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Model Based Driving Analysis for A novel Stepped Rotary Flow Control Valve ⋆

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Abstract: This paper investigates the driving techniques for a novel stepped rotary flow control valve which has been developed for a hydraulic Independent Metering (IM) control system. This valve has promising features such as observed controllability and stability. Its main structure is composed of a stepper motor coupled directly to a rotary orifice. The rotation of the stepper motor changes the orifice opening area and therefore the rate of the fluid flow. Two main techniques have been used to drive the stepper motor which are the full step and the micro-step rotary movements of the stepper motor and with it the rotary control orifice. Investigation of the relationship between these driving techniques and the dynamic performance of the valve is necessary to develop a control algorithm for this new IM configuration. This investigation is based on the mathematical model of the valve, and indicates that the driving signals have a different effect on the dynamical performance of the valve. For example, the rest points using the full step technique affects the friction torque produced by the rotary orifice.

Keywords: Indpendent Metering, Micro-Indpendent Metering, Multi-step Response Analysis, Hydromechatronics, Aircraft Brake Control System.

1. INTRODUCTION

Hydraulic systems have been widely used due to their significant properties such as high power density, flexibility, and high stiffness Parr (2011). Their applications range from military and aerospace through to industrial and earth moving machines applications. Energy saving and controllability are important concerns in these driving systems Mattila et al. (2017). Different systems have been developed to enhance hydraulic drives performance. In a typical hydraulic circuit the meter in and meter out functions which control cylinder movement are mechanically connected within a traditional control valve. Separating the meter-in and the meter-out functions increases the system flexibility, reduces energy losses and permits implementing advanced control methods or algorithms Vukovic et al. (2016). This configuration, based on function separation, is called Independent Metering. Many valves were designed to be embedded in the IM system. Poppet valves are important type Opdenbosch et al. (2011). However, this valve suffers from instability and low flow rate Eriksson (2010), which has resulted in lack of industrial use of this poppet valve. However, a new stepped rotary flow control valve has been developed to be used in higher flow rate applications Okhotnikov et al. (2017) and Abuowda et al. (2019b) which leads to a new circuit configuration for independent metering (Figure 1) Abuowda et al. (2019a), such circuit can be used for aerospace, aircraft and fighter brake control system Stimson et al. (2002).

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Investigation of the driving techniques for this valve is important for control applications. In literature, previous research included a mathematical model of a proportional pressure control valve which was developed and was represented using Bond graphs Yang et al. (2012). A dynamic analysis of a proportional solenoid controlled valve was investigated by Dasgupta and Watton (2005). Analysis of interaction between the mechanical and the fluid parts of the a proportional solenoid valve was studied Meng et al. (2016). A servo valve was mathematically analysed and modelled in Anderson and Li (2002) and Acuña-Bravo et al. (2017). Regarding the poppet valve, a mathematical model and simulation were investigated in many types of research such as Fales (2006). A linear model of a hydraulic rotary actuator containing coulomb friction was evaluated by Pollok and Casella (2017). A model of a three-way rotary electrohydraulic valve was investigated by La Hera et al. (2009). It shows a mathematical model of the valve combined with DC motor which illustrated the viscous torque, friction torque and flow torques. However, most of the mentioned review is about solenoid or proportional sliding spool valves, and highlights the mechanical part of the valves with some of them including the solenoid PWM interactions. As this new rotary valve has a different construction, the interaction between the valve parameters, based on the inserted control signal, is an interesting point to study. This investigation using the numerical model is multi-step response analysis. The multi-step has different forms which are the full step and the mirco-step. The investigation indicated that the rest point of the full step driving technique effect increases the friction's ripples.

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The structure of the paper as follows: Section 2 covers the valve structure and its mathematical representation, Section 3 covers the stepper motor driving techniques. Section 4 covers the response analysis while the Conclusion is presented in Section 5.

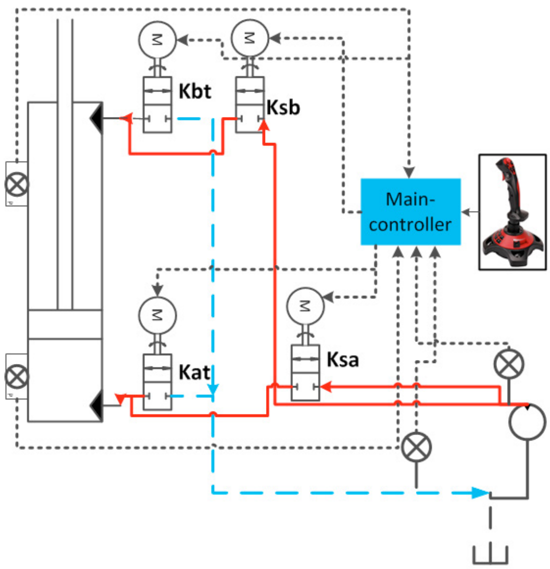

Fig. 1. The configuration of the micro-independent metering system. The red line is the pumped line and the blue is the drained line

2. THE ROTARY FLOW VALVE STRUCTURE AND MATHEMATICAL MODEL

The rotary flow control valve considered in this research is shown in Figure 2. The flow is controlled by the position of the rotor in the stepper motor. When the driving circuit of the motor starts feeding current into the coils, an electromagnetic force is produced in the stators Kenjo and Sugawara (1994). This force rotates the stepper rotor which is connected to the valve spool. And Consequently the opening area of the orifice is changed Figure 2.

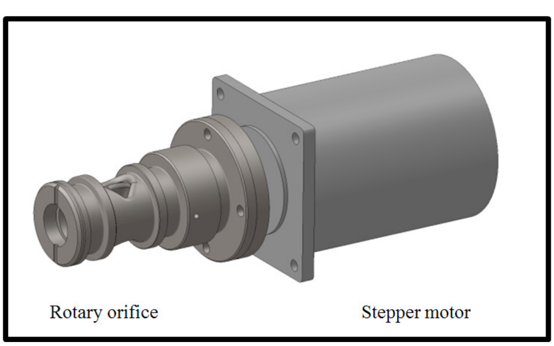

Fig. 2. The rotary flow control valve

The main subsystems of this valve are shown in Figure 3. When the PWM signals are adopted at the H Bridge arms, the resultant voltage is changed according to the working principle of the chopper circuit, for more details Mi et al. (2008). This signal arrangement is responsible for the working technique of the motor, full step, half step, and micro-step. As the developed voltage directly affects the amount of current in the stepper motor coils, different signals of current are produced, and thus there is a change on the effects on the torque and the speed of rotation. The rotation of the rotor results in friction, steady-state flow torques, and transient flow torques. These torques should be held by the resultant torque from the motor electromagnetic field to assure the valve controllability. Modelling and simulation, using the valve mathematical model, is the selected technique to study these relationships.

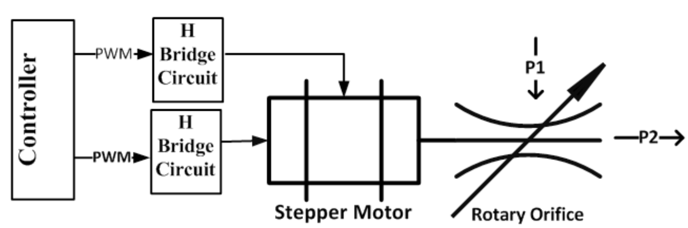

Fig. 3. The main subsystems of the valve

A previous investigation which conducted by the authors Abuowda et al. (2019b) and Okhotnikov et al. (2017) studied the dynamic model of this valve, and it can be summarized as follow:

- The steady flow torque:

$$T_{st.fl} = \frac{2C_c \Delta p A_o R_{e.sp} \sin\theta}{1 - C_c^{\ 2}} \quad . \tag{1}$$

where Q_t is the total flow rate passing through the valve, through both orifices, ρ is the oils density, $R_{e.sp}$ is the radius of the spool external cylinder, θ is the flow jet angle which is a function of the spool angular position φ, and the contraction coefficient C_c.

- The transient torque:

$$T_{tr.fl} = \frac{((R_{e.sp})^4 - R_{i.sp}^4) A_{sp.op} \rho}{R_{e.sp}} \frac{d\omega}{dt} \quad . \tag{2}$$

where $T_{tr.fl}$ is the transient flow torque, $R_{e.sp}$ is the external spool radius, $R_{i.sp}$ is the internal spool radius, ω is the angular velocity, $A_{sp.op}$ is the spool opening area.

- The applied friction model:

$$\frac{dz}{dt} = \omega - \frac{\sigma_o |\omega|}{g(\omega)} z \quad . \tag{3}$$

where ω is the relative angular velocity between the two rubbing surfaces, σ_0 bristle stiffness, $g(\omega)$ velocity dependent function describing Coulomb friction and Stribeck effect as following,

$$g(\omega) = T_c + (T_s - T_c) \exp^{-\left(\frac{\omega}{\omega_s}\right)^2} \quad . \tag{4}$$

where T_c is the Coulomb friction torque, and T_s is the stiction or static friction torque.

- The stepper motor model

$$
\begin{bmatrix} \dfrac{d\theta}{dt} \\ \dfrac{d\omega}{dt} \\ \dfrac{di_a}{dt} \\ \dfrac{di_b}{dt} \end{bmatrix} = \begin{bmatrix} \omega \\ \dfrac{1}{J}[-K_m i_a \sin(N_r\theta) + K_m i_b \cos(N_r\theta) \\ -B\omega - T_L] \\ \dfrac{1}{L}[V_a - Ri_a + K_m \sin(N_r\theta)] \\ \dfrac{1}{L}[V_b - Ri_b - K_m \cos(N_r\theta)] \end{bmatrix}
$$

where ω is the angular velocity, J is the inertia, K_m is the detent torque constant, N_r is the number of teeth, R is the resistance, T_L is the total load torque, B is the visouce friction constant, i_a is the coil A current, i_b is the coil B current, V_a is the coil A supplied voltage, and V_b is the coil B supplied voltage.

As friction is the main contributor of the applied torque on the motor, a test rig for the friction is shown in Figure (4). It contains pressure transducer, torque transducer and stepper motor. The practical performance of the rotary orifice friction is shown in Figure (5).

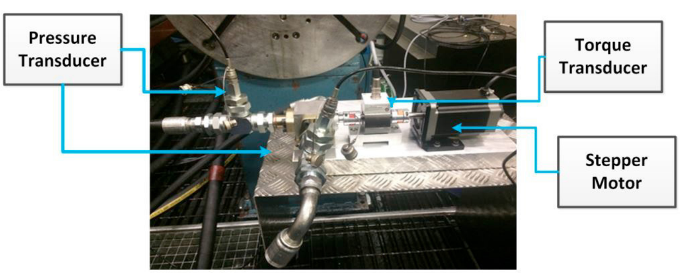

Fig. 4. The test rig for rotary flow control valve friction torque

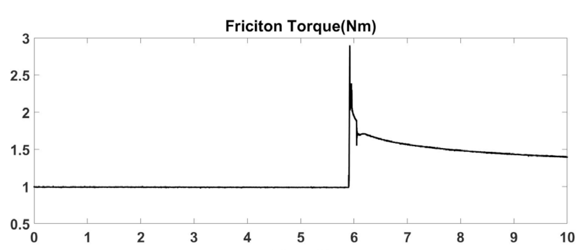

Fig. 5. The real friction performance of the rotary orifice

3. STEPPER MOTOR DRIVING TECHNIQUES

A number of operating methods can be used to energize the stepper motor. These approaches are full step, half step and micro stepping. The full step technique is performed when each phase of the stepper motor is supplied separately. Half step method is performed by supplying both phases with equal currents Bellini et al. (2007). However, these two modes produce a rest position which affects the shaft revolution, torque and rotation velocity. This effect is represented by poor torque dynamic, torque ripples and mechanical vibration. To overcome these shortcomings, an extra division which is limited by the mechanical tolerance, friction torque in this design, can be introduced. The used approach is termed as micro-stepping, and results in reduced the torque ripples and improved smoothness of the shaft revolution Moon and Kim (2014). Its work principle is conveying a current from a coil to another with 90° phase.

Table 1. The selected stepper motor for the simulation analysis

Stepper	resistance	inductance	detent torque	inertia
1	3.07	0.00118	0.068	0.022
2	0.74	0.0089	0.30	0.120

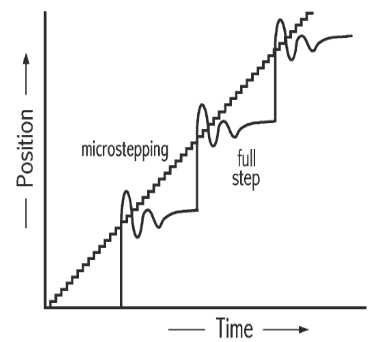

Fig. 6. Illustrates the difference between the micro step and the full step techniques.

An H Bridge is used to produce the required current and keep it to the required level. Its output is based on the applied pulse width modulation (PWM) signal. Different modulations algorithms have been developed to produce the required PWM signal for the H bridge Gaan et al. (2018). A two-level SPWM is used to simulate the micro-stepping for this valve. The analysis procedure starts by selecting the driving technique, followed by the current and torque simulation which will determine if the valve is stable using the selected technique. To insure repeatability of the test, two stepper motors were selected which are included in Table (1).

4. MULTI-STEP RESPONSE ANALYSIS

In the full step mode, the charging and discharging of the coils are performed in series, i,e, the first coil is charged and discharged, then the second coil is charged and discharged. Charging and discharging periods are responsible for the rotation speed. For the analysis of the proposed system, two frequencies which are 80 Hz and 160 Hz for the first stepper and 150 Hz and 300 Hz for the second stepper have been considered. The PWM signal of the driver was modelled using a logic method based on voltage to frequency converter Mihalache et al. (2013). When an 80 Hz pulse train was supplied to the stepper motor, the current produced is 5 A, which is not the rated current. The resultant torque is 5.3 Nm, as shown in Figure (7) (1,a). The achieved opening is 90 degree, but with speed oscillation and high friction affect as shown in Figure (7) (1,b and 1,c). Increasing the operation speed to 160 Hz reduces the current and thus the torque produced is reduced, so the valve is not stable Figure (7) (1,e, 1,f, and

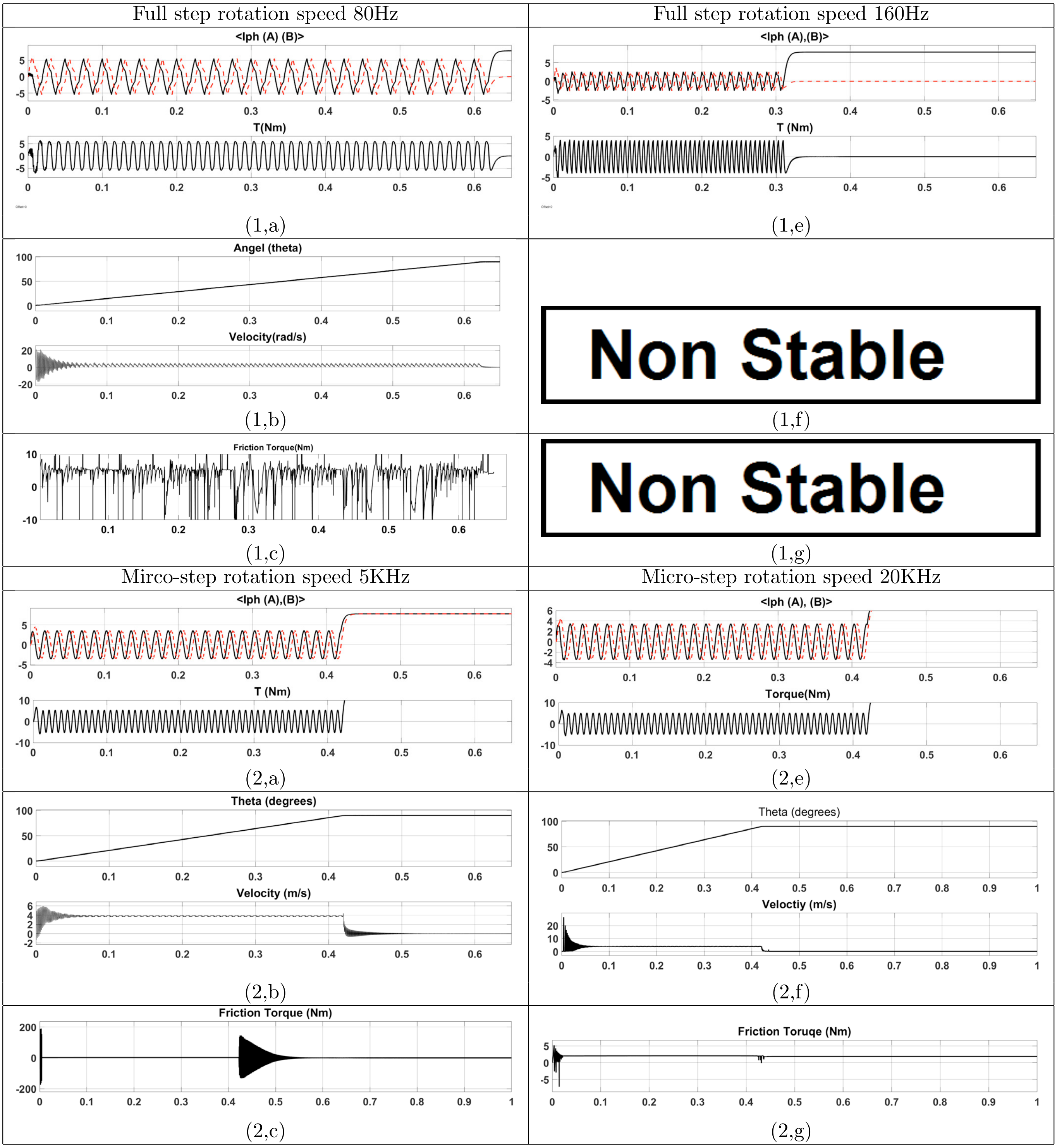

Fig. 7. Responses for the full step and the micro-step techniques using the first stepper motor model

1,g). Based on these analyses, the first stepper motor is not suitable for this valve using the full step technique.For the second stepper motor, the same analysis was performed as shown in Figure (8). When the signal frequency is 150 Hz, the current in the motor coils is 5A, which is the rated current, and the torque produced is around 6 Nm as illustrated in Figure (8) (1,a). The effect on the rest points is clear on the velocity and the friction produced is as shown in Figures (8) (1,b and 1,c). Increasing the operational speed by changing the pulses frequency to 300 Hz, reduces the current in the motors coils to 2 A and the torque to 3 Nm, therefore the opening degree is one step 1.8 degrees and the speed is almost 0 (Figure (8) (1,e and 1,f)). The friction torque effect is illustrated in Figure (8) (1,g). Based on this analysis, the second stepper motor can be embedded into the system using the full step technique, but with a limited frequency range. Also, there is still the effect of vibration by friction ripples.

Regarding the micro-step technique, two frequencies 5 KHz and 20 KHz have been selected for the two stepper

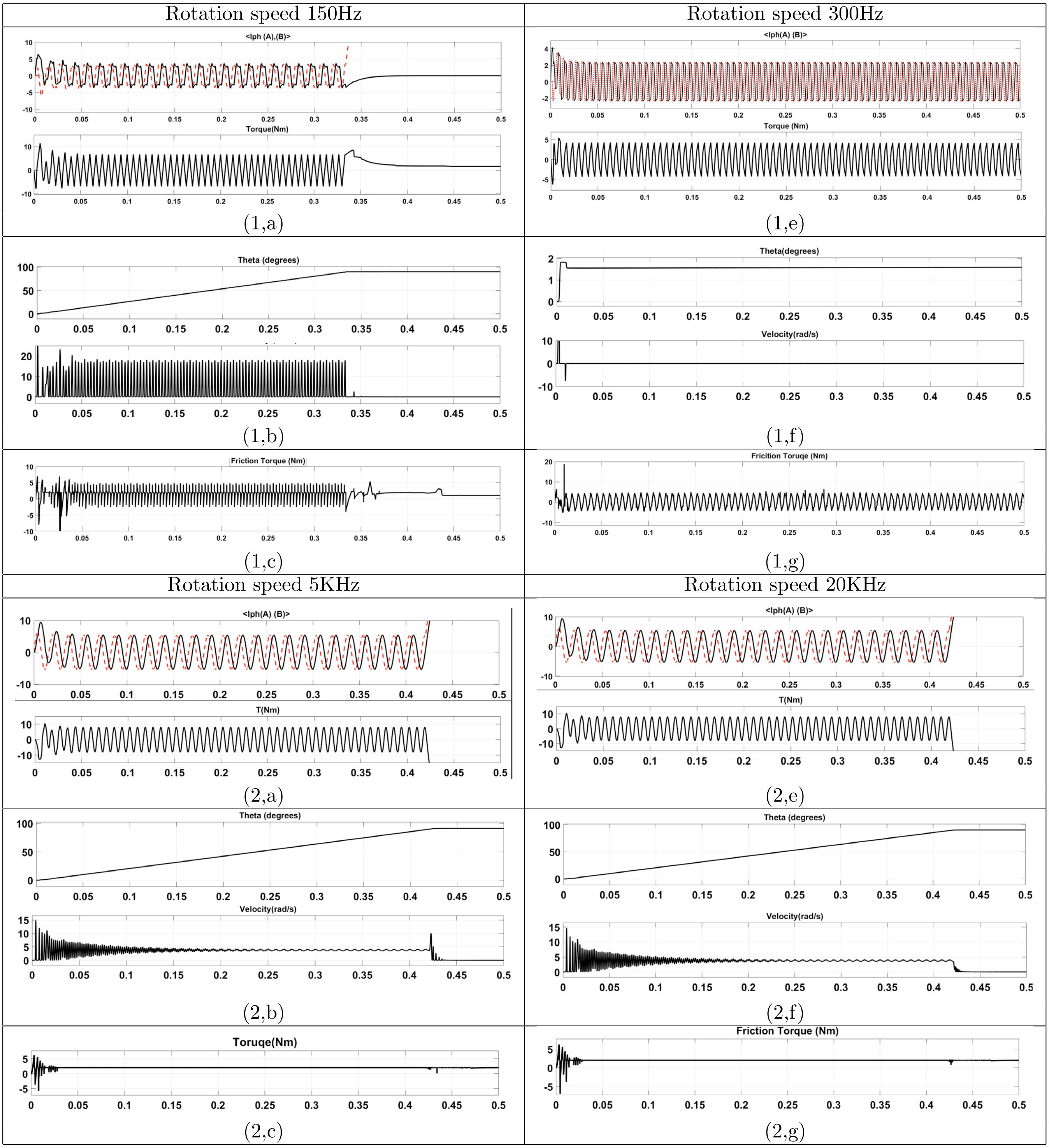

Fig. 8. Response for the full step and the micro-step techniques using the second stepper motor

motors. For the first stepper motor, using this technique has not changed the current peak value 5 A, but it changes the signal shape into a sine-wave. Where the torque produced is 5.3 Nm as illustrated in Figure (7) (2,a). The velocity ripple is reduced when compared to the full step and thus the friction torque as shown in Figure (7) (2,b and 2,c). When 20 KHz was selected, the current reduced to 4 A and the torque produced into 4.5 Nm as illustrated in Figure (7) (2,e). The velocity ripples were reduced and thus the friction torque to average of 3 Nm.

The second stepper motor in both frequencies 5 KHz and 20 KHz, the current produced is a sine-wave shape, and the value is 4 A, which is the rated current, Figure (8) (2,a and 2,b). The micro-stepping reduced the velocity ripples and the friction torques as illustrated in Figure (8) (2,c) and (2,g).

To summarize, the full step technique which has rest points during the stepper motor rotation produces friction ripples and therefore this technique can be used within limited frequency range. The micro-stepping technique is able to eliminate the friction ripples and different ranges of operation frequencies can be implemented.

5. CONCLUSION

In this paper, a model of the new rotary stepped flow control valve has been used to analyse its possible driving techniques. This valve is composed of a stepper motor and a rotary orifice. As the stepper motor is the electrical actuator for it, the multi-step response analysis of the valve has been investigated. It indicates that there is a direct relationship between the activation technique and the resultant friction torque. The investigation concludes that micro-stepping technique is more suitable when compared with the full step. The micro-stepping driving technique reduces the friction ripples and also it can be implemented with different ranges of the supplied signal frequencies. For future work, these results can be practically evaluated, and because of the fluid system non-linearity, different kinds of disturbances can be inserted into the model to discover the performance from a different side.

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