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REDUCING THE VIBRATIONS OF AN UNBALANCED ROTARY ENGINE BY ACTIVE FORCE CONTROL

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ABSTRACT

In this article, the Active Force Control (AFC) method is implemented for reducing the vibrations that are caused by an unbalanced rotary engine. By using Matlab Simulink, the dynamic model of an unbalanced rotary engine was simulated. Then a Proportional–Integral–Derivative PID controller with the AFC loop was added. The obtained simulation results proved that when the PID controller was operating without the AFC loop, the vibrations were reduced but with very less efficiency when compared to the case in which the AFC loop was engaged with the PID controller. This means that the amplitude of vibrations was extremely reduced when the PID controller was equipped with the AFC loop, and the same results were observed for the frequency domain case. The robustness of the AFC method was also tested and again the method of AFC was very capable in reducing the vibrations.

Keywords: Active Force Control; PID; Unbalanced rotary engine; Vibrations

1. INTRODUCTION

The main and basic features of reciprocating and rotary engines are the connecting rod, crank and the piston. Vibrations in rotary engines are caused mainly due to the inertia forces related to the moving components (Rao, 2011; Crede, 1951). Analysis of these forces that are produced due to inertia are explained in detail in normal vibration texts (Rao, 2011).

These vibrations normally cause damage to different components of the engine and also other parts of the machine, e.g. automobile or turbine, etc., (Ogbonnaya et al., 2013; Warminski & Balthazar, 2003). Thus it is very important and required to reduce the vibrations that are produced by a rotary engine and unbalanced rotary mechanisms (Kolhar & Patel, 2013; Ogbonnaya et al., 2013; Warminski & Balthazar, 2003).

The method of isolation is commonly used to reduce the effects of the vibrations produced by rotary engines (Soliman and Hallam, 1968), in which a flexible platform isolator is used for absorbing the vibrations to prevent them from harming the other components. Another method used for reducing the vibrations of a rotary engine is the active vibration control method, (Ruzicka, 1969; Vilnay, 1984). In this procedure by means of an actuator, an external force is applied to the vibration system and it causes the overall vibration to be reduced.

To suppress the vibrations and noise that are generated in a rotating engine, a closed loop control system, known as an Active Force Control (AFC) system is used. One of the advantages of the AFC method is its ability to reject noises or disturbances that are imposed on

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the system through appropriate management of the selected parameters. Moreover, the method leads to fewer computational problems and is well established for real-time use. The AFC method was first presented by Hewit and Burdess (1981). This method turned out to be very robust and effective in controlling a robot arm. Later on other researchers successfully implemented this procedure for a robot arm by combining artificial intelligent (Mailah, 1998; Mailah & Rahim, 2000), as well as controlling pneumatic actuators (Mailah et al., 2009). The AFC method was very capable and successful for decreasing friction induced vibrations (Hashemi-Dehkordi et al., 2009a; Hashemi-Dehkordi et al., 2010; Hashemi-Dehkordi et al., 2009b; Hashemi-Dehkordi et al., 2012; Hashemi-Dehkordi et al., 2014). The AFC method was applied to dynamic models of friction induced vibrations that were produced by modal coupling and negative damping.

2. DYNAMIC MODEL

The dynamic model that represents the behavior of an unbalanced rotary engine is shown in Figure 1. It can be seen that it has only 1 degree of freedom and an unbalanced mass *m* that rotates with an angular velocity ω at a distance of radius *r*.

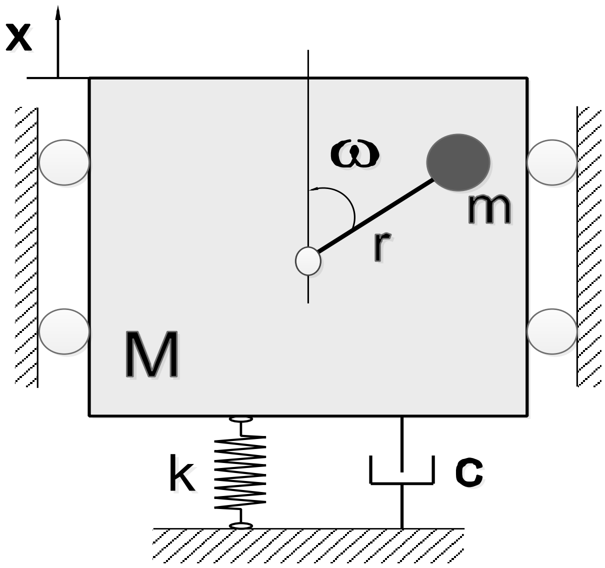


Figure 1 The dynamic model of an unbalanced rotary engine

Equation 1 shows the equation of motion for this model:

$$M\ddot{x} + c\dot{x} + kx - mr\omega^2 \sin(\omega \cdot t) = 0 \tag{1}$$

where *M* is the mass of the rotatory engine, *m* is the mass of the unbalanced rotation, *r* is the radius of the unbalanced mass form the axis of rotation, ω is the angular velocity, and *t* is time.

By using Matlab Simulink, the behavior of the unbalanced rotary engine was studied, and the values that are assigned to the parameters of the model are written as follows:

M = 20 Kg
m = 0.6 Kg
r = 0.15 m
ω = 5000 rpm
c = 0.005 N.s/m
$k = 1.6\times10^7$ N/m

Figure 2 shows the Simulink block diagram of the dynamic model, which is a passive system. After obtaining the block diagram and assigning the required values, the simulation was executed for 180 seconds or 3 minutes and the obtained results are presented in Figure 3 in both time and frequency domains.

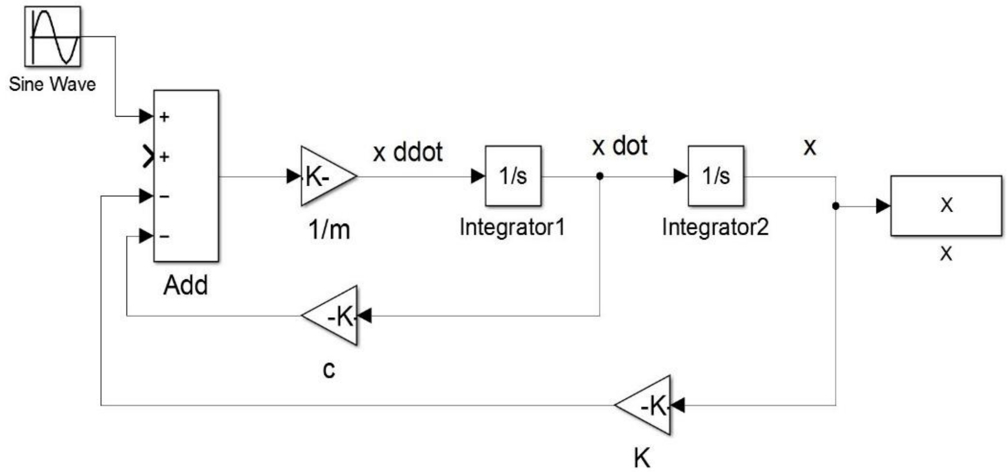
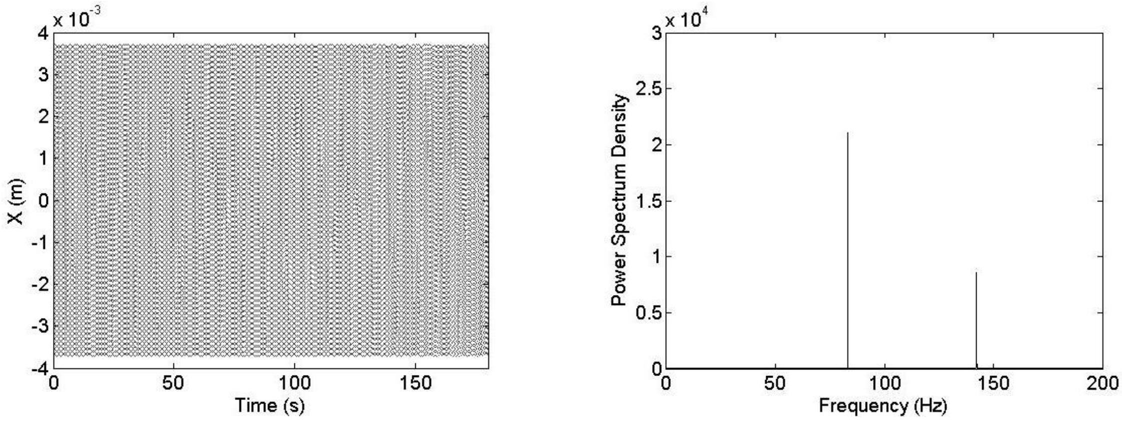


Figure 2 The block diagram of the unbalanced rotary engine (passive system)



(a) Time domain (b) Frequency domain

Figure 3 Response of the passive system

It can be seen that dynamic model vibrates with an amplitude of more than 3.5 mm, and with 2 peaks of frequencies that are around 80 Hz. and 140 Hz.

3. CONTROL STRATEGY

The Active Force Control (AFC) method is the methodology that will be used to reduce the vibrations of a rotary engine. Figure 4 shows the schematic of this methodology. The basic AFC equation is related to the calculation of the expected disturbance or noise F_d as shown in Equation 2:

$$F_d = F - m_{EM} a \quad (2)$$

where F is the actuator's force, m_{EM} is regarded as the estimated mass value and a is the acceleration. The developed value F_d is multiplied by an inverse transfer function of the actuator and then summed up with the PID control's signal. A theoretical analysis of the AFC process has been suitably described by Burdess and Hewit (1986).

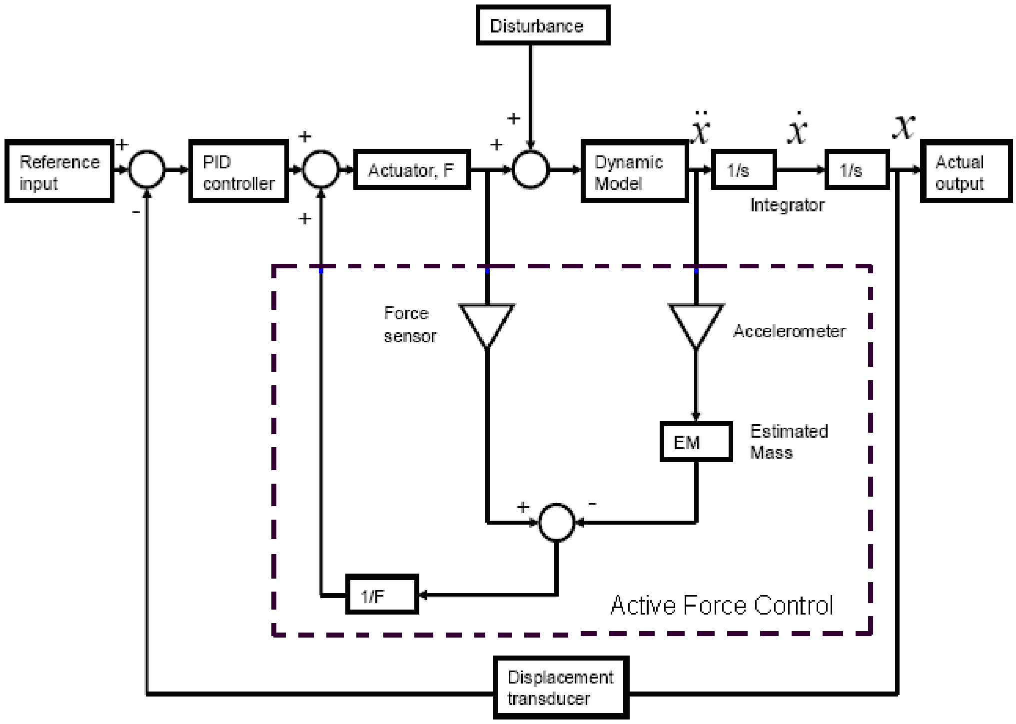


Figure 4 The schematic diagram of the active force control method

4. SIMULATION OF THE CONTROL STRATEGY

Matlab Simulink is implemented to simulate the dynamic model of the unbalanced rotary engine and have it equipped with the control system in order to obtain an active system. To tune the PID controller the method of *Ziegler-Nichol* was used at first for obtaining an initial value for the coefficients of the PID controllers. To obtain good performance for the operating system, manipulations were performed on the coefficients. The value for the estimated mass in the AFC loop was obtained by trial and error. Figure 5 shows the Active Force Control Method, when the Simulink block diagrams of the PID controller in the active system and AFC loop are added to the passive system.

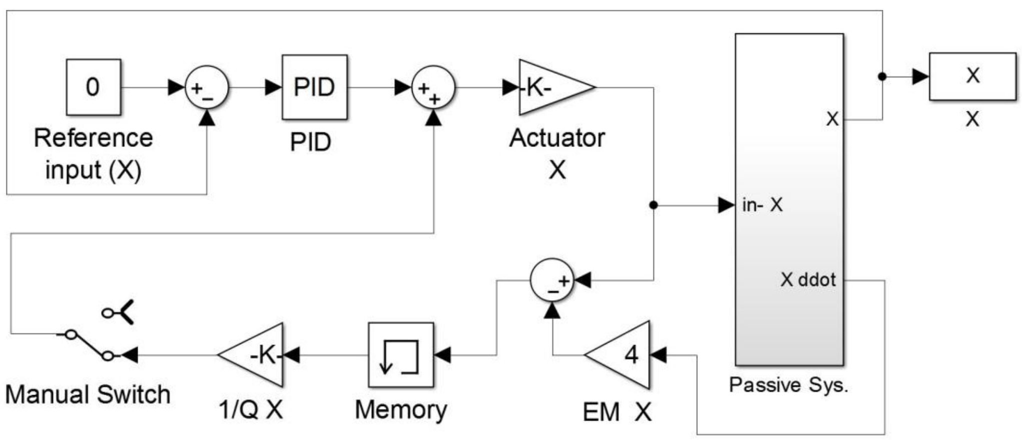


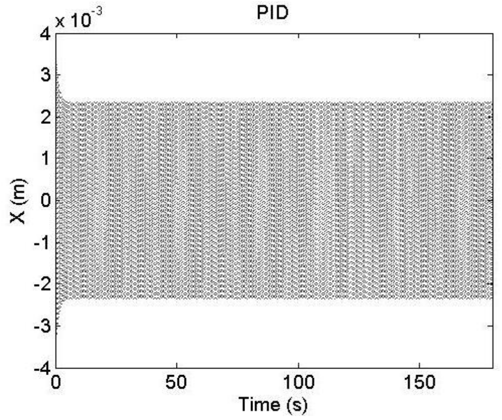
Figure 5 The Simulink block diagram of the active system

The obtained variables for the PID controller and the estimated mass are:

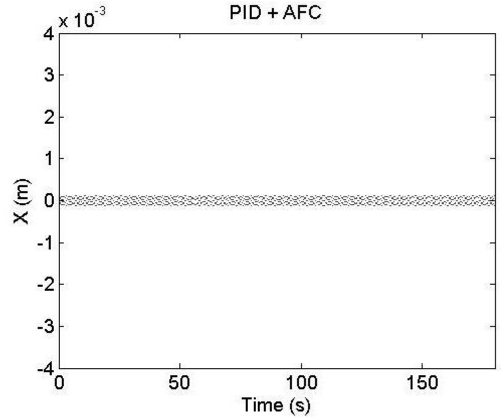
Estimated mass (m_{EM}): 4.0
Actuator Coefficient: 5.5
Proportional value for the PID controller: 2.70
Integrational value for the PID controller: 3.50
Derivative value for the PID controller: 6.20

5. RESULTS AND DISCUSSION

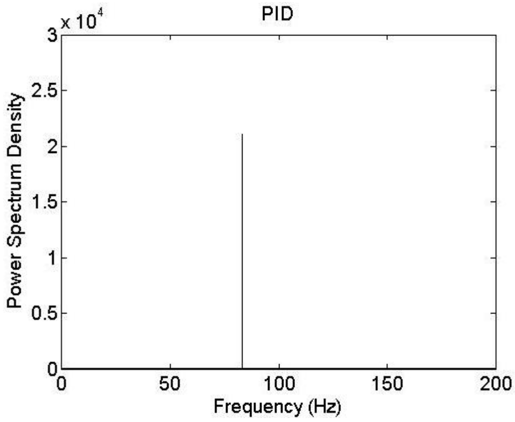
At first the simulation of the active system was executed in a manner that meant only a PID controller was used and the AFC loop was disengaged. Later on the simulation was executed again in a way that the AFC loop was engaged along with the PID controller. Figure 6 shows the comparison of the obtained results in both the time and frequency domains.



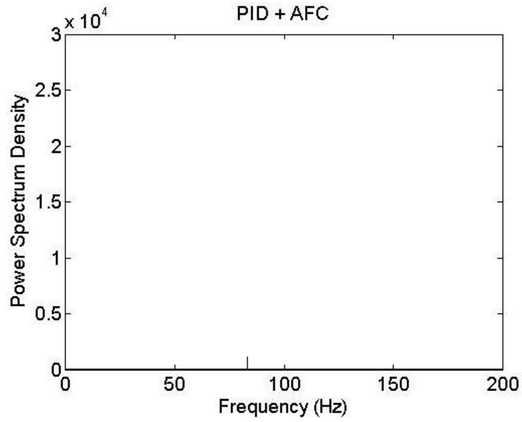
(a) Time domain with PID only



(b) Time domain with PID + AFC



(c) Frequency domain with PID only



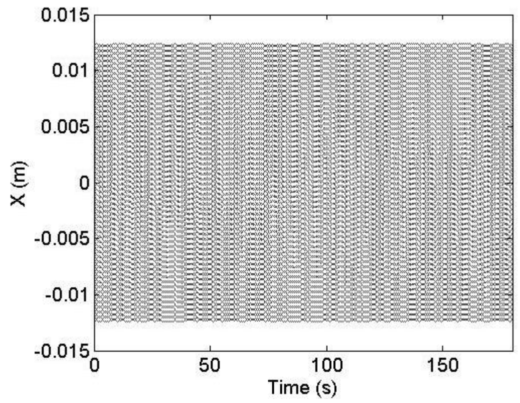
(d) Frequency domain with PID + AFC

Figure 6 The results obtained from the active system

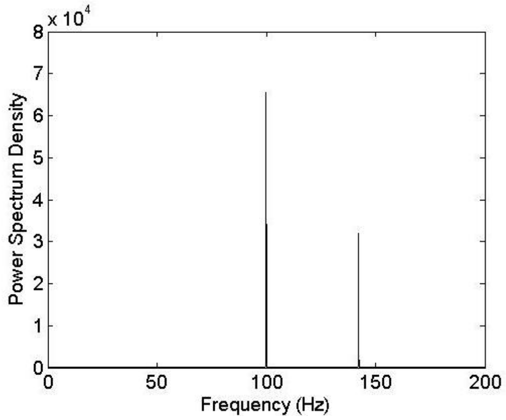
It can be seen that when the active system is operating with only a PID controller, the amplitude of the vibrations are reduced to approximately 1.5 mm in comparison to the amplitude of the passive system. On the other hand, when the PID controller is equipped with the AFC loop, the amplitude of the vibrations are reduced to less than 0.5 mm, meaning that when the AFC loop is added, the efficiency is increased. The same situation is observed for the frequency domain results.

To evaluate the robustness of the control system, another simulation was executed in a manner that the rotational velocity of the dynamic model was increased from 5000 rpm to 6000 rpm

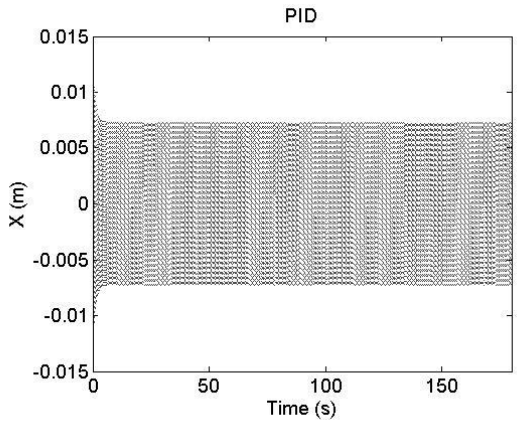
(20% increase) and the amount of the unbalanced mass was increased from 0.6 kg to 1 kg (around 67% increase). The results of this simulation are shown in Figure 7, in which at first the dynamic model was operated without any controller (passive system). Then the simulation was executed with only a PID controller and finally both the PID controller and AFC loop were engaged.



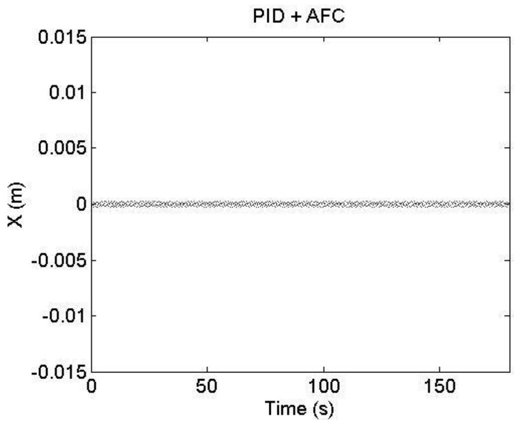
(a) Time domain of the Passive System



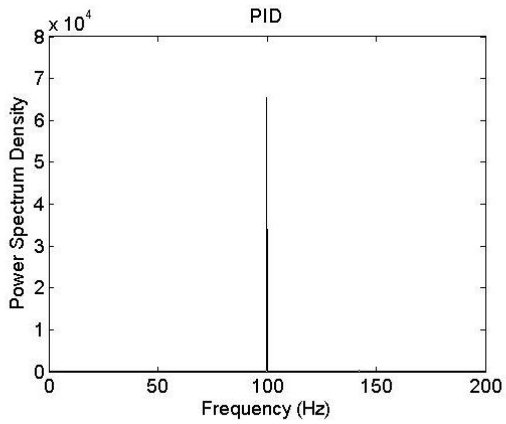
(b) Freq. domain of the Passive System



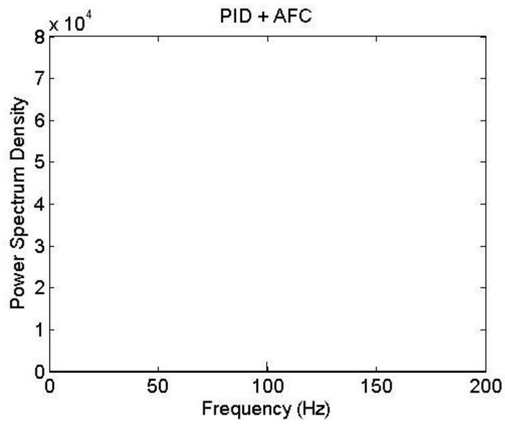
(c) Time domain with PID only



(d) Time domain with PID + AFC



(e) Frequency domain with PID only



(f) Frequency domain with PID + AFC

Figure 7 The results obtained from the active system when the angular velocity and the unbalanced mass were increased to 6000 rpm and 1 kg, respectively

Again it can be seen that when the PID controller is operating alone, the amplitude of the vibrations are 7 mm and concurrently the amplitude of the vibrations in the passive system are

13 mm. This means that when the active system is operating with only a PID controller, it manages to reduce the vibrations to around 5 mm. On the other hand, when the active system is operating with both PID and AFC, the amplitude of the vibrations are reduced to less than 1 mm. This condition proves that when the PID controller is operating with the AFC loop, the efficiency of the active system is increased. The same situation is observed as well for the frequency results.

6. CONCLUSION

A single degree of freedom model of an unbalanced rotary engine is taken into consideration. For suppressing the generated vibrations, an Active Force Control (AFC) technique was considered along with a conventional PID controller. It was observed that when the active system was operating with only a PID controller, the vibrations were reduced, but the process was inefficient. On the contrary, when the AFC loop was added to the PID controller, the vibrations were reduced to a noticeable amount with a very high efficiency. The robustness of the control system was also tested. Again the AFC method was very effective in reducing the vibrations to a noticeable amount.

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