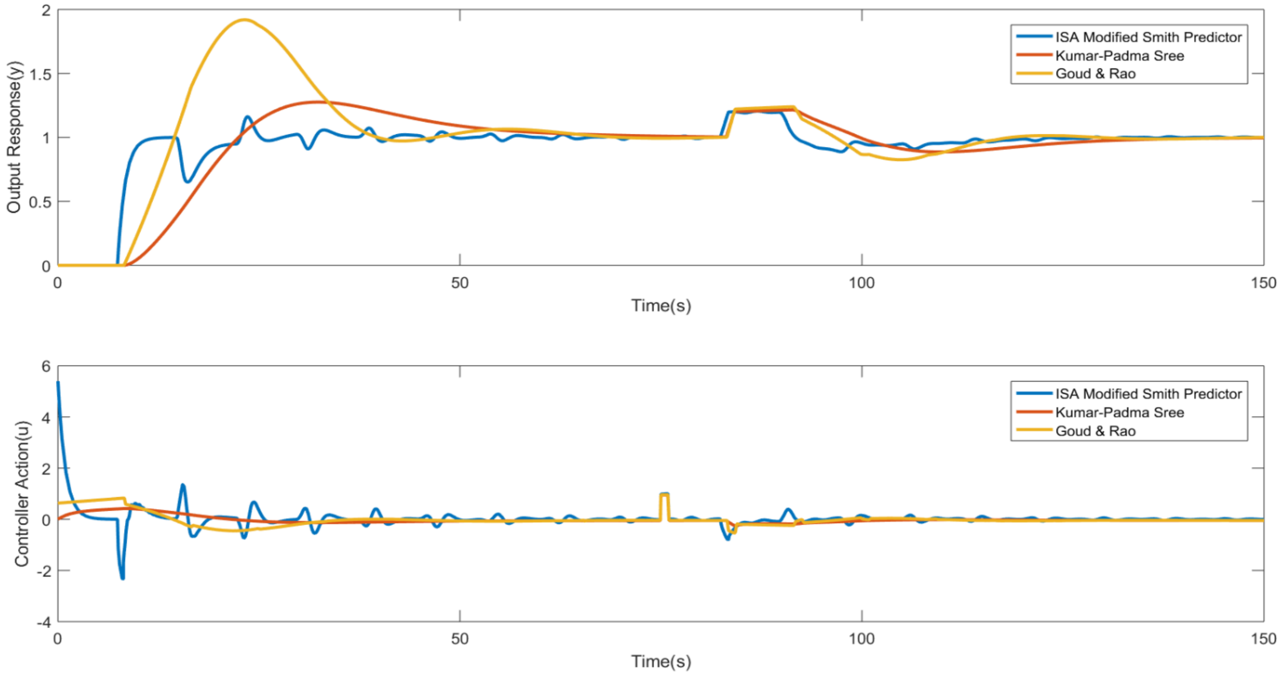
Fig. *Performance Index Analysis of the MSP and Recently Published Works for Model 2 under Nominal Conditions*

Table *Performance Index Analysis of the MSP and Recently Published Works for Model 2 under Nominal Conditions*

Parameter	Modified Smith Predictor	IMC Based Modified Smith Predictor	Goud & Rao
Rise Time (Sec)	1.66	3.32	4.20
Settling Time (Sec)	8.99	12.10	49.84
Settling Min	0.91	0.90	0.91
Settling Max	1.00	1.00	1.69
Overshoot (%)	0.00	0.00	69.00
Undershoot (%)	0.00	0.00	0.00
Peak	1.00	1.00	1.69
Peak Time (Sec)	96.70	103.40	17.70

Performance Index	Modified Smith Predictor		IMC Based Modified Smith Predictor		Goud & Rao	
	Without Load	With Load	Without Load	With Load	Without Load	With Load
ISE	0.38	0.38	0.75	0.75	12.56	12.68
ITSE	0.14	0.33	0.56	1.01	124.30	133.50
IAE	0.76	0.91	1.52	1.80	19.06	20.78
ITAE	0.60	11.69	2.41	24.10	277.50	412.9
TV	20.00	26.29	20.00	25.07	61.65	65.28

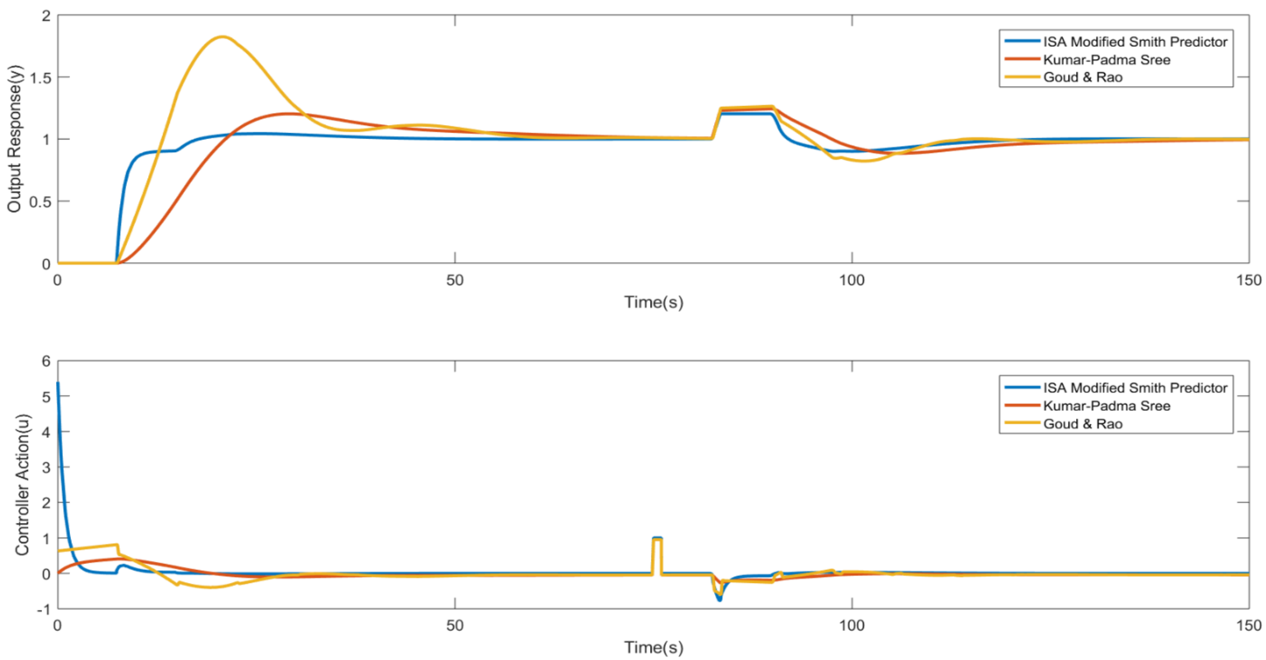
Perturbations Separately Applied to Model 1



Process Model $G_{p1} = \frac{0.2}{s} e^{-7.4s}$

Perturbed Process Model $G_{p1} = \frac{0.2}{s} e^{-8.14s}$

Fig. *Performance Analysis of the MSP and Recently Published Works for Model 1 with 10% Time Delay Perturbation*



Process Model $G_{p1} = \frac{0.2}{s} e^{-7.4s}$

Perturbed Process Model $G_{p1} = \frac{0.22}{s} e^{-7.4s}$

Fig. *Performance Analysis of the MSP and Recently Published Works for Model 1 with 10% Process Gain Perturbation*

***Table** Performance Index Analysis of the MSP and Recently Published Works for Model 1 with 10% Time Delay Perturbation*

Parameter	Modified Smith Predictor	Kumar - Padma Sree	Goud & Rao
Rise Time (Sec)	2.06	10.11	4.99
Settling Time (Sec)	63.05	67.31	65.33
Settling Min	0.65	0.90	0.90
Settling Max	1.16	1.28	1.92
Overshoot (%)	16.08	27.58	91.94
Undershoot (%)	0.00	0.00	0.00
Peak	1.16	1.28	1.94
Peak Time (Sec)	23.62	32.27	23.22

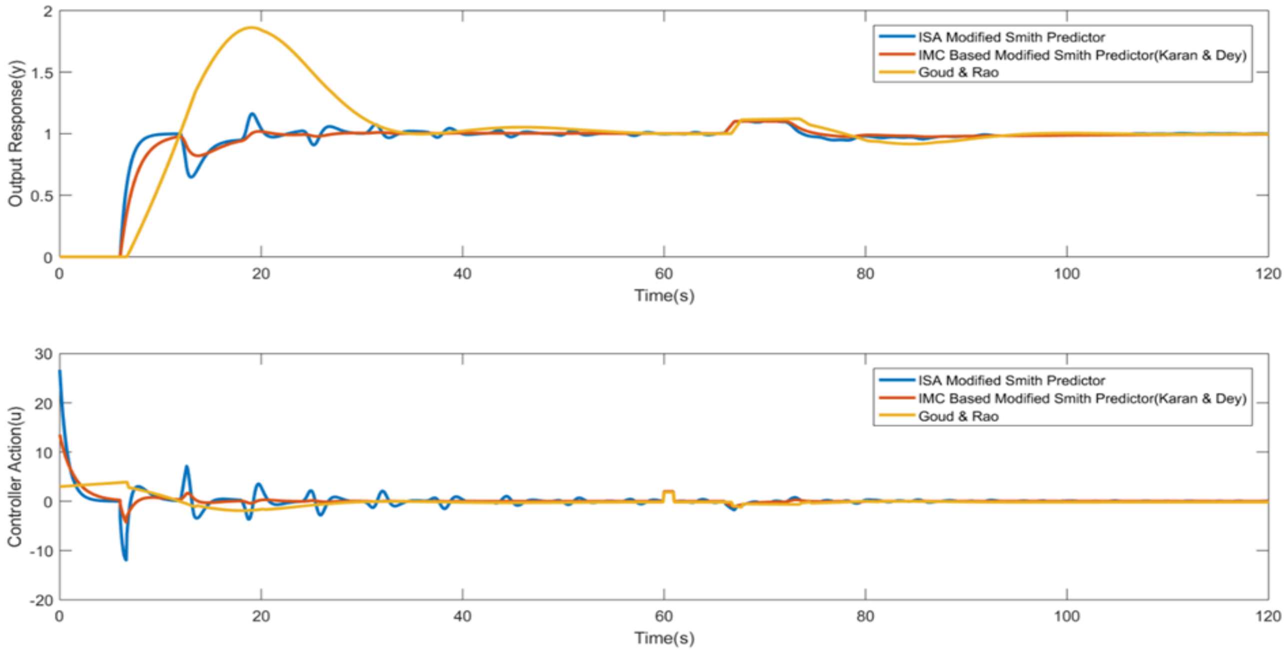
Performance Index	Modified Smith Predictor		Kumar - Padma Sree		Goud & Rao	
	Without Load	With Load	Without Load	With Load	Without Load	With Load
ISE	0.62	0.64	8.81	9.52	19.38	20.15
ITSE	2.70	4.50	161.48	228.52	272.30	345.40
IAE	2.76	3.25	22.18	26.35	25.40	30.08
ITAE	56.18	104.90	638.88	1054.85	449.63	913.78
TV	16.73	20.95	13.53	15.42	18.77	21.21

Table *Performance Index Analysis of the MSP and Recently Published Works for Model 1 with 10% Process Gain Perturbation*

Parameter	**Modified Smith Predictor**	**Kumar - Padma Sree**	**Goud & Rao**
Rise Time (Sec)	5.33	9.58	4.59
Settling Time (Sec)	36.08	68.39	58.23
Settling Min	0.90	0.90	0.91
Settling Max	1.04	1.20	1.82
Overshoot (%)	4.30	20.30	82.34
Undershoot (%)	0.00	0.00	0.00
Peak	1.04	1.20	1.82
Peak Time (Sec)	25.41	29.14	20.76

Performance Index	**Modified Smith Predictor**		**Kumar - Padma Sree**		**Goud & Rao**	
	Without Load	**With Load**	**Without Load**	**With Load**	**Without Load**	**With Load**
ISE	0.43	0.45	7.39	8.17	15.95	16.74
ITSE	0.22	1.41	119.99	191.12	188.96	261.81
IAE	1.09	1.46	20.14	24.20	22.81	82.24
ITAE	4.01	38.50	576.44	973.41	387.49	819.51
TV	5.44	8.494	11.82	13.77	16.42	19.00

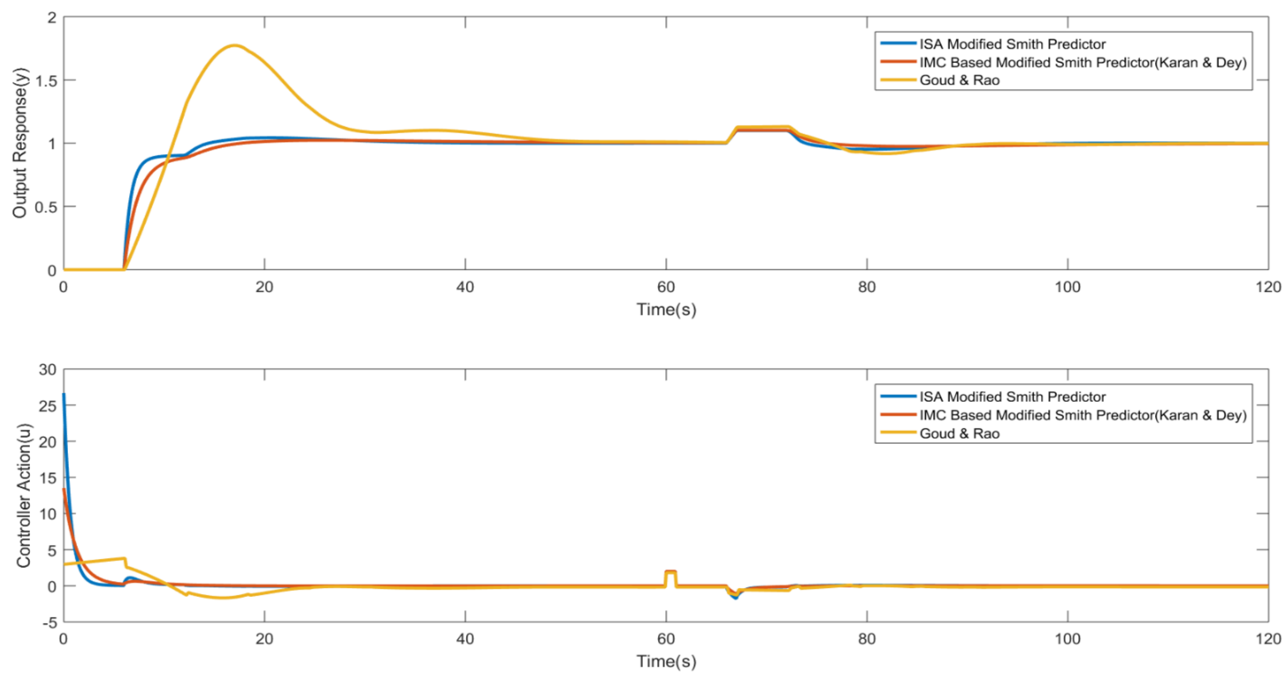
Perturbations Separately Applied to Model 2



Process Model $G_{p2} = \frac{0.05}{s} e^{-6s}$

Perturbed Process Model $G_{p2} = \frac{0.05}{s} e^{-6.6s}$

Fig. *Performance Analysis of the MSP and Recently Published Works for Model 2 with 10% Time Delay Perturbation*



Process Model $G_{p2} = \frac{0.05}{s} e^{-6s}$

Perturbed Process Model $G_{p2} = \frac{0.055}{s} e^{-6s}$

Fig. *Performance Analysis of the MSP and Recently Published Works for Model 2 with 10% Process Gain Perturbation*

***Table** Performance Index Analysis of the MSP and Recently Published Works for Model 2 with 10% Time Delay Perturbation*

Parameter	Modified Smith Predictor	IMC Based Modified Smith Predictor	Goud & Rao
Rise Time (Sec)	1.66	3.32	4.20
Settling Time (Sec)	51.13	25.85	53.89
Settling Min	0.65	0.82	0.91
Settling Max	1.16	1.02	1.87
Overshoot (%)	16.36	1.82	86.19
Undershoot (%)	0.00	0.00	0.00
Peak	1.16	1.02	1.86
Peak Time (Sec)	19.10	19.80	19.00

Performance Index	Modified Smith Predictor		IMC Based Modified Smith Predictor		Goud & Rao	
	Without Load	With Load	Without Load	With Load	Without Load	With Load
ISE	0.51	0.51	0.80	0.80	15.15	15.31
ITSE	1.84	2.07	0.99	1.46	169.60	181.50
IAE	2.27	3.25	2.10	2.38	20.29	22.18
ITAE	37.86	49.51	10.06	31.88	289.00	438.90
TV	67.60	74.34	28.74	34.30	67.28	70.96

***Table** Performance Index Analysis of the MSP and Recently Published Works for Model 2 with 10% Process Gain Perturbation*

Parameter	Modified Smith Predictor	IMC Based Modified Smith Predictor	Goud & Rao
Rise Time (Sec)	4.51	6.55	3.86
Settling Time (Sec)	29.31	31.24	49.01
Settling Min	0.90	0.90	0.91
Settling Max	1.04	1.02	1.77
Overshoot (%)	4.29	2.27	77.24
Undershoot (%)	0.00	0.00	0.00
Peak	1.04	1.02	1.77
Peak Time (Sec)	20.70	25.90	17.00

Performance Index	Modified Smith Predictor		IMC Based Modified Smith Predictor		Goud & Rao	
	Without Load	With Load	Without Load	With Load	Without Load	With Load
ISE	0.35	0.35	0.71	0.71	12.59	12.74
ITSE	0.15	0.32	0.58	1.00	119.30	130.80
IAE	0.89	1.04	1.76	2.022	18.48	20.27
ITAE	2.68	13.78	8.19	29.02	259.50	398.80
TV	21.74	27.73	20.91	25.88	58.77	62.62

Model 1 with both Time Delay and Process Gain Perturbations

Process Model $G_{p1} = \frac{0.2}{s} e^{-7.4s}$ Perturbed Process Model $G_{p1} = \frac{0.22}{s} e^{-8.14s}$

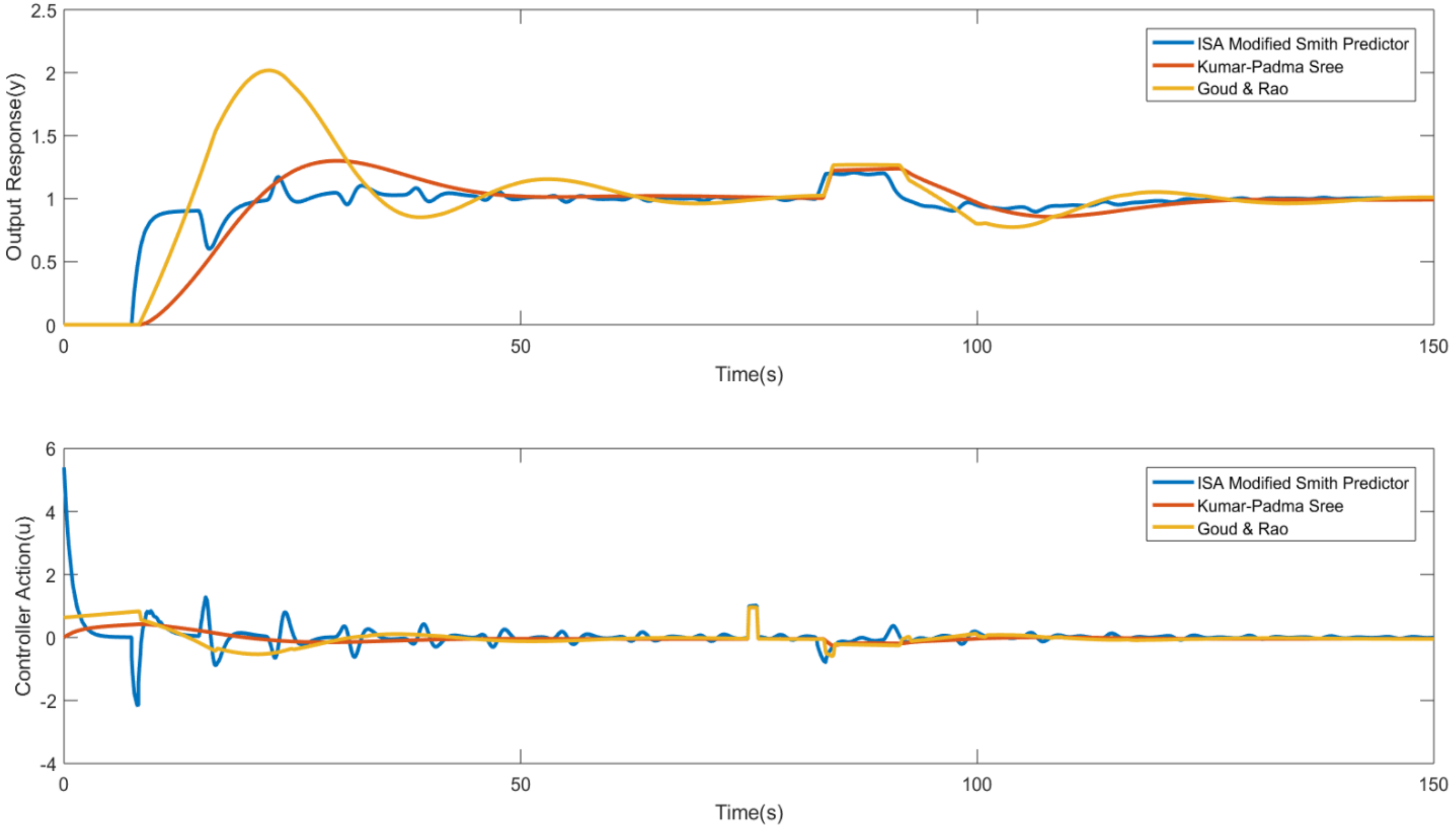


Fig. *Performance Index Analysis of the MSP and Recently Published Works for Model 1 for both 10% Time Delay and 10% Process Gain Perturbation*

***Table** Performance Index Analysis of the MSP and Recently Published Works for Model 1 for both 10% Time Delay and 10% Process Gain Perturbation*

Parameter	**Modified Smith Predictor**	**Kumar - Padma Sree**	**Goud & Rao**
Rise Time (Sec)	5.44	9.21	4.59
Settling Time (Sec)	62.67	68.70	86.85
Settling Min	0.60	0.90	0.85
Settling Max	1.17	1.30	2.02
Overshoot (%)	17.21	30.02	101.75
Undershoot (%)	0.00	0.00	0.00
Peak	1.17	1.30	2.02
Peak Time (Sec)	23.41	29.77	22.45

Performance Index	**Modified Smith Predictor**		**Kumar - Padma Sree**		**Goud & Rao**	
	Without Load	**With Load**	**Without Load**	**With Load**	**Without Load**	**With Load**
ISE	0.58	0.60	8.54	9.41	20.36	21.46
ITSE	2.74	4.49	145.46	226.69	293.03	397.71
IAE	2.81	3.301	21.23	25.61	27.17	32.83
ITAE	61.15	109.50	589.14	1018.15	546.11	1118.76
TV	16.97	21.18	12.65	14.59	19.35	22.50

Model 2 with both Time Delay and Process Gain Perturbations

Process Model $G_{p2} == \frac{0.05}{s} e^{-6s}$ Perturbed Process Model $G_{p2} == \frac{0.055}{s} e^{-6.6s}$

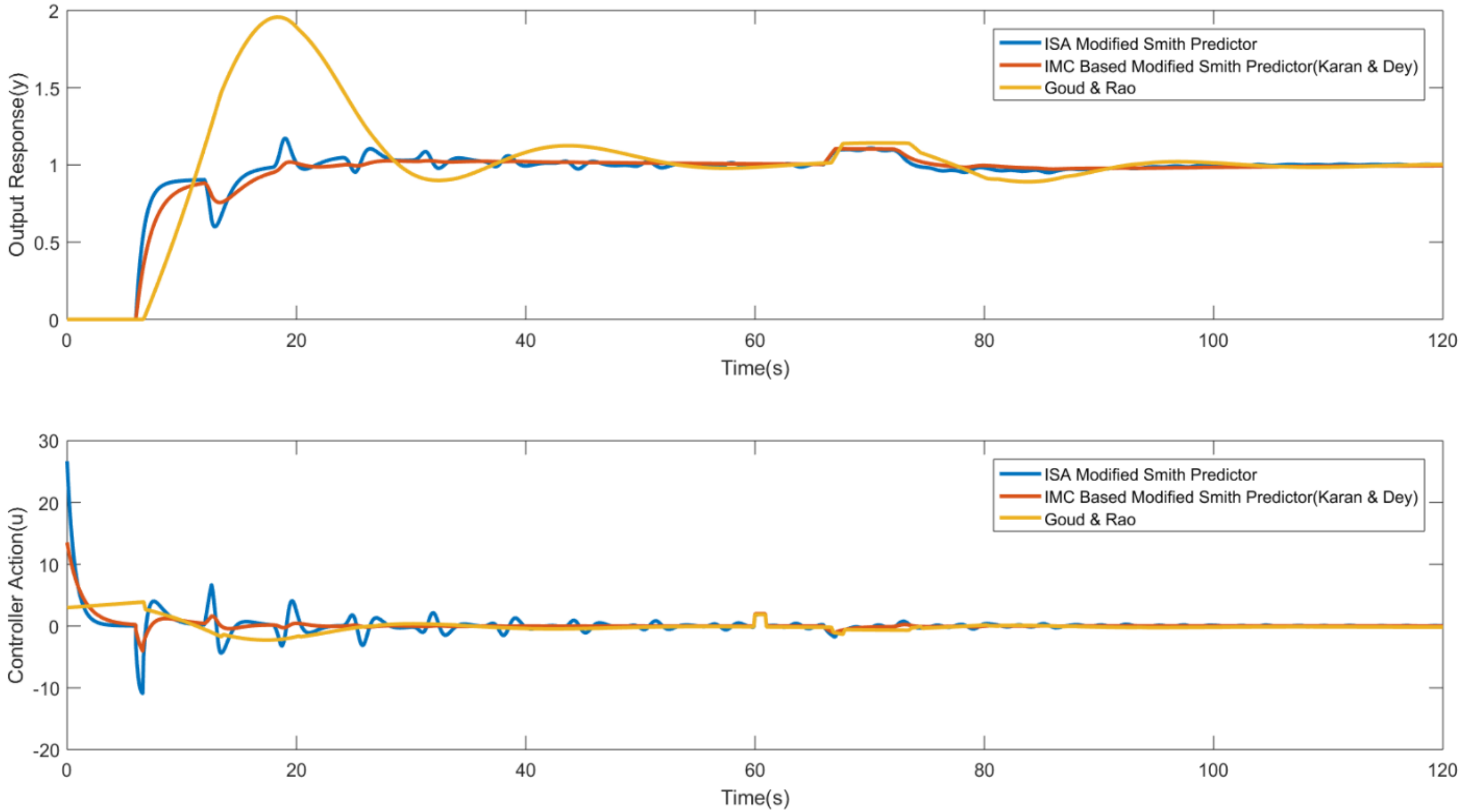


Fig. *Performance Index Analysis of the MSP and Recently Published Works for Model 2 for both 10% Time Delay and 10% Process Gain Perturbation*

***Table** Performance Index Analysis of the MSP and Recently Published Works for Model 2 for both 10% Time Delay and 10% Process Gain Perturbation*

Parameter	Modified Smith Predictor	IMC Based Modified Smith Predictor	Goud & Rao
Rise Time (Sec)	4.38	10.11	3.86
Settling Time (Sec)	50.83	40.46	58.75
Settling Min	0.60	0.90	0.90
Settling Max	1.17	1.03	1.96
Overshoot (%)	17.31	2.68	95.63
Undershoot (%)	0.00	0.00	0.00
Peak	1.17	1.03	1.96
Peak Time (Sec)	19.00	31.50	18.40

Performance Index	Modified Smith Predictor		IMC Based Modified Smith Predictor		Goud & Rao	
	Without Load	With Load	Without Load	With Load	Without Load	With Load
ISE	0.48	0.60	0.75	9.41	15.74	21.46
ITSE	1.83	4.49	0.99	226.69	177.80	397.71
IAE	2.30	3.301	2.20	25.61	21.10	32.83
ITAE	40.82	109.50	14.27	1018.15	325.70	1118.76
TV	68.13	21.18	28.08	14.59	68.32	22.50

Robustness and Stability Analysis

Table *Stability Analysis for Model 1 and Model 2*

Model	**Complementary Sensitivity Function (CSF)** C (jω)	**Process gain perturbation** (ΔK)	**Stability with gain perturbation** $\|C(j\omega)\|_\infty <$ $\left(\frac{1}{\frac{\Delta K}{K}}\right)$	**Time delay perturbation** (θ_m)	**Stability with time delay perturbation** $\|C(j\omega)\|_\infty <$ $\left(\frac{1}{\frac{-j\omega\theta m}{j\omega\frac{\theta m}{2}+1}}\right)$
$\frac{0.2}{s}\, e^{-7.4s}$	$\frac{7.44\, j\omega + 2}{1.38 j\omega^2 + 9.3 j\omega + 2}$	0.16 (+80%)	$\|C(j\omega)\|_\infty < \left(\frac{1}{0.80}\right)$	0.296 (+%4)	$\|C(j\omega)\|_\infty <$ $\left(\frac{j0.148\omega+1}{-j0.296\omega}\right)$
$\frac{0.05}{s}\, e^{-6s}$	$\frac{6.4\, j\omega + 2}{0.256 j\omega^2 + 8 j\omega + 2}$	0.035 (+70%)	$\|C(j\omega)\|_\infty < \left(\frac{1}{0.70}\right)$	0.06 (+%1)	$\|C(j\omega)\|_\infty <$ $\left(\frac{j0.3\omega+1}{-j0.06\omega}\right)$

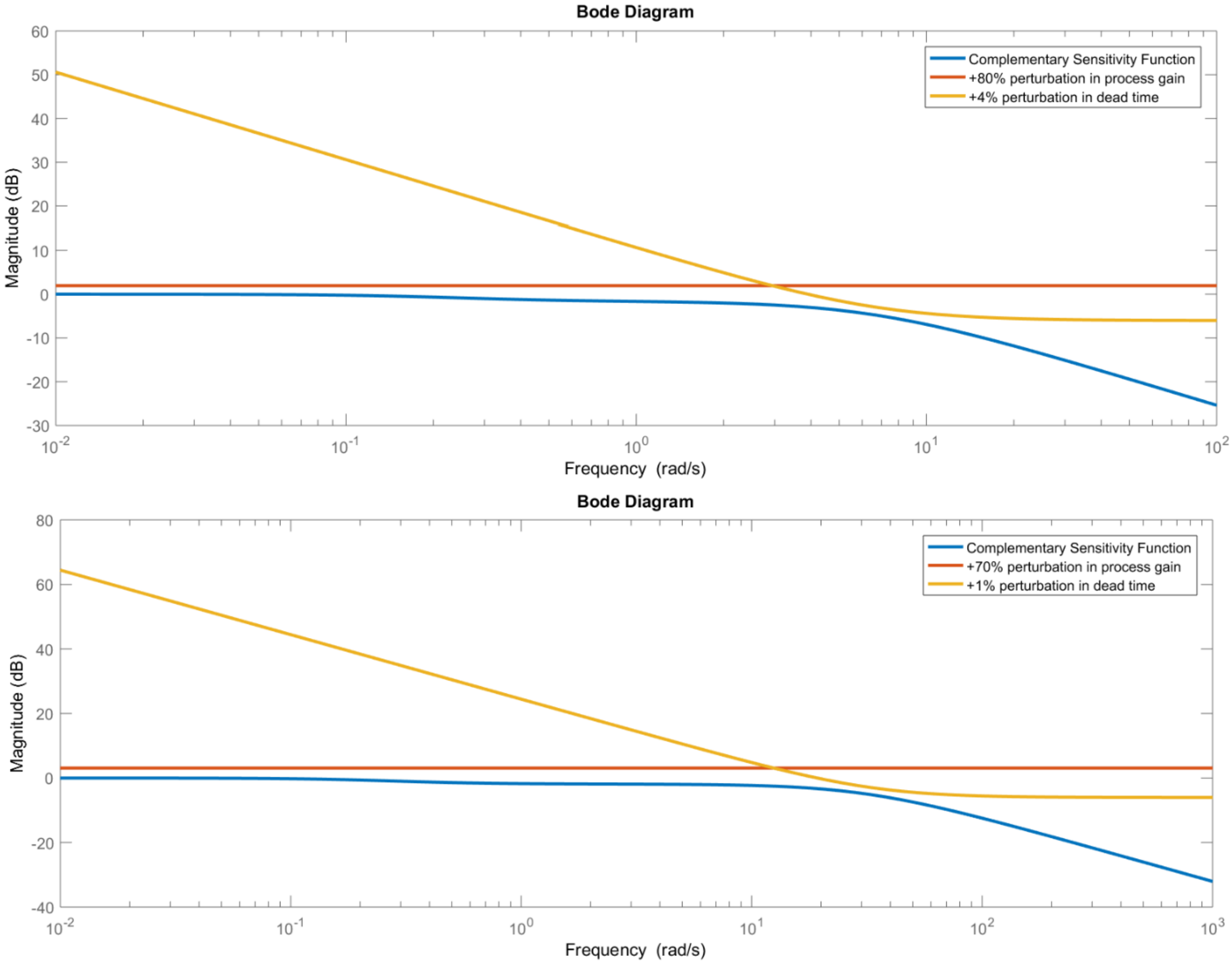


Fig. *Stability Analysis for Model 1 (above) and Model 2 (below)*

Observations and Conclusion

- MSP Based control techniques can be applied to various the integrating and unstable processes where conventional controller tuning techniques cannot be applied.
- MSP Based control techniques are capable of providing better performance than conventional tuning techniques in terms of closed-loop response and disturbance rejection even if the conventional technique was specifically tuned for that particular process.
- Compared to conventional Smith Predictor techniques, MSPs provide better overshoot compensation and disturbance rejection with proper tuning.
- MSP implemented in this project gives a satisfactory result in terms of response time, robustness and process disturbance rejection while being a general purpose technique that can be applied over a wide range of integrating process with large dead time

Future Scope

- Optimisation after evaluating performance with slower process with larger time delays and other types of process models such as Second Order Plus Dead Time Processes, Unstable Processes, Double Integrating Processes, etc.
- Implementation of improvements after performance evaluation in the practical world such as an unstable bioreactor where there exits unknown model uncertainties and disturbances
- Implementation of a system of controller-auto tuning which is a mechanism of tuning controller gains based on a plant model or plant data in real-time

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THANK YOU