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Dynamic analysis and fuzzy logic control for the vane-type air motor †

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Abstract

Air motors are widely used in the automation industry with special requirements, such as park-prohibited environments, mining, chemical manufacturing, and so on. However, during the past only few literatures discussed the dynamics of air motors or their control strategies. The purpose of this paper is to analyze the dynamics of a vane-type air motor, and design a fuzzy logic controller. It is found that the rotational speed of the air motor is strongly affected by the pressure and flow rate of the compressed air. Further, due to the mechanical friction, the overall system is actually nonlinear with dead-zone and has hysteretic behavior. The performance of conventional PI controllers implemented on the air motor usually results in large overshoot, slow response and significant fluctuation errors. To cope with the nonlinear effects of dead-zone and hysteretic behavior, we developed a fuzzy logic controller to improve the performance. The experimental results show that the proposed controller can effectively control the system with a settling time within 0.2 second, the error fluctuation less than 0.5% for high speed operation and 1.5% for low speed operation, and without any overshoot.

Keywords: Air motor; Dead-zone; Hysteresis; Fuzzy control design

1. Introduction

Modern automation techniques have been helping manufacturers to improve product quality and reduce process cost. Although electrical motors are still the main conveying devices in most manufacturing plants, air motors have attracted more and more attention during the past few decades because they are cheaper, safer, cleaner, smoother and more efficient (by maintaining higher power to weight ratio) [1-4]. Moreover, at some special locations, such as spark-prohibited environments, mining industry plants, chemical manufactories, vehicles and/or storages with explosive materials, etc., the air motor will be the better, and sometimes the only, feasible device to be used.

For many applications, air motors are employed in situations with lower precision requirement. However, due to the accuracy consideration, the demand for better performance (in terms of higher precision and faster response) for air motors has become more and more dominating, and has attracted many research works [5-8] in recent years. But the air motors discussed in these articles were mostly operated at low speed range up to 1000 rpm, which in general limits the applications of these air motors. In this paper, we will analyze the dynamics and design a fuzzy logic controller for a vane type air motor, and the overall controlled systems will be tested through experiments from low to high speeds.

An air motor converts the energy of compressed air into mechanical energy. In general, air motors demonstrate highly nonlinear behaviors due to the compressibility of air and the frictions of the mechanisms. In previous articles [5-8], there had been several investigations and analyses on the dynamics of air motors. In [5], a linear system model was developed by

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considering all nonlinear phenomena as un-modeled uncertainties. A fourth-order nonlinear model was developed in [6] and its parameters were identified through experiment data. However, this model has a large number of parameters and hence the process of deriving these parameters is complicated and time consuming. A different approach of using neural network techniques is proposed in [7]. Instead of using a high order nonlinear model, a neural-model reference control was proposed to control the rotational speed of the air motor. The air motors described in previous articles were mostly operated at low speed range and the controller parameters may not work well for high-speed range operation.

The purpose of this research is to investigate the dynamics of the air motor and develop a suitable controller for all range of speed operation. It is found that the control parameters should be chosen differently for different reference speeds, and for different response time to obtain best performance. However, a sudden switch of parameters does not improve the performance and may induce uncertain dynamics. Hence, the fuzzy logic control for smoothing different rules [9] was implemented in this paper to improve the performance of the system. The fuzzy logic control has been discussed in many articles for nonlinear systems [9-11], but few have dealt with the applications for hysteretic systems such as air motors. Basically, a fuzzy logic controller contains three major processes [10, 11]: fuzzification, fuzzy inference and defuzzification. In the fuzzification process, the physical measurements are transformed to fuzzy variables, which are described by fuzzy sets [12]. The rules used in the fuzzy inference process are usually created according to experts' experience and knowledge [9-11]. The control results as fuzzy variables are induced through fuzzy set operations based on these rules. In the defuzzification process, these results are used to calculate the physical control inputs, such as voltages, currents, and so on. In [13], the mode reference adaptive control (MRAC) is proposed with fuzzy control to eliminate the dead-zone caused by friction in an air motor system. The experimental results showed that the MRAC could be tracked and that an accurate speed control performance was attainable. In this paper, we will apply the fuzzy smoothing control algorithms to smooth the switching between different control rules and obtain faster, non-overshooting and less chattering response for air motor control. The fuzzy smoothing control proposed in this paper can be effective to achieve precise performance on velocity control.

The following sections are organized as follows. The introduction to a vane type air motor system is described in Section 2, its system dynamics is analyzed in Section 3, the traditional PI control and the modified fuzzy smoothing control are discussed in Section 4, the experiment results are also shown in Section 4, and the conclusion is stated in Section 5.

2. Vane type air motor system

Fig. 1 shows a sketch map of a vane-type air motor. There is a rotational drive shaft with four slots; each slot is fitted with a freely sliding rectangular vane. When the drive shaft starts to rotate, the vanes tend to slide outwards due to centrifugal force but are limited by the shape of the rotor housing. Depending on the flow direction, this motor can rotate in either clockwise or counterclockwise directions. The difference of air pressure at the inlet and outlet will provide the torque required to move the shaft. Hence, higher flow rate and larger pressure difference will create a larger toque on the shaft and a higher rotational speed.

The air motor system, as shown in Fig. 2, consists of an air motor (GAST 1AM), an air tank, an electronic proportional directional control valve (FESTO MPVE), a filter/regulator with lubricant (SHAKO FRL-600) and a digital signal processor (DSP, TI C240). The airflow path starts from the air tank through the filter, control valve and finally enters the air motor. The airflow entry of motor will be determined by the valve position, which is controlled by externally applied voltage, denoted by v. When v equals 5V, the valve will stay at the middle and both left and right entries are closed. The valve will move to a right position when v is above 5V and fully opened when v reaches 10V. Similarly, the valve will move left if v is less than 5V and will be fully opened

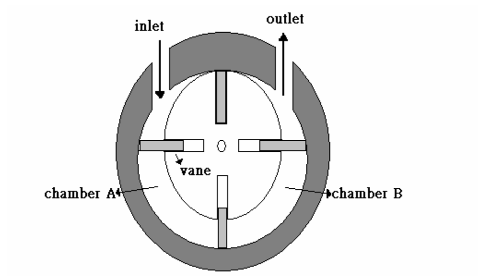

Fig. 1. Vane-type air motor.

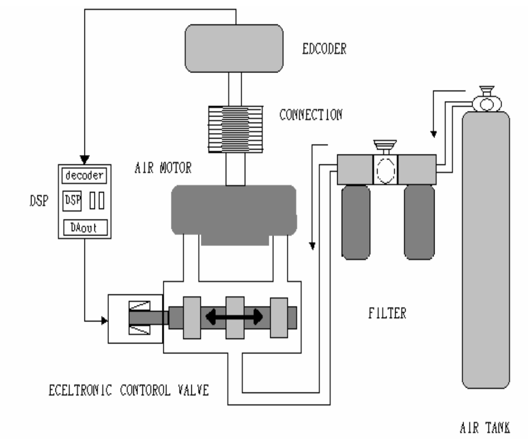

Fig. 2. The schematic diagram of the air motor system.

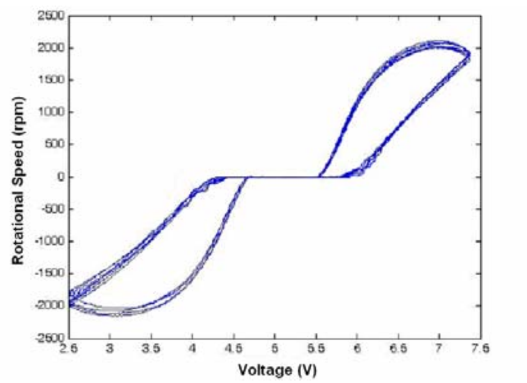

Fig. 3. The static relationship between the applied voltage and rotational speed.

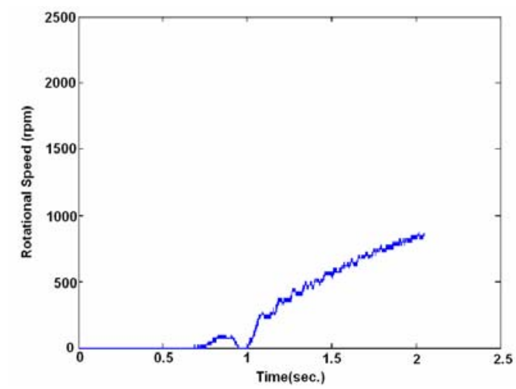

Fig. 4. Time response for input voltage equal to 6.2V.

at 0V. The direction of the air motor depended on whether the voltage *v* is above or below 5V. The control input from DSP, denoted by *u*, will be converted into *v* as $v=u+5$.

3. System dynamics and nonlinear behaviors of air motor system

Fig. 3 shows results of the experiments we designed for researching the relationship between the applied input voltage and the rotational speed of the air motor. During the experiment, the control input *u* was adjusted following the cycle 0V→ 2.5V→ -2.5V→ 0V with a two-second period. It is found that there were dead-zone and hysteretic phenomena in this system. The voltage-speed curve in Fig. 3 demonstrated different relationships during the voltage increasing and decreasing procedures. During the increasing procedure, the motor remained motionless when the voltage is less than 1V. After exceeding 1V, the voltage and rotational speed demonstrated a linear relationship. When the voltage was reduced from 2.5V to 0V, the speed-voltage relationship did not follow the same rising path but demonstrated a nonlinear behavior. The motor stopped around 0.8V instead of 1V. Similar results were found for the procedures with voltage below 0V.

From the experiment results, we found the dead zone spanning from -1.5V to 1V on the way up and from 0.8V to -0.6V on the way down. These phenomena were due to the friction in the mechanism and the pressure drop of the supply air at the starting moment. During the experiments, we found that the air pressure dropped about $0.8\,kg/cm^2$ just at the moment of valve opening. For instance, if the air pressure was set to $1\,kg/cm^2$, the actual air pressure at the moment of valve opening would drop to $0.2\,kg/cm^2$, which was not enough to overcome the static friction and hence caused a delay in the system's response. Fig. 4 shows the time response of the air motor when the voltage is set at 1.2V. The time delay was about 0.7 second before the air motor started to rotate. Note that the speed dropped to zero again right after it moved. This is because the space of air motor's chamber expanded at that moment and hence caused the air pressure to drop to a lower value. If the setting voltage was large enough, the time delay phenomenon will not be so obvious. This is because the air pressure, even with the pressure drop at the beginning, is large enough to overcome the static friction. The time delay, about 6ms, was the time for the air to travel in the pipe from the tank to the air motor.

4. Fuzzy smoothing control

Although the overall system is nonlinear with the dead end and hysteretic behaviors, the proportional plus integral control [2], expressed as follows, was first used to control the system:

$$u(t) = k_P e(t) + k_I \int e(\tau) d\tau \quad (1)$$

In the above equation, $e(t)$ represents the difference between the referenced and measured output signal, and k_P and k_I represent the proportional and integral control gains, respectively. The results in [2] show there still exist large overshoot and steady errors for constant speed control, especially at speed lower than 1000 rpm. In some cases, the rotational speed overshoots to 2800 rpm when the reference speeds are set as1000 rpm or 2000 rpm. Further, the steady error of motor speed can be more than 100 rpm in these cases.

It is found during the experiments that the dead-zone and hysteretic behavior should not be neglected if one wishes to achieve good performance. As shown in Fig. 5, when k_P and k_I were selected as 0.5 and 1.5, respectively, there existed time delay and sticking at the beginning stage, and the settle time was about 1.5 second. If k_P and k_I were changed to 2 and 11, respectively, the rising and settle times were improved and the sticking was eliminated. However, Fig. 6 shows that the above control parameters resulted in large overshoot when the rotational speed was higher than 2500 rpm.

To improve the performance, we implemented a fuzzy logic control scheme for the air motor system. There were two major consecutive steps in designing this controller. First, we tried to select best parameters for proportional integral controller only based on the error and its integration as described in Eq. (1). Due to the nonlinear properties of dead zone and hysteretic behaviors, the selections of k_P and k_I should be different for different reference speeds and also for different stages of the dynamic responses. Hence, we implemented the fuzzy logic control to improve the overall performance.

Since at low speed range, the friction and hysteretic behaviors played a significant role, additional control inputs were necessary to compensate these effects. However, these compensations may deteriorate the system performance by introducing large overshoot and chattering. Hence, the compensation should be attenuated once the nonlinear effects become less

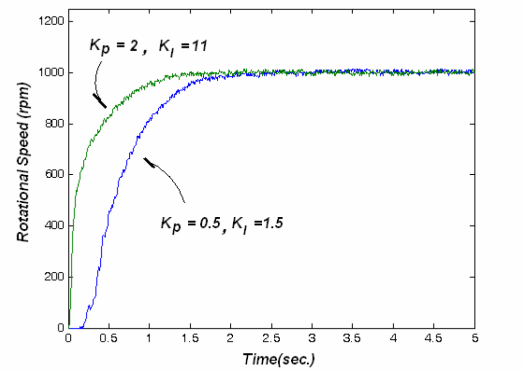

Fig. 5. The time response for different k_P and k_I values (reference speed =1000 rpm).

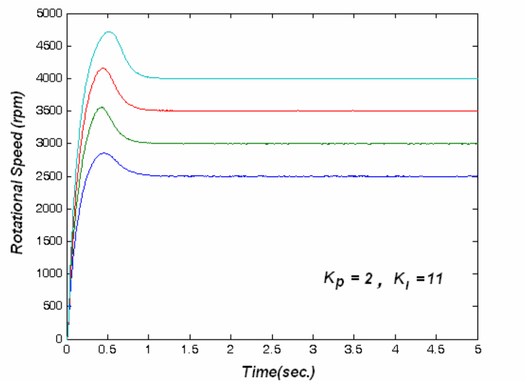

Fig. 6. The time responses for different reference speed settings.

dominant. The implementation and attenuation of additional compensations should be smoothly applied. At the beginning stage, large k_P and k_I were required to obtain enough control power to overcome static friction and improve the transient response. After the transient period, k_P and k_I decrease to small values to maintain good performance at the steady state stage. However, sudden switch of k_P and k_I will deteriorate the performance and result in larger setting time. Hence, we developed the switching rules based on the following fuzzy inference rules, which were developed according to the operators' experience.

$$\text{IF } E \text{ belongs to } \tilde{S}_{Ei} \text{ AND } D \text{ belongs to } \tilde{S}_{Di}, \text{ THEN } \tilde{k}_p \text{ belongs } \tilde{S}_{kp} \text{ AND } \tilde{k}_i \text{ belongs to } \tilde{S}_{ki} \quad (2)$$

where E and D represent error and its variation rate, respectively, $\tilde{S}_{Ei}$ and $\tilde{S}_{Di}$ represent the corresponding fuzzy sets, $\tilde{k}_p$ and $\tilde{k}_i$ represent the corresponding fuzzy variable of k_P and k_I, and their corresponding fuzzy sets are represented as $\tilde{S}_{kp}$ and $\tilde{S}_{ki}$, respectively. The membership functions of $\tilde{S}_{Ei}$, $\tilde{S}_{Di}$, $\tilde{S}_{kp}$ and $\tilde{S}_{ki}$ are shown in Figs. 7-8. The notations in these figures, NL, NM, NS, PS, PM, PL, ZE, etc., represent the fuzzy sets. For instance, NL represents "negative large", PS represents "positive small", and so on. The way to classify "positive large" and so on were described by the membership functions shown in Fig. 7. Although one could choose any types of membership functions, the triangle shape functions were used in this paper because of their simplicities.

The '*AND*' operation of two fuzzy sets $\tilde{S}_{Ei}$ and $\tilde{S}_{Di}$ was first proposed by Zadeh [12] as follows.

$$\mu_{\tilde{E}i \cap \tilde{D}i}(x) = \min\{\mu_{\tilde{E}i}(x), \mu_{\tilde{D}i}(x)\} \quad (3)$$

where $\mu_{\tilde{E}i}(x)$ and $\mu_{\tilde{D}i}(x)$ are the degree of membership that E and D belongs to $\tilde{S}_{Ei}$ and $\tilde{S}_{Di}$, respectively, and $\mu_{\tilde{E}i \cap \tilde{D}i}(x)$ is the degree of membership that "E belongs to $\tilde{S}_{Ei}$" and "D belongs to $\tilde{S}_{Di}$". Another widely used definition for the '*AND*' operation on fuzzy sets is the algebraic product [11], that is,

$$\mu_{\tilde{E}i \cap \tilde{D}i}(x) = \mu_{\tilde{E}i}(x) * \mu_{\tilde{D}i}(x) . \quad (4)$$

In this paper, we adopted the latter definition because of its simplicity and easy for implementation.

Defuzzification is the process of converting a fuzzy quantity, represented by a membership function, to a crisp value. The weighted average method, defining the crisp value as the weighted average of membership functions, is commonly used in industry. This method is valid only for the case when the output membership function is a union result of several fuzzy quantities [11].

$$k_x = \sum_{i=1}^{n} w_i k_{xi} \Big/ \sum_{i=1}^{n} w_i \quad (5)$$

where the index x represents either p or i, and k_{xi} represented the maximum value of i-th fuzzy membership functions of $\tilde{S}_{kx}$ and w_i represented the weighted value of that membership function.

The fuzzy control algorithm was programmed in the DSP for real time implementation. The experiment results are shown in Fig. 9. Both the rising time and settle time were less than 0.2 second for different reference speeds. Moreover, the time-delay and overshoot were totally eliminated. The steady speed errors were less than 10 rpm for the setting speed above 2000 rpm and within 20 rpm for lower speed setting. The adverse effects of friction and hysteretic behaviors, which tend to sabotage the performance for low reference speeds, are now successfully overcome by the proposed fuzzy control algorithm. Compared with the previous published results in [2], this fuzzy control provides a much better performance.

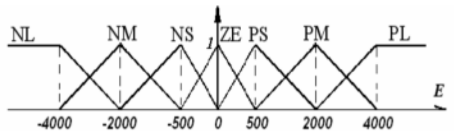

Fig. 7. The fuzzy membership functions $\tilde{S}_{Ei}$, for the error E.

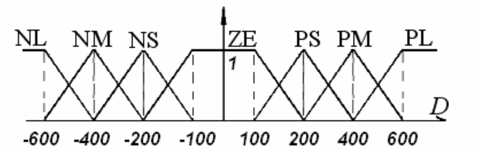

Fig. 8. The fuzzy membership functions $\tilde{S}_{Di}$, for the error rate D.

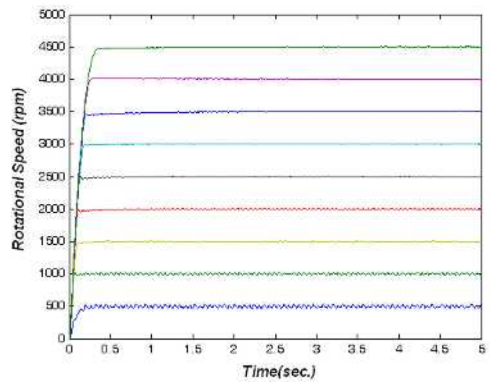

Fig. 9. The time responses applying fuzzy smoothing control for different speed settings.

Figs. 10 and 11 show the tracking responses of the air motor system for sinusoidal and trapezoid references, respectively. The reference output in Fig. 10 can be represented as the following equation.

$$r(t) = A + B\sin(\omega t) \quad (6)$$

where B and ω represent the amplitude and frequency of the sinusoidal wave, respectively and A represents the offset of the waves. Different combinations were tested during experiments and similar results were obtained. Fig. 9 shows the cases for B=100

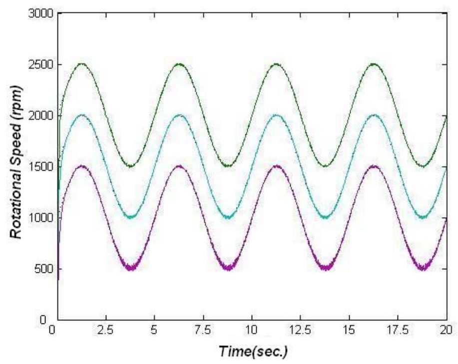

Fig. 10. Time response for tracking sinusoidal waves.

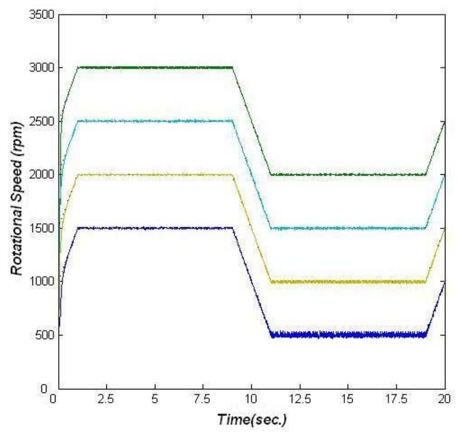

Fig. 11. Time response for tracking trapezoid trajectories.

and ω =0.2 while A ranging from 1000 to 2000. Fig. 10 shows the results for the trapezoid trajectories with offset up to 1000 rpm. These results indicate that our controller provides better tracking results than previous controllers.

5. Conclusion

We analyzed the dynamics of an air motor system and designed a fuzzy logic controller. The rotational velocity of the air motor is related to the inlet compressed air, and due to the compressibility of the air and friction in the mechanism, the overall system is nonlinear with pressure input. The experiment results showed that the proposed algorithms effectively eliminated the time delay and overcame the hysteretic properties of the system. Compared to the previous works, our control provided much better performance. We achieve a 0.2-second settling time without overshoot, and a steady-state error less than 0.5% for high speed operation and 1.5% for low speed operation.

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