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A Model Reference Adaptive Control (MRAC) System for the Pneumatic Valve of the Bottle Washer in Beverages Using Simulink

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Abstract

One of the most important processes in beverage manufacturing companies is the bottle washing process. When the bottles are returned from the customers they are first cleaned in the bottle washer before they can be reused. The pneumatic valve of the bottle washing machine which controls the discharge of clean bottles sometimes sticks or fails which results in significant loss of production in the plant since all the other processes which follow depend on the bottle washing machine. The main causes of failure are temperatures and pressure outside the required ranges, and also minor contributions by moisture and abrasive particles. These parameters were controlled by designing a Fuzzy Logic Controller using MATLAB and it was found that pressure and temperature should be maintained between 0.5 - 2.99 bars and 50 - 85˚C, respectively, with moisture levels at 2.5% and dust levels at 0.5 %. This is an artificial intelligent (AI) technique whereby the system will be able to plan, sense, reason, act and learn in a human intelligent way. Two solutions were developed to control the operation of the valve in cases of disturbances and non-linearity, namely; the Model Reference Adaptive Fuzzy Controller (MRAFC) and MRAC with PID controllers. Simulations were carried out and the MRAFC design showed excellent tracking results as compared to MRAC PID controller.

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Keywords: Model Reference Adaptive Control (MRAC), Pneumatic valve, Bottle washer, root cause, Model Reference Adaptive Fuzzy Control (MRAFC), Artificial Intelligence (AI).

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Nomenclature

h = the stroke of the valve
T = tension
θ = angle of tilt of valve
J= Polar second moment of area
c= Viscous damping coefficient (Nm/s)
m= mass of valve (kg)
g= acceleration due to gravity

1. Introduction and background

Beverage companies provide continuous food production by using highly automated systems to manufacture their products within a short period of time. The products manufactured include fruit juices, bottled water, carbonated and non-carbonated beverages, etc. [1-3]. Alcoholic products such as Lion Lager, Golden Pilsner, Zambezi Lager and Black Label are manufactured in beverage companies. Robots are mainly used in the beverage manufacturing industries [4, 5]. Robots are multifunctional, re-programmable manipulators which are designed to handle parts and move materials and tools [6]. The use of robots increases productivity, quality, safety, efficiency and consistency of products while the use of AI in robots enables the adaptation to the changing system dynamics [7]. Fuzzy logic (FL) uses mathematical theory, probability theory, and AI to enable the system to solve various problems using the human approach [8]. The Fuzzy Logic Controller (FLC) has better noise rejection and is more robust to the changing plant parameters as compared to PID controllers [9]. Compared to the conventional control method, the main advantage of the FLC is that no complex mathematical model is required for the system controller design. However, the FLC cannot adapt themselves to the changing environmental and operating conditions [10] but are capable of adjusting their behaviour from the execution of one rule to the next. It is therefore necessary to use some form of adaptation to achieve the desired requirements of the system to changing environmental and operating conditions. In this research the Model Reference Adaptive Control (MRAC) system is adapted to provide the adaptation required to achieve desired system performance. Most of the beverage companies use the Krones machinery in Germany. The Krones group of companies has its headquarters situated in Neutraubling, Germany [11]. This company specialises in developing, planning and manufacturing of machines such as bottle washers, bottling machines, packing machines, bottle fillers, palletisers, labellers and inspecting machines [11]. This paper is focusing on the pneumatic valve of the Krones Double-end Lavatek bottle washer.

Fig. 1: Krones bottle washer [11].

In beverages companies one of the most important processes is bottle washing. Glass bottles returned from the customers are reused hence a thorough cleaning of these bottles is required [12]. The bottles received are first conveyed into the bottle washing machine. The bottle washer is a machine which uses water and caustic soda solution to remove contaminants in the bottles. Bottles are fed into the machine and discharged at different positions to ensure maximum hygiene. The bottles are first pre-cleaned to remove any bottle fragments and granular contamination. They are then sprayed whilst they are upside down with rotating spraying nozzles, cleaning the inside of the bottles from different spraying positions. The outside of the bottles is cleaned by jetting units from above. The bottle washer uses a pneumatic valve which uses pneumatics to control the entering and discharge of the cleaned bottles. This valve consists of sensors and robots to control the movements. Before the bottles are discharged, the pneumatic valve should senses if the bottles are clean. The problem most beverage companies are facing is that this pneumatic valve is allows bottles to be discharged before they are clean. The unclean bottles are then rejected by the Fulls Bottle Inspector (FBI) hence, this increases costs as some of the bottles are broken [12]. The failure of the pneumatic valves results in the release of unclean bottles at times leads increased costs, delays and quality control problems. The production line at beverage companies should continuously run with less interference. MRAC can be used to automatically and continuously measure the desired output required with the dynamic system behaviour. This control process then uses the difference between the desired output and the behaviour of the system to vary the parameter of the systems hence, maintaining optimal performance. Problems which could lead to valve failure would be detected and corrected promptly, before the breakdown of the machine or the failure of the valve. For every one hour of downtime the company loses 42,000 bottles. Hence, the implementation of this artificial intelligent system will help reduce costs, energy, delays and rework. Quality control problems can also be reduced [4]. Model reference adaptive control is a class of adaptive systems which are designed to give a description of the desired outcomes of the plant being controlled, using a reference model [15]. The optimal system performance is achieved by taking measures to compensate for system disturbances and variations. The indirect control and direct control approaches are the classes of MRAC [16, 17].

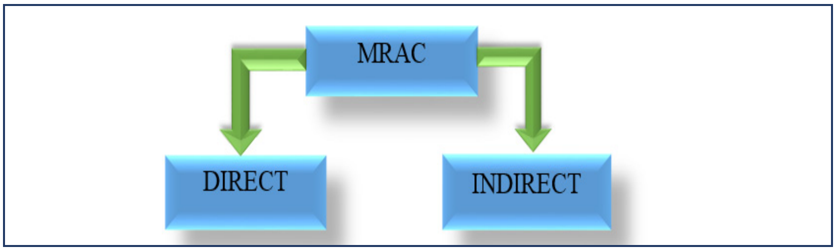

Fig. 2: Classes of MRAC

In the direct approach, the output error is minimized by directly adjusting the parameters of the appropriate controller structure. Before the control input is chosen, the indirect approach estimates the unknown plant parameters by using a model of the plant [16].

2. Materials and methods

Type of valve is $5/2$ way pneumatic valve, pneumatic connection is $G1/2$, standard nominal flow rate is 4500 litres/min, product weight is 1130 g, stroke is 500 mm, pressure operating range is 0 – 10 bars and number of cycles per minute is 60 1itres/min (for piston size 12 mm) [26]. The following tools were used;

- MATLAB 2011a software to simulate and model the fuzzy logic controller
- Simulink

3. Results and discussions

When failure occurs in any manufacturing process it is critical to identify and analyse the root causes leading to that failure. This helps to solve the real problem and to prevent recurrence. This section gives the possible causes of failure of the pneumatic valve of the Krones bottle washing machine using the Ishikawa diagram. A Mamdani fuzzy controller is also proposed in this chapter to model the error changes in the system due to its ability to capture expert knowledge, its intuitive nature which allows it to be used for decision support applications and it has a widespread acceptance. The parameters to be monitored in this design are temperature, pressure, dust, moisture regulation and tilt angle of the valve. Two possible simulations were carried out in this paper using triangular membership function, namely; the effect of temperature and pressure on the pneumatic valve and the effect of dust and moisture on the valve. The MRAC system for the valve was also developed using the PID controllers and FLC. The results were simulated using Simulink.

4. Model reference adaptive control of pneumatic valve using fuzzy logic controller

The model reference adaptive control mechanism using the fuzzy logic controller (MRAFC) is a scheme whereby adaptation mechanism of the systems will be performed by FL. The indirect approach of MRAC which is commonly used for controlling dynamic plants with unknown parameters is used for this design. The change of error and the error measured in the system is applied to the fuzzy logic adaptation mechanism (FLAM). The FLAM will in turn force the system to start behaving like the reference model. This will be achieved through the modification of the knowledge base of the FLC or it can also be achieved by adding to the FLC output an adaptation signal. This designed system will replace PID controllers with the fuzzy logic controller because the FLC is more robust to the changing plant parameters and they also have better noise rejection. The MIT rule is going to be used in this design. The model for MRAC using the MIT rule is represented in the figure below.

4.1. Valve free body diagram.

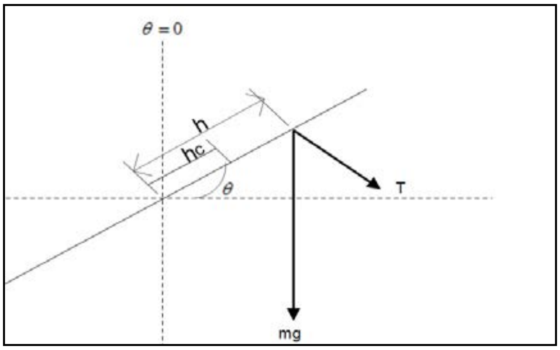

Fig. 3: Valve free body diagram

From Newton's laws of motion and the conservation of angular momentum, equation of motion for the valve:

$$J\ddot{\theta} + c\dot{\theta} + mgh_c \sin\theta = Th_1 \tag{1}$$

Assuming the valve balanced angle θ = 45°
From fig 3; internal diameter, d_2= 14mm
Let t= thickness of the cylinder
For a thin cylinder according to [24],

$$\text{Thickness}, t < \frac{1}{20} d_2 \tag{2}$$

∴ t<0.7 mm
Taking the thickness of the cylinder to be about 0.6 mm to ensure for safe design
d_1 = 14+ 0.6 +0.6 =15.2 mm

4.2. Adaptive mechanism

The adaptive mechanism designed will adjust the parameters in the control law and it also guarantees stability of the control system. The convergence of the tracking error to 0 is also guaranteed by this adaptive mechanism. Taking partial derivatives of e with respect to θ_1 and θ_2, the sensitivity derivatives can be determined. The reference input U_c is insignificant because it does not take into consideration the parameters.

$$y_{plant} = \left(\frac{0.534}{s^2 + 0.075s + 0.418}\right) u_c$$

$$\frac{d\theta_1}{dt} = -\gamma e \frac{\delta\theta}{\delta\theta_1} = -\gamma e \left(\frac{0.340}{s^2 + 0.075s + 0.418}\right) u_c \textit{ and;}$$

$$\frac{d\theta_2}{dt} = -\gamma \frac{\delta\theta}{\delta\theta_2} = \gamma e \left(\frac{0.340}{s^2 + 0.075s + 0.418}\right) y_{plant}$$

4.3. Reference model

$$\text{The reference model of the pneumatic value} = \frac{w_n^2}{s^2 + 2\delta\omega_n + \omega_n^2}$$

Where ω_n = natural frequency of the system= 53.95 rad/s

$$\delta = \text{damping ratio} = 0.9$$

$$= \frac{2910{,}6}{s^2 + 97.1s + 2910.6}$$

4.4. Proposed mrafc scheme

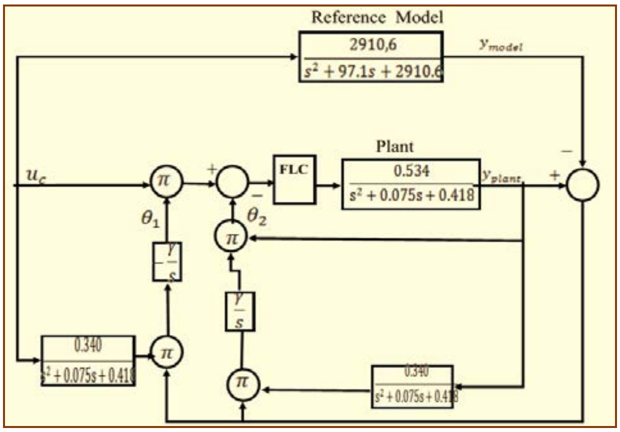

Fig 4: Proposed block diagram of MRAC using the MIT rule

Fig.4 shows the proposed design of the model reference adaptive fuzzy logic control system using the MIT rule. The difference between y_{plant} and y_{model} is used to tune the fuzzy controllers rules. The controller output will then determine whether the valve should be fully open, open or closed. This design was tested using Simulink to test whether the plant will follow the reference model to reduce error and give the desired performance. The simulink models of MRAC using PID, MRAC with FLC and PID control of the system are going to be developed.

4.5. Simulink model of mrac using pid control

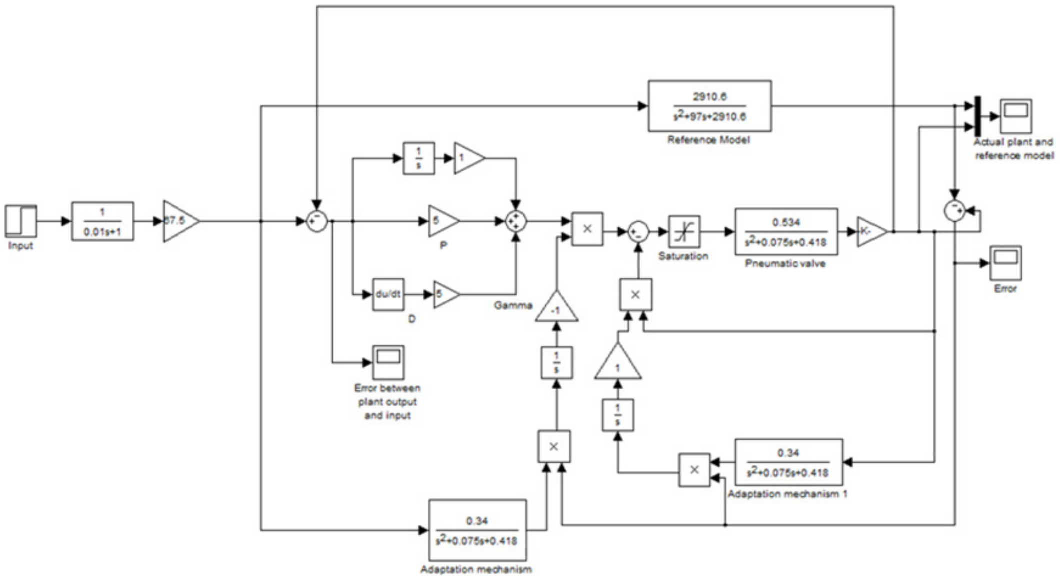

Fig 5: Simulink Model of Valve using MRAC with PID controller

4.6. Simulation results and discussion of MRAC using PID control

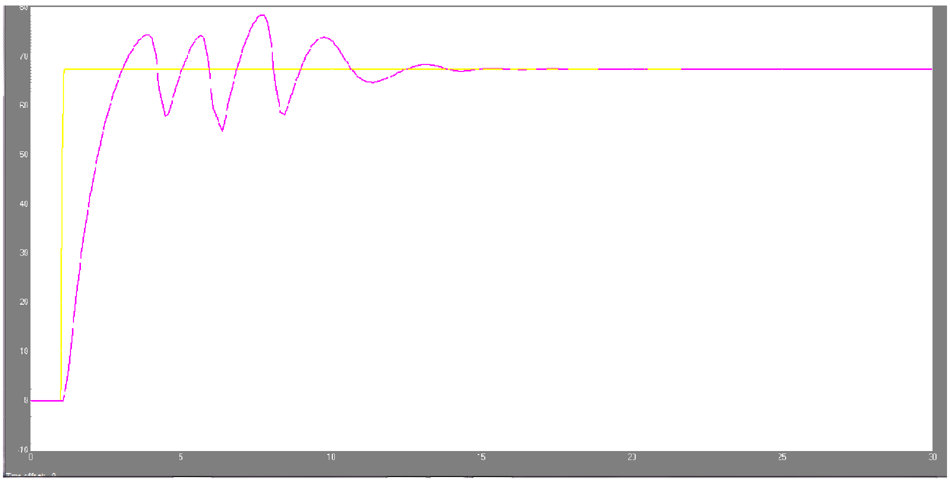

Fig 6: Actual plant and reference model

The simulation results of the valve using MRAC with PID controller is shown in fig.6. The results show the transient response of the system before a steady state value is reached. The system was designed with a set point temperature of 67.5℃. Since pressure supplied does not affect the valve operation, the system was only tested for temperature conditions. The properties of this system are given in Table 1 below. The Yellow line represents the Reference model (desired system performance) and the Purple line shows the Actual performance of the valve with respect to time. Therefore, implementation of the adaptive control mechanism to the non-linear system using PID controllers results in the improved system behaviour. Poor performance usually arises when using PID controllers alone especially when the loop gains of the PID must be reduced so as reduce or eliminate system overshoot and oscillations. The addition of the adaptive control mechanism results in the reduced system oscillations and overshoots with time.

Table 1: MRAC PID system response

Parameter	MRAC PID
Overshoot (˚ C)	11.5
Settling time (s)	13
Transient	Present
Rise time (s)	3.125

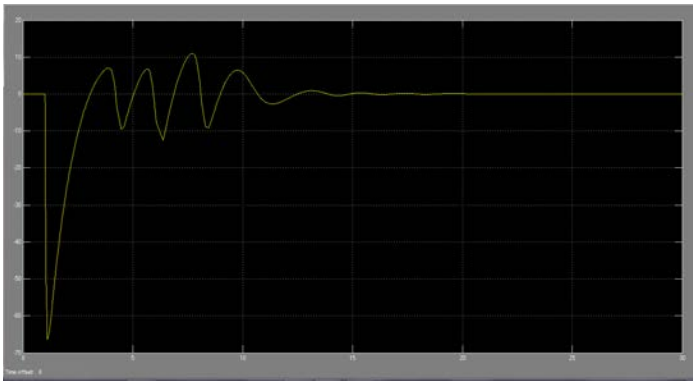

Fig 7: Error between system output and reference model

The difference between the reference model output and system output is shown in Fig.7. The error tends to zero as the system reaches a steady state. During the transient response of the system the values of the error produced will be oscillating.

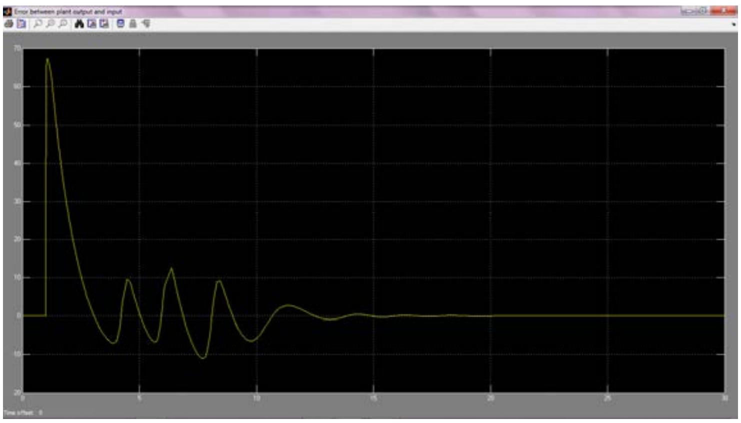

Fig. 8: Error between actual system output and input

Fig. 8 shows that after the system reaches a steady state value the system output will achieve the desired set point. The error increases from 0 – 67.5 and then decreases gradually to 0.

4.7. Simulink model of MRAC using fuzzy logic controller (MRAFC)

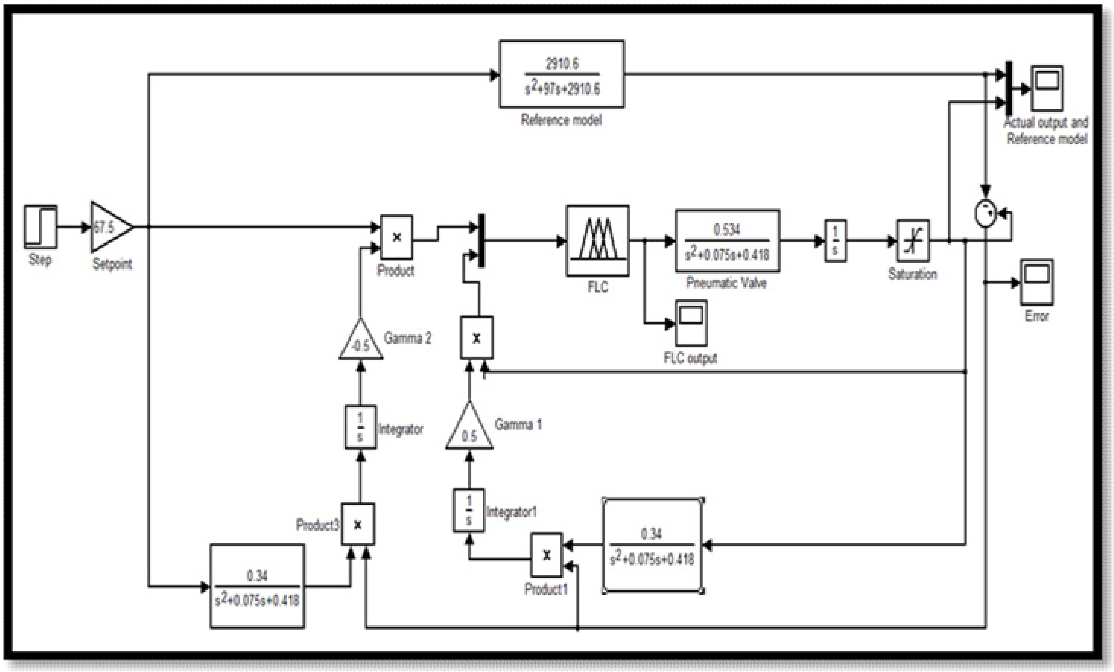

Fig 9: Simulink model for Valve using MRAFC

This system uses the FLC to control the valve operation.

5. Recommendations and conclusion

5.1. Recommendations

The FLC model was developed for the valve after the root cause analysis of the problems leading to the sticking and failure. The controller controls the temperature ranges, pressure, dust and moisture leading to the sticking of the valve. From the fuzzy logic rule viewer, it is recommended that the dust should be kept between 0 and 0.55 %. Dust can cause scoring and wearing of the valve material which could lead to the failure of the valve. Maintaining the levels of dust in the required ranges can result in the reduced number of breakdowns of the bottle washing machine. Reducing the number of breakdowns will result in increased production and operating efficiency and thereby reducing losses. It is also recommended that the temperature should be maintained between 50 and 85^{o}C. Deviation from the recommended operating temperature could lead to the damage of the valve over time hence causing breakdowns which could also result in significant loss of production. The valve should be fully opened within the required ranges of temperature. The ranges of pressures recommended are between 0.51 – 2.99 bars within which the valve will function optimally. This can be achieved by implementing the AI system on the bottle washing machine to control the opening of the valve in response to the changing environmental conditions The current controllers used on the bottle washer are the PID controllers. In the presence of non- linearity, they do not provide optimal control due to their inability to react to the behaviour changes of the process and also the lagging effect in response to large disturbances. Therefore it is recommended to implement the artificial intelligent system, MRAFC, which adapts to the changing process behaviour of the system and produce the desired output. The Implementation of MRAFC to the pneumatic valve will improve the steady state performance in the presence of non-linearity or disturbances within the system.

5.2. Conclusion

The main objective of this research was to analyse the root causes leading to the sticking and failing of the pneumatic valve of the Krones bottle washing machine and to develop an artificial intelligent system that would help reduce the frequency of sticking and failure of the pneumatic valve and hence, reduce breakdowns of the bottle washing machine. The root cause analysis showed that temperature, pressure, and minor contributions dust and moisture were the main causes leading to the sticking of the valve. The AI system should learn the process dynamics of the valve and be able to adjust the valve angle in response to the conditions. The MRAFC scheme was proposed for the control of the pneumatic valve. A comparison between the MRAFC and MRAC with PID controllers was carried out using simulations and the MRAFC controller proposed showed excellent tracking results as compared to MRAC PID controller. The simulation results showed that transient performance of the system can be improved significantly by the proposed MRAFC scheme.

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