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REAL-TIME CONTROL OF A RADIAL PISTON AIR MOTOR

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Abstract: This paper presents an investigation into the real-time control of an air motor incorporated with a pneumatic equivalent of the electric H-bridge. The pneumatic H-bridge has been devised for speed and direction control of the motor. A gain scheduling control strategy is adopted to control the motor, characterised by two distinct regions of operation with different characteristics. Local controllers are developed using a pole-assignment design and linear parametric models characterising the two operating regions of the motor. The control strategy is tested with the motor within the two defined regions of operation. Experimental results show that a good level of speed control of the motor is achieved. *Copyright © 2002 IFAC*

Keywords: Air motor, gain scheduling, pneumatic H–bridge, pole-assignment, radial piston motor, real-time control.

1. INTRODUCTION

Air motors are compact, lightweight sources of smooth vibration-less power. They start and stop almost instantly, and are unaffected by continuous stalling or overload, and thus are suitable for intermittent operation. Air motors are relatively cheap, easy to maintain, and have the versatility of variable speed, high starting torque, are intrinsically safe in hazardous areas, and will operate in exceptionally bad environments (Hitchcox, 1995; Morgan, 1984; Simnett and Anderson, 1983). Moreover, several other advantages are associated with air motors as compared to electric motors (Hitchcox, 1995).

Common designs of air motors include axial piston, radial piston, rotary vane, gerotor, turbine, V-type and diaphragm (Hitchcox, 1995; Mahanay, 1986). The motor utilised in this work is of the radial piston type (Automation Airmotors, 1998; Tokhi *et al*., 2001). This type of motor constitutes a robust, oil-lubricated construction and is well suited to continuous operation. The motor has the highest starting torque of any air motor and is particularly beneficial for applications involving high starting loads. Overlapping power impulses provide smooth torque in both forward and reverse directions.

The basic characteristics of pneumatic motors are well understood and have been published extensively. However, studies concerned with its control have been so few that a universally accepted method is still a research topic. A feedback speed control mechanism with an electro-pneumatic proportional valve has been studied and reported by Noritsugu (1987). In this study the I-PD control scheme has been adopted. With this approach, the controller is simply implemented by electronic proportional, integral and derivative elements. The design of the control system is based on the partial model matching method, which is easily applicable to a system including a dead-time component. An electro-pneumatic servo type speed control method with a pulse width modulated (PWM) technique was proposed by Noritsugu (1988), which requires an inexpensive on-off solenoid valve and uses the I-PD controller in a similar manner as indicated above.

Speed and position control of air motors is commonly achieved through regulating the flow into the motor by using electro-pneumatic proportional valves. For forward and reverse direction, 3-way and 4-way spool valves are employed. Accordingly, as the motor decelerates to a stop position before changing direction, airflow is reduced and suspended before flow is reversed (Tokhi *et al.*, 2001). During this suspended period, or dead-band, the motor shaft is not under control. This situation can affect the target position. Thus, this inherent dead band in the characteristics of the spool valve is not desirable, and the pneumatic H-bridge method was proposed and developed to reduce or eliminate this problem (Tokhi *et al.*, 2001). The main contribution of the work presented in this paper is the control of the air motor by regulating the airflow with the H-bridge. Previous work on a feasibility study of control of the air motor, incorporating the pneumatic H-bridge, has considered a fixed PID control strategy (Tokhi *et al.*, 2001). The current paper extends on the previous study by incorporating a gain scheduling approach. The rest of the paper is organised as follows.

Section 2 provides a brief description of the experimental set-up utilised in this study. Section 3 briefly describes the modelling approach. Section 4 describes the design of the gain scheduled control strategy adopted. Section 5 discusses the implementation of the control strategy and presents an experimental assessment of the performance of the control strategy. The paper is concluded in Section 6.

2. THE EXPERIMENTAL SET-UP

The experimental set-up utilised in this work incorporates an air motor, a pneumatic H-bridge and a Pentium PC with interface system. The motor under consideration is of the radial piston type (Tokhi, *el al.*, 2001). An optical encoder is mounted on an extension of the motors' output shaft. The encoder transmits information that allows motor speed and direction to be detected.

The functional set-up of the H-bridge system is shown in Fig. 1. Four piezo poppet type valves are arranged to form an H-bridge around the two motor ports. Poppet valves A1 and A2 control a variable rate of airflow through the motor, and poppet valves B1 and B2 control the motor direction. Poppet valve A1 in association with poppet valve B2 will allow air flow through the motor in a particular direction, whilst A2 in association with B1 will allow air flow in the opposite direction. For operation in any one direction, only one of this set will be active whilst the other pair will be closed.

A Pentium PC with necessary hardware is used to source and read all plant devices. Where signal compatibility is a problem, an appropriate preconditioning is employed to facilitate proper interfacing between the computer and the plant.

An RTI815 I/O board is used to provide real-time interface between the PC and the air motor (Analogue Devices, 1994). The board contains a single 12-bits analogue-to-digital converter (ADC), receiving 0 to $10\,\mathrm{V}$ with a conversion resolution of 12 bits (4096 counts) providing an LSB value of 2.44 mV. A/D conversion is software triggered at a speed of $25\,\mu\mathrm{s}$. The board contains two independent voltage output channels, each with 12-bit D/A converter. The two channels can individually output voltage in the range of 0 to $10\,\mathrm{V}$. The D/A conversion resolution is 12 bits (4096 counts), with an output settling time of $20\,\mu\mathrm{s}$ for full-scale step change. The 12-bits resolution provides LSB value of 2.44 mV.

An Applocon Liveline PC14AT digital I/O timer counter card is incorporated within the interface circuitry of the system. This is a half-sized plug-in board, which provides 48 programmable input/output lines organised into six ports, and three independent programmable 16-bit counter/timers. The counter/timer facility was programmed to measure the signal frequency.

3. MODELLING APPROACH

A black box identification approach was adopted for modelling the system. Several tests were conducted in order to determine the linear operating regions of the air motor system. In these tests, a ramp input having a V-profile was applied to the open-loop system. The ramp input was such that the speed of the motor was ramped down from an initial speed of about 670 RPM to a lower speed, and then ramped back up to its initial speed. It was noted that there was a dead-band below 380 RPM, where the ramp-up system response did not match the ramp-down response. Thus, to model the system with linear parametric models, the operating region of the motor from 385 RPM to 680 RPM was divided into the low-speed (385–543 RPM) and high-speed (543–680 RPM) regions. Accordingly, the auto-regressive moving average with exogenous inputs (ARMAX) type, was used to characterise the low-speed and high-speed operating regions of the system. This is given as

$$A(z^{-1})y(t) = z^{-k}B(z^{-1})u(t) + C(z^{-1})\varsigma(t) \quad (1)$$

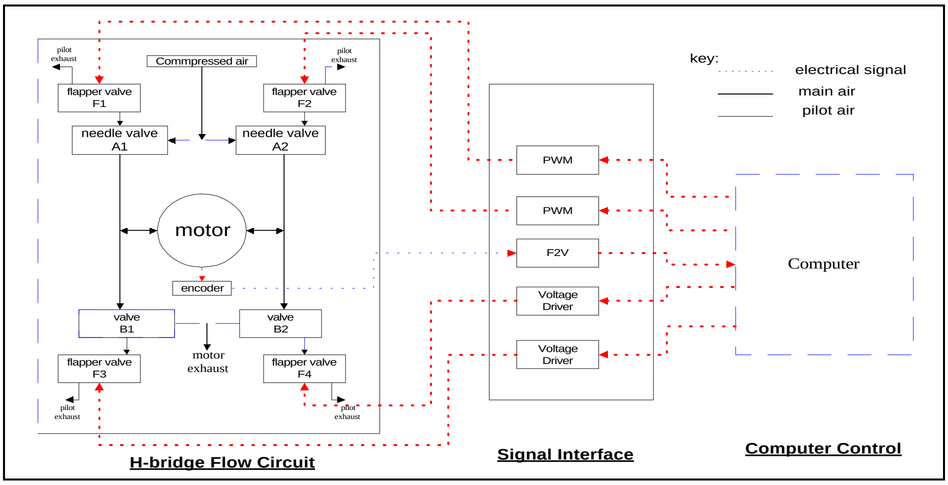

Fig. 1. Functional set-up of the H-bridge.

where

$$A(z^{-1}) = 1 + a_1 z^{-1} + ... + a_{n_a} z^{-n_a}$$

$$B(z^{-1}) = b_1 + b_2 z^{-1} + ... + b_{n_b} z^{-n_b+1}$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + ... + a_{nc} z^{-n_c}$$

z^{-k} represents the system delay, and $u(t)$, $y(t)$ and $\varsigma(t)$ represent the system input, output and zero-mean white noise signals.

To estimate parameters of the model in equation (1), a least squares algorithm is utilised (Söderström and Stoica, 1989). A pseudo-random binary sequence (PRBS) input signal was used to excite the system and 1000 input/output data points were collected for estimation of the model parameters. To ensure that the models were an adequate representation of the characteristics of the system, they were validated through a number of tests. These included significance of parameters, correlation tests and estimation and test sets (Reynolds, 2000).

4. CONTROL SCHEME

In this work a gain scheduling control strategy is considered. Traditionally, gain scheduling has been perhaps the most common systematic approach to the control of strongly non-linear systems in practice (Åström and Wittenmark, 1989). It has some favourable engineering advantages such as simple design and tuning and low computational complexity.

A gain scheduling control system consists of two major components, namely a family of controllers and a scheduler. The task of the scheduler is to assign, at each time instant, a controller to be applied to the plant. The control system can be considered as having multiple local controllers that are applied in different operating regimes. For the air motor system under consideration, local controllers for the two operating regions, namely low-speed and high-speed are designed.

The local controllers employed in this work are of the pole-assignment type, as this is simple to design. The idea in pole-assignment is to determine a controller that gives desired close-loop poles. Moreover, the control system is required to achieve several other goals, such as (a) to attenuate load disturbances, (b) to reduce the effect of measurement noise, (c) to follow command signals, and (d) to have low sensitivity to modelling errors.

In this study, it is assumed that load disturbance and measurement noise are present at the plant output. Accordingly, a pole-assignment control structure incorporating the plant model

$$A(z^{-1})y(t) = z^{-k}B(z^{-1})u(t) + n(t) + d(t) \qquad (2)$$

where $d(t)$ and $n(t) = \left[C(z^{-1})/A(z^{-1})\right]\varsigma(t)$ represent the load disturbance and measurement noise respectively, was utilised with the control law

$$F(z^{-1})u(t) = H(z^{-1})r(t) - G(z^{-1})y(t) \qquad (3)$$

where $r(t)$ represents a reference input and $F(z^{-1})$, $G(z^{-1})$ and $H(z^{-1})$ are the controller polynomials. The closed-loop system equation accordingly is

$$y(t) = \frac{z^{-k}BH}{FA + z^{-k}BG} r(t) + \frac{FC}{FA + z^{-k}BG} \varsigma(t) + \frac{FA}{FA + z^{-k}BG} d(t) \qquad (4)$$

Thus, the closed-loop characteristic polynomial is given as

$$FA + z^{-k}BG = P_{cl} \qquad (5)$$

The design method involves specifying the desired closed-loop characteristic polynomial P_{cl}. This can be expressed as

$$P_{cl}(z^{-1}) = P_c(z^{-1})P_0(z^{-1}) \qquad (6)$$

where $P_c(z^{-1})$ is referred to as the controller polynomial and $P_o(z^{-1})$ as the observer polynomial. In the design procedure, the polynomial $P_{cl}(z^{-1})$ is considered to be a design specification that is chosen to give desired properties to the closed-loop system. Equation (5), which plays a fundamental role in this process, is commonly referred to as the Diophantine equation.

The polynomials $F\left(z^{-1}\right)$ and $G\left(z^{-1}\right)$ follow from equation (5). Accordingly, the closed-loop system behaviour is determined by the controller polynomial $P_c(z^{-1})$. The polynomial $H\left(z^{-1}\right)$ is chosen so that it cancels the observer polynomial $P_o(z^{-1})$. This implies that command signals are introduced in such a way that they do not generate observer errors. Hence

$$H(z^{-1}) = t_0 P_o(z^{-1}) \qquad (7)$$

where the parameter t_0 is chosen to result in the desired static gain of the system; for unity closed-loop gain e.g. $t_0 = P_c(1)/B(1)$.

The disturbance $d(t)$ is assumed to be a step. This is a valid assumption, as under normal operating conditions, the motor will be suddenly loaded or unloaded. For example, the motor may be driving a conveyor belt in which objects are suddenly placed on or removed from it. This has the effect of changing the operating speed of the motor to some other value. To avoid steady-state errors, it is required that the change in speed due to the disturbance is zero. It follows from equation (4) that this is possible if $F(1) = 0$. Therefore, it is necessary that $\left(1 - z^{-1}\right)$ is a factor of $F\left(z^{-1}\right)$ or that the controller is required to have integral action.

The effect of measurement noise can be reduced by choosing suitable values for the observer poles. The observer poles also influence the response to load disturbances. Thus, a compromise has to be made between the two responses when selecting the observer poles.

The process of design of the scheduler involves (a) definition of the scheduler variables and (b) devising a scheduling algorithm for selection of the local controller to be applied. Scheduling variables are usually selected on the basis of two heuristics (Shamma and Athans, 1992), that they: (1) should capture the non-linearities, (2) should be slowly time-varying compared to the desired bandwidth of the closed-loop system.

The gain scheduled control structure used in this study is the switching (between controllers) type. The scheduling variable is chosen as the shaft speed of the motor (i.e. the plant output), as this clearly indicates which of the two regions the motor is operating in at any time. To achieve proper operation of the scheduler s set of 'IF–THEN–' rules are used (Reynolds, 2000). These rules will ensure that the scheduler switches to the correct controller at the appropriate time. Moreover, to achieve smooth transition between the local controllers, past samples of the command input, plant output and plant input of the selected controller are initialised to zero just after switching. In doing this, the newly selected controller begins approximately where the previous controller has discontinued. Note that in this process the local controllers generate an output signal relative to a common co-ordinate system with origin at the transition point along the system input/output characteristics. Note that in case of a load disturbance, which results in a shift of the origin of the common co-ordinate system, bumpless transition can be ensured by taking account of the shift in the scheduler rules above (Reynolds, 2000).

5. EXPERIMENTATION

In the experimental set-up utilised, the motor speed is measured using a shaft encoder. This represents the measured speed in terms of frequency. A frequency-to-voltage (F2V) converter transforms this to a voltage in the range $0-5\,\mathrm{V}$. This analogue voltage is then converted into binary form by an A/D converter, which is read by the computer. The controller uses this measured speed along with other variables to generate a control signal. A D/A converter converts the control signal from its binary form into an analogue voltage. This analogue voltage when applied to the pressure control valve (PCV) regulates the air pressure to the motor, thus controlling the speed of the motor.

A Pentium PC is utilised for implementation of the control algorithm in real-time. The control algorithm is coded in Modula-2. The timing requirements were realised by utilising the existing real-time clock (DOS clock). The clock contents can be accessed via a simple routine. The time is returned in terms of number of clock ticks of the clock. A tick being a resolution of the clock, that is the smallest interval of time the clock can measure, and runs at a rate of 18.2 Hz.

5.1. Control in the high-speed region

Initially, a square wave was applied as the command input to the system operated in the high-speed region. Figure 2 shows the system response to this input. It is noted that the system achieved the set-point speeds very well and there was neither an overshoot nor an under-shoot in the system response. The system response settled within 5 seconds and the variation due to measurement noise was about $\pm 0.8\%$, which is well within tolerable limits. Thus, the performance of the controller in the high-speed region was very good.

The performance of the system was further evaluated by testing its ability to track command inputs. A ramp signal of frequency 0.08 rad/sec was used for this test. Figure 3 shows the result of this test. It is noted that the system tracked the command signal at low frequencies very well.

5.2. Control in the low-speed region

Figure 4 shows the system response to a square wave in the low-speed region. It is noted that the system response was very oscillatory, especially at the lower set-point speed, the settling time of the upper set-point speed was much less than that of the lower set-point speed. The upper set-point speed was achieved fairly accurately, and the system could attain the lower set-point speed but over a longer period of time. These observations suggest that the performance of the controller in the low-speed region was not very good. There are, however, two main reasons for the poor level of control obtained in the low-speed region. Firstly, hysteresis is more evident in the low-speed region than in the high-speed region. Secondly, the system is very sensitive to changes in the control signal in this region. A small change in the control signal resulted in a very large change in the system output.

The ability of the system to track low-frequency command signals was also evaluated in the low-speed region. A ramp signal of frequency 0.08 rad/sec was used for this test. The response of the system to this signal is shown in Fig. 5. It is noted that, despite the un-even characteristic of the plant in the low-speed region, the system was still able to track the command signal fairly well. The step-like appearance of the plant's response is thought to be due to hysteresis.

5.3. Evaluation of the scheduler

To test the switching ability of the scheduler, a square wave input, which first operates in the high-speed and then switches to the low-speed, was applied to the system. This will force the scheduler to change controllers. The corresponding system response is shown in Fig. 6, where the dotted line represents the transition speed. It is noted that the scheduler selected the correct controller for an operating region. This can readily be deduced, as the level of control obtained in each region is comparable to that obtained above.

To evaluate whether smooth transition of control is achieved, a ramp command signal, which spanned over the high-speed and low-speed operating regions, was applied to the system. The corresponding system response is shown in Fig. 7, where the dotted line represents the transition speed. It is noted that the smoothness of the transition between the local controllers is fairly good, especially when transition was made from the low-speed to the high-speed controller.

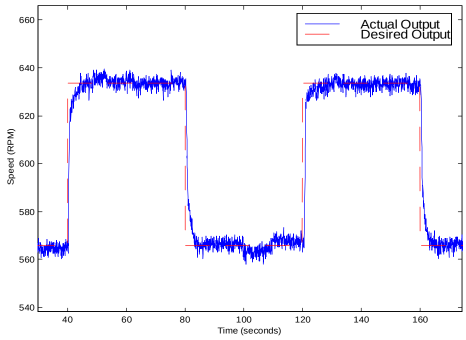

Fig. 2. System response to square wave input (high-speed region).

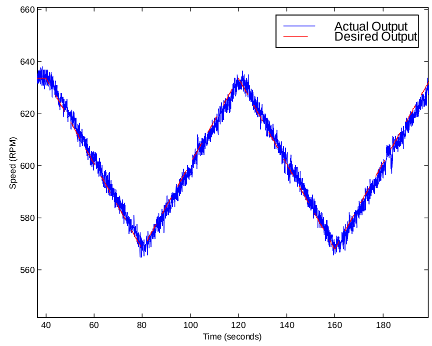

Fig. 3. System response to a ramp input (high-speed region).

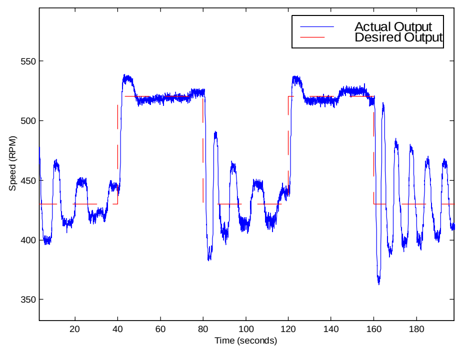

Fig. 4. System response to square wave input (low-speed region).

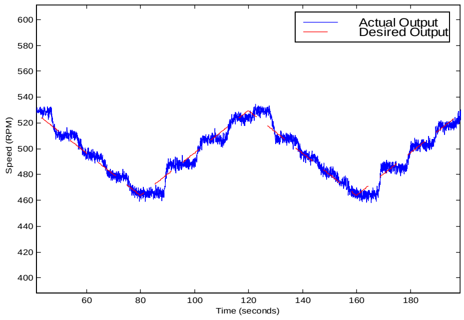

Fig. 5. System response to a ramp input (low-speed region).

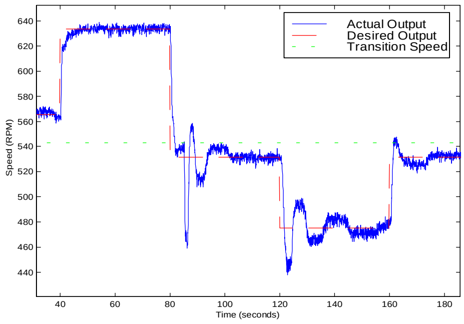

Fig. 6. System response to a square wave command operating in the high- and low-speed regions.

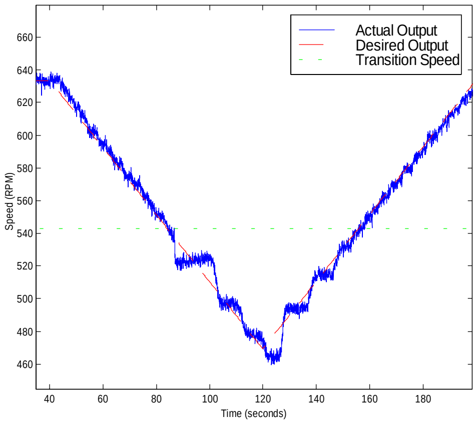

Fig. 7. System response to a ramp command operating in the high- and low-speed regions.

6. CONCLUSION

An investigation into real-time modelling and control of a radial piston type air motor has been presented. The air motor has been characterised by local models corresponding to the low-speed and high-speed operating regions.

A gain scheduling control strategy has been adopted for the system. Local controllers for the low-speed and high-speed operating regions of the system have been designed using a pole-assignment design. The set point and command tacking ability of the local controllers have been evaluated and verified experimentally. It has been shown that each controller performs to a satisfactory level. Furthermore, the switching ability of the scheduler has been shown and it has been demonstrated that the scheduler selects the correct local controller for an operating region and smooth transition between the two local controllers is achieved.

It has been demonstrated that speed regulation of the air motor can be achieved with the pneumatic H-bridge in real-time. It has been noted that the motor characteristics incorporate hysteresis at the low-speed region. Accordingly, the performance of the devised linear control method at the lower set points in the low-speed region has not been as good as for higher speeds. Future research will investigate this issue.

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