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FUZZY LOGIC-BASED CURRENT CONTROL LOGIC FOR PROPORTIONAL FLOW CONTROL VALVE SYSTEM OF MEDICAL VENTILATORS

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Abstract

The critical control parameters in ventilators that provide life support to patients are the flow of air and oxygen. Ventilators typically use Proportional Flow Control Valves (PFCV) and flow sensors to achieve precise flow accuracy. Maintaining accurate flow from the PFCV is essential to minimize the thrust exerted on the patient's lungs. Fuzzy logic is particularly well-suited for this task, as it effectively captures the subjective human judgments often required in clinical settings. This study aimed to develop a fuzzy logic algorithm to control pressure support ventilation. The research describes the fuzzy logic algorithm and presents experimental studies that evaluated the flow accuracy of a commercially used PFCV in ventilators. Additionally, the reduction in output flow due to thermal effects was investigated. A correlation between the solenoid coil current (measured as voltage across the coil) and the actual output flow through the PFCV was experimentally established using a current sensing circuit. Based on the characteristic curves obtained from the test setup, a Fuzzy Logic system was developed to minimize the error in the PFCV's flow. The implementation of PFCV using this Fuzzy Logic-based current control approach demonstrated a significant reduction in error, from 10% to 3%, in airflow delivery across its operating range, with additional sample results discussed. This reduction in flow error is crucial for assessing the suitability of PFCVs in infant ventilators. The described methodology can be experimentally applied to any PFCV variant before its use in medical ventilator applications to enhance delivered flow accuracy.

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Key words: PFCV, current-control system, calibration, flow sensor, flow sensor measurement

Introduction. A medical ventilator is an electro-pneumatic device designed to deliver an air-oxygen mixture to a patient, typically an adult. The ventilator unit broadly consists of monitoring devices that measure the volume of the air-oxygen mixture entering and exiting the patient's lungs. The key parameters that must be controlled during the ventilation process include respiratory rate, tidal volume, inspiratory time, and the fraction of O_2 [1]. An infant ventilator is another electro-pneumatic device, similar to an adult ventilator, but it delivers a smaller amount of air-oxygen mixture, typically in the range of 1 to 30 liters per minute (lpm), with precise control at lower pressures, generally between 5 to 25 cm of H_2O. The infant ventilator also provides smooth airflow that synchronizes with the infant's natural breathing patterns, thereby reducing strain on the lungs. Respiratory system diseases are a significant concern, accounting for 22% of infant mortality in India [2]. Similar observations have been reported globally, emphasizing the need for effective respiratory improvement strategies to keep infants alive. Implementing such strategies is crucial in various parts of the world to address the high mortality rates associated with respiratory system diseases in infants [2].

The design of ventilators becomes complex due to the variability in delivered tidal volumes. For a target tidal volume of 8 ml/kg, the actual delivered tidal volumes across different ventilators can range from 3.6 to 11.4 ml/kg. This variability poses a challenge in ensuring consistent and precise ventilation, especially in critical care settings [3]. The reported errors in ventilators are often linked to discrepancies between the target tidal volume and the actual volume delivered, which is adjusted based on the child's weight. Proportional Flow Control Valves (PFCVs) available in the market exhibit a significant reduction in delivered flow rates for any given flow setting prescribed by doctors. This reduction in flow is influenced by operating temperature, which tends to fluctuate during the ventilator's operation in real-world conditions [3]. Borrello [4] addresses the challenges of flow control in ventilation using the synthesis method of Model Reference Adaptive Control (MRAC). In this approach, the valve transfer function is represented as a variable "constant", leading to the design of a simple controller with a single degree of freedom. Lee et al. [5] addressed the issue using a simulation tool for a non-linear model-based adaptive control approach. The results of their study are discussed in their findings. An adaptive inverse hysteresis module was employed to mitigate the effects of hysteresis, allowing for rapid changes in the operating points of the proportional flow control valve [6]. High-frequency oscillating PFCVs permit spontaneous breathing [7]. Dynamic response of Pulse Width Modulation driven ON/OFF, PFCV valve showed that the output flow smoothly followed the reference flow patterns [8]. Current sensing circuits employed in such applications, to sense the coil voltage of solenoids are discussed in the application note [9, 10].

Thus, one of the critical challenges in designing medical ventilators is the experimental assessment of the accuracy of the proportional flow control valves (PFCVs) used. Minimizing the output flow error of these PFCVs is essential for evaluating their suitability for infant ventilators. In infant ventilators, significant errors in the actual flow delivered by the PFCV could have serious consequences for the child's health. Therefore, precise control of the air and oxygen flow rates is crucial for ensuring the safety and effectiveness of infant ventilators [11].

This paper investigates a commercially available proportional flow control valve (PFCV) used in medical ventilators by experimentally characterizing its flow variation and estimating the error in the output flow over time. The error is significantly reduced by developing a Fuzzy Logic feedback system applied to the valve's current control system. The suitability of this valve for precision flow control in applications such as infant ventilators is examined, and the results are discussed.

Proposed methodology. The proportional flow control valve is a crucial component that regulates the flow of air and oxygen at a pre-determined rate to meet the patient's requirements [1]. The proportional flow control valve (PFCV) studied is a commercially available model capable of delivering a flow of up to 120 liters per minute (lpm) at 2 bar pressure. For its application in infant ventilators, it is crucial that the error in the actual flow delivered by the valve is minimal.

In this work, the performance characteristics of the PFCV were experimentally established using a test setup. The error values in the actual output flow were measured with a TSI Mass Flow Sensor 4040. Typical results of the set flow versus the actual measured flow are illustrated in Fig. 1. The actual measured values of flow, Q_{actual} are plotted for two typical sets of values of flow, Q_{target} i.e. 65 lpm and 20 lpm, as a function of time. In Fig. 1, one set-value of flow equals 65 lpm, corresponding to the mid-range of the PFCV (0–120 lpm); the other set-flow value, was selected in the lower range i.e. 20 lpm, which is typically a flow that is appropriate for infant ventilators. It can be observed that the actual measured flows are consistently lower than the set values in both typical cases when monitored over time. The errors in flow were found to be 6.4 liters per minute (lpm) and 8 lpm in the steady-state, corresponding to set values of Q_{target} equal to 65 lpm and 20 lpm, respectively.

The observed flow errors, ranging from 10% to 40%, are significant and highlight the need to minimize these errors without resorting to high-cost, high-accuracy hardware solutions. The PFCV is equipped with a driver circuit that requires a specific supply voltage to deliver a given set flow, as defined by its manufacturer's characteristic curve. The decrease in flow is primarily attributed to the heating of the coil in the PFCV over time, which increases the coil's resistance. This increase in resistance reduces the current flow for a given applied voltage to the electric coil of the PFCV. [8]. The following section outlines the methodology used to reduce the errors in the output flow of the PFCV for various

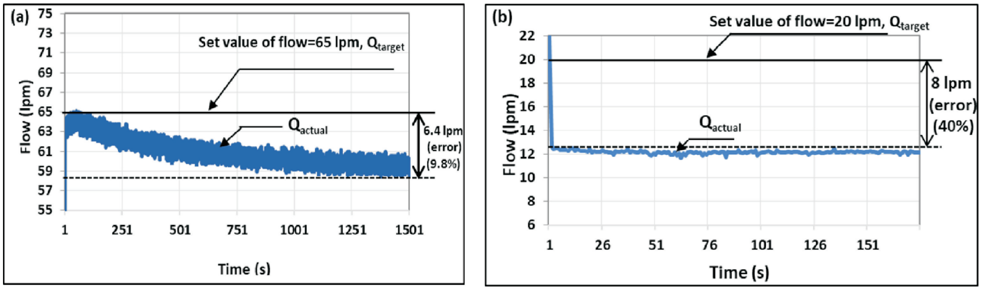

Fig. 1. Variation of measured output flow (lpm) of PFCV concerning time, for two different set values of flows, Q_{target} (a) 65 lpm (b) 20 lpm

set flow values within its operating range.

PWM actuation of proportional flow control valve. The proportional solenoid valve can be actuated with variable DC voltage. However, friction at the guiding point of the plunger leads to poor response sensitivity, high hysteresis, and a step-like structure in the characteristic curves (stick-slip effect). To mitigate this effect, the standard input signal is converted into a pulse-width modulated (PWM) solenoid excitation. This PWM signal causes the plunger to oscillate around its equilibrium position with low amplitude, maintaining it in its sliding friction state. Consequently, the PFCV is actuated using a PWM voltage signal [8].

The PWM frequency was set to 2.5 kHz to match the intrinsic frequency and attenuation of the spring-plunger system, as well as the inductance of the magnetic circuit. Higher PWM frequencies, such as 50 kHz, resulted in very short ON and OFF times, which were unsuitable for precise voltage control during flow adjustments. Conversely, lower frequencies, such as 100 Hz, introduced undesirable noise into the proportional flow control valve. Thus, an optimal frequency of 2.5 kHz was selected for the PWM, enabling a 1% variation in set flow to produce a flow change of 0.01 lpm, which is sufficient for infant ventilator applications [13]. The next crucial component of the test setup is the current control system, which is detailed in the following section.

Current control system. The preliminary correlation between the output flow from the PFCV and the voltage difference across the coil was experimentally established for various output flows using the described setup. The flow sensor measured the output flow from the PFCV, while the PIC24 microcontroller was programmed to regulate different coil voltage values. The output flow was then measured using the TSI flow sensor. By controlling the current to a predetermined value, the desired flow can now be accurately maintained.

Calibration of the PFCV using the current control method. To determine the performance characteristics of PFCV using the current control method, the voltage across the coil was incremented in steps of 0.027 V, corresponding to 1% of the duty cycle of the valve. This process is referred to as increasing flow data collection.

I. Coil voltage from the current sensing circuit

II. Airflow using TSI flow Sensor

The salient steps in the calibration process are listed below:

- The 80% duty cycle was maintained for a prolonged duration to ensure the coil gets self-heated adequately.
- The duty cycle was decremented from 80% to 30% in steps of 1% and the above-mentioned data were monitored and stored. This is called the decreasing flow of data collection. Similarly, an increasing flow of data collection was also made.
- The above increasing flow and decreasing flow data collection process was repeated 10 times under different temperature conditions to maintain consistency; the coil temperature could not be measured due to practical difficulties.
- The average values of output flow, Q_{actual} and the corresponding coil voltage V_c for different duty cycles were computed and a fourth-order polynomial curve was fit for the above data as in Eq. 1. The statistical parameter r^2 value, coefficient of determination was estimated and the same was found to be satisfactory.

The calibration of the valve was done for different temperature conditions with sufficient and varied time intervals. The coil voltage and the flow were logged onto a measurement file and the results were recorded. A typical calibration data of the PFCV valve was conducted for the duty cycle varying from 30% to 70% in steps of 1% of the associated coil voltage, V_c (V) (which monitors the coil current) and the measured flow Q_{actual} (lpm) for both the cases of (i) increasing flow and (ii) decreasing flow were observed. The independent variable, coil voltage, V_c (V) was plotted in the y-axis, keeping in mind the future utility of the above graph, i.e., estimating the coil voltage, to meet a specified flow requirement, Q_{actual}, in a given application. A fourth-order polynomial equation was fit using MATLAB to the curve of coil voltage, V_c (V), versus output airflow, Q_{actual} (lpm) obtained experimentally.

$$(1)\quad V_c = -1.21E{-}08(Q_{actual})^4 + 3.27E{-}06(Q_{actual})^3 - 3.02E{-}04(Q_{actual})^2 + 1.83E{-}02(Q_{actual}) + 7.73E{-}01,$$

where V_c is the coil to voltage (V) and Q_{actual} refers to the flow of PFCV to be achieved (lpm).

The coefficient of determination, r^2 was found to be 0.998 using MATLAB; it is useful because it gives the proportion of the variance of the predicted variable, the output flow of PFCV, Q_{actual} which is estimated by varying the independent variable, i.e., coil voltage, V_c. This measure helps determine the confidence level in making predictions based on the study. The duty cycle is converted into a corresponding hexadecimal value, which is then sent to the microcontroller to generate the PWM signal with the required duty cycle.

Fuzzy logic controller. This section introduces Fuzzy Logic Control (FLC) methods, which aim to mimic human behaviour and reasoning. Unlike binary True/False logic, which cannot fully capture human cognition, FLC utilizes a continuous range from 0 (False) to 1 (True) to represent human thought processes. An FLC system operates using rules of the form: IF-THEN (control action). This approach is applicable in real-world scenarios, such as controlling a plant. The Mamdani fuzzy inference technique was employed due to its straightforward min-max structure. Expert knowledge and control engineering principles have been applied to develop the IF-THEN rules used in this technique. [12]. Finally, all defuzzification experiments employed the centroid (centre of gravity) technique. This approach analyzes the centre of the curve to determine the most representative value for the fuzzy set.

Membership function. In this scenario, the challenge has been reduced to two inputs and one output. The input variables are e(k) and r(k), which pertain to error in flow, ΔQ_{actual} and rate of change of flow $\Delta Q_{actual}/\Delta t$, the output u(k) being flow (Q_{actual}), respectively. These variables have three linguistic values – {Negative (N), Zero (ZE), Positive (P)}.

To reduce the variability in the output flow, Q of the PFCV, the fuzzy control algorithm – rule base was employed to minimize flow oscillations. It has IF-THEN rules with antecedent and consequent portions based on fuzzy system inputs and output (e, r, u) (k). This was done using Mamdani min-max inference. IF-THEN rules were created by experts with control engineering backgrounds as shown in Table 1. Depending on the relation between the error and the rate of change of error, the flow was increased, lowered or maintained. In Table 1, S represents increase in flow, M represents maintaining the same flow, and L represents lowering the flow.

Table 1

Fuzzy logic rule matrix

Error, e(k)	Rate of change of error, r(k)		
	N	ZE	P
N	S	S	M
ZE	S	M	L
P	M	L	L

This section describes the results of the implementation of the current control strategy, in realizing a target flow with minimal error. The following are the steps involved:

- Set the desired flow (Q_{actual}) in the front panel.

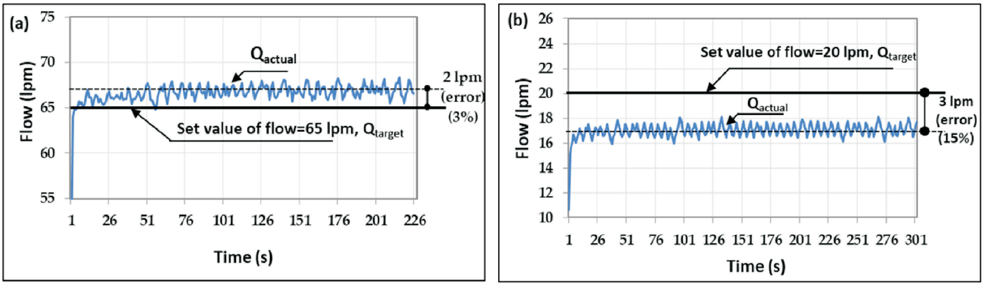

Fig. 2. Variation of measured output flow, Q_{actual}(lpm) of PFCV concerning time (s), for two different set values of flows, Q_{target} (a) 65 lpm (b) 20 lpm, based on current control logic method

- The percentage of the duty cycle for the desired flow is computed from the calibration data.
- Using Fig. 2, and Eq. 1, the coil voltage, V_c required to be maintained for the set flow (Q_{target}) is estimated.
- The duty cycle is increased or decreased in steps of 0.5% to meet the estimated coil voltage (V_c). The increment/decrement step of 0.5% was finalized by trial and error, to limit both settling time and overshoot error.
- The Fuzzy Logic Control is superimposed on the current control approach discussed in the previous section.

Results and discussions. Typical results of the implementation of the current control using the Fuzzy Logic Control (FLC) approach for 65 lpm and 20 lpm set-flow (Q_{target}) requirements of the PFCV are shown in Fig. 2. There is a significant reduction in error, with the errors being 2 lpm and 3 lpm for the respective set values. The range of errors decreased from 11–40% (as shown in Fig. 1) to 3–15%. This major reduction in error is attributed to the control strategy, which directly monitors the appropriate coil voltage to meet the set-flow while accounting for thermal effects.

However, the final error values still exhibit some scatter due to variations in calibration curves obtained for the valve when duty cycles were incremented and decremented multiple times. The calibration curves' path-dependence, as evident from Fig. 2, contributes to this inherent scatter. The negative error (-3 lpm) corresponding to $Q_{target} = 20$ lpm poses a risk of hypoventilation, where the ventilator delivers less volume than it measures [3].

Conclusion. In conclusion, an algorithm has been developed for adjusting ventilation using measurements of Q_{actual} and Q_{target} based on fuzzy logic and current controlled logic. This algorithm dynamically adjusts the Q_{actual} support level depending on evaluations and status changes. However, the controller exhibits increased oscillation and overshooting compared to simulations with constant lung compliance. The results demonstrate a significant reduction in the error of the actual flow delivered by the commercially available PFCV when applying fuzzy logic to the PFCV's flow characteristic curves. Such a reduction is crucial for assessing the suitability of the PFCV for infant ventilators. This process can be experimentally applied before using any PFCV variant in medical ventilator applications to enhance flow accuracy.

Future work will focus on expanding these investigations to include the effects of parameters related to chest wall and lung mechanics, such as compliance and resistance, on the delivered flow accuracy of PFCVs. Additionally, the load-side impedance is expected to play a crucial role in the output flow characteristics of PFCVs used in medical ventilators.

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