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Active Vibration Control of Isolation Systems by Adaptive Pole placement Control

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Abstract. With the rapid advance of the precise measurement technology of last years, effective anti-vibration measures are required to obtain precise and repeatable results. Although a passive isolation system offers a simple and reliable means of protecting precision equipment from a vibration environment, it has performance limitations since its controllable frequency range is limited. An effective method for reducing an oscillation is by using an active vibration isolation system. This system contains spring and layer for passive vibration isolation elements and actuator for active isolation system. In this paper adaptive pole placement controller (APPC) is employed for controlling vibration. We use recursive least square with forgetting factor for online identification. Designed controller is compared with adaptive PID controllers.

Keywords: Active Vibration Isolation System; Adaptive control; Pole Placement control; PID control.

1. Introduction

Active vibration isolation systems (AVIS) have been widely used especially in high precision instruments and become stricter even in nanometres level. Since the disturbances exist in manufacturing application, the circumstance is important factor to influence the quality of the products. Disturbance is mainly vibration coming from machine operation, industry facility, ground and etc.

Isolation from disturbance is achieved through either passive or active vibration control systems. Passive isolation systems typically use a compliant mount positioned between the vibration source and the isolated device. Although passive system is simple and reliable means of vibration reduction, it has performance limitation. An effective and useful method is by using an active vibration isolation system. The use of this method in practical application is studied in [1, 2, and 3]. As regard to the studies in active vibration control, many control methods including the combinations of independent modal space control , direct velocity feedback control , feed-forward control, optimal control, adaptive control, fuzzy control and neural network control were usually used for getting better control effectiveness. The intelligent AVIS is studied in [4] that used combination of neural networks method. A significant improvement in the vibration isolation quality can be achieved by using an AVIS controlled by optimized algorithms [2]. An alternative hybrid control strategy is proposed in [5]. This strategy switches between a robust controller and an adaptive controller to achieve both controllers' merits. Adaptive control and robust control are two popular approaches for the control of uncertain systems. However, either approach has its own advantages and disadvantages. For example, an adaptive controller can achieve high performance for a slowly time-varying or time-invariant uncertain plant after parameter estimation convergence, but it is possible to exhibit poor transient response when the adaptation is initiated. Another disadvantage of adaptive control is that it is sensitive to unmolded dynamics and disturbances [6]. On the other hand, a well-designed robust controller can guarantee robust stability of the closed-loop system under a reasonable class of disturbances and system uncertainties. However, robust controller design is usually conservative because the controller is often based on a worst-case scenario and thus sacrifices part of the achievable performance to guarantee system robustness [7].

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Comparing to the model constructing method in designing a controller, the use of self-tuning controllers is more flexible and more adaptive when dealing with a time varying system.

In Section 2, model of the vibration isolation system is introduced. This model is presented in [5]. The discrete model is used to design controller. Section 3, the concept of adaptive controller is described. It is contains the concepts of Recursive Least Square algorithm with forgetting factor, Pole Placement (PPC) and PID controller. Finally, the simulation results are presented. The simulations show that the adaptive control can provide request design, however it has a poor transient response. It can be seen that PPC controller can close the system to desired system but the PID controller just can close the system's pole to desired poles.

2. Modelling

The modelling of the active vibration isolation system is presented in [5]. In most active vibration isolation application, the measurement of the disturbance position is difficult but measurement of disturbance acceleration is easier than disturbance position. The disturbance acceleration can be measured by lacing an accelerometer on the base in Fig. 1. It is difficult to measure the absolute position of the isolated mass (x) but easy to measure its relative position (x - z) as shown in Fig. 1.

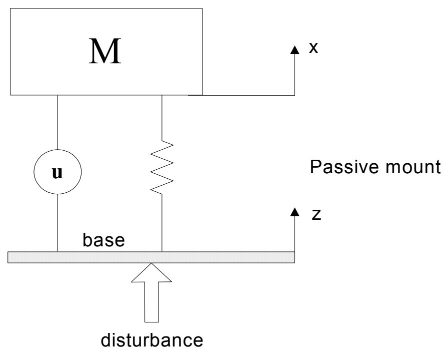

Fig. 1: Active Isolation System components.

Correspondingly, the more useful transfer function relationship between the disturbance acceleration and the relative position of the isolated mass $x_{ref} = x_{des} - z$ can now be written as:

$$G_{ref}(s) = \frac{x_{ref}}{\ddot{z}} = -\frac{s + 2\zeta\omega_n}{s(s^2 + 2\zeta\omega_n s + \omega_n{}^2)} \quad (1)$$

Transfer function from the disturbance acceleration to the relative position of the isolated mass to be the same as Eq. (1). Therefore, the active vibration control problem can be formulated as a position tracking control problem depicted in Fig. 2.

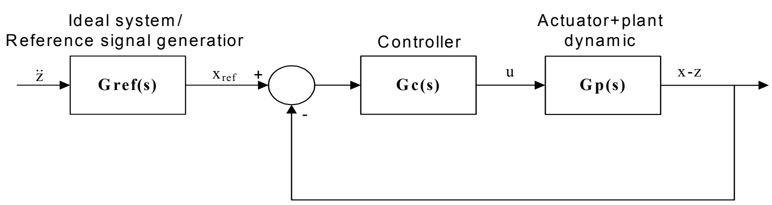

Fig. 2: Block diagram of controlled system.

According to [5], the transfer function of experimental setup is described by (2).This transfer function contains actuator and plant dynamic and identified after some experimental. The transfer function for G_{ref} is described by (1) with $\zeta = 1$ & $\omega_n = 20\pi$.

$$G_p(s) = \frac{4775}{s(S^2 + 464s + 119360)} \quad (2)$$

The desired model was chosen after some designed iteration and it is same as follow:

$$G_m(s)=\frac{1.35e11(s+1.6)(s+100)}{(s^2+1000s+3.725e5)(s^2+800s+3.625e5)(s+1)(s+160)} \tag{3}$$

For designed process transfer functions in (2, 3) is discredited by zero order hold method and sampling time 0.01.

$$G_p(z)=\frac{0.0002309z^2+0.0002214z+1.731e(-5)}{z^3-0.8358z^2-0.1546z-0.009658}\frac{m}{V} \tag{4}$$

$$G_m(z)=\frac{0.8386z^5-1.158z^4+0.3321z^3-0.005022z^2+0.0002967z+1.934e-6}{z^6-1.172z^5+0.1761z^4+0.0035z^3+9.016e-5z^2+8.981e-7z+3.044e-9} \tag{5}$$

3. Adaptive Control

3.1. On Line Parameter Estimation

Electro hydraulic systems often exhibit time-varying and nonlinear characteristics. The system dynamics change with respect to oil temperature, supply pressure, etc. There for online identification algorithm is used to estimates the system parameters. A Recursive Least Square (RLS) algorithm is used for estimation. Since controllers are implemented in discrete, estimation algorithm is used in discrete form.

Corresponding equations for the above algorithm is as follows:

$$\varepsilon(k)=y(k)-\theta(k-1)x(k) \tag{6}$$

$$G(k)=\frac{P(k-1)x(k)}{\lambda+x^T(k)P(k-1)x(k)} \tag{7}$$

$$\theta(k-1)=\theta(k-1)+G(k)\varepsilon(k) \tag{8}$$

$$P(k)=\frac{1}{\lambda}(I-G(k)x^T(k))P(k-1) \tag{9}$$

Where $\varepsilon(k)$ is identification error, $y(k)$ is system output, $x(k)$ is regression vector that include inputs and outputs in the past, $\theta(k-1)$ is estimated parameters system vector, $P(k-1)$ is covariance matrix and λ is forgetting factor. From the equation (4), the estimated vector and the regression vector are defined as follows:

$$\hat{\theta}(k)=[b_i(k)|_{i=1}^{3}\ a_i(k)|_{i=1}^{3}]^T \tag{10}$$

$$x(k)=[u(k-i)|_{i=0}^{2}\ y(k-i)|_{i=1}^{3}]^T \tag{11}$$

In each step the system parameters are updated and controller's coefficients are changed according to estimated Parameters. [8, 9]

3.2. Pole Placement Control

The polynomial approach is used to design a controller. Relation between the reference, controller and output signals of close loop system is described as follow:

$$R(z^{-1})u(k)=T(z^{-1})x_{ref}(k)-S(z^{-1})y(k) \tag{12}$$

The close loop transfer function of system is

$$G_{cl}(z^{-1})=\frac{T(z^{-1})}{A(z^{-1})R(z^{-1})+B(z^{-1})S(z^{-1})} \tag{13}$$

In this equation $R(z^{-1})$, $T(z^{-1})$ and $S(z^{-1})$ are controller polynomials and $R(z^{-1})$ is monic. A degree of $R(z^{-1})$ must be larger than $T(z^{-1})$ and $S(z^{-1})$ to designed controller will be reachable. In order to achieve the desired characteristic polynomials, the controller's polynomials must satisfy in Diophantine equations [8, 9].

$$A(z^{-1})R(z^{-1})+B(z^{-1})S(z^{-1})=A_c(z^{-1})A_o(z^{-1}) \tag{14}$$

$A_c(z^{-1})$ and $A_o(z^{-1})$ are desired and observer monic polynomials. From equation (13), System's zeros are changed by choosing $T(z^{-1})$. This is advantage of pole placement method to some ones such as PID designing. In equation (14), if the degrees of $A_c(z^{-1})A_o(z^{-1})$, $A(z^{-1})$ and $B(z^{-1})$ are assumed p, n, n-1 with $p > n$, then unknown polynomials is computed with least square from following relation

$$[R_{coff} \quad S_{coff}] = \begin{bmatrix} A_{diag} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ [0]_{(p-n)\times(n-m+1)} \qquad B_{diag} \end{bmatrix} = C_{coff} \tag{15}$$

here R_{coff} is a $(1\times p-1)$ vector, contains coefficients of polynomial $R(z^{-1})$, S_{coff} is a $(1\times p-n)$ vector, contains coefficients of polynomial $S(z^{-1})$, C_{coff} is $(1\times p+1)$ a vector, contains coefficients of polynomial $A_c(z^{-1})A_o(z^{-1})$, A_{diag} matrix and B_{diag} are matrix with $(p-n+1)\times(p+1)$ and $(p-n)\times(p-n+m)$ dimension that have shifting structure. This means each row of these matrices has zeros and coefficients of related polynomial. The first row begins with polynomial coefficients and other elements are zero. To make the second row, shift the coefficients vector right and put other elements zeros. This proceeding has been continuo foe the last row. So the structure of A_{diag} and B_{diag} are as follow. In definition of vector "a" and "b", a_i and b_i denoted to coefficient of Z^i in their polynomials.

$$a = [a_{n-1} \quad a_{n-2} \ a_{n-3} \ \cdots \ a_1 \ a_0] \tag{16}$$

$$b = [b_{n-1} \quad b_{n-2} \ b_{n-3} \ \cdots \ b_1 \ b_0] \tag{17}$$

$$B_{diag} = \begin{bmatrix} b & 0 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & b & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & b & 0 & \cdots & \cdots & 0 & 0 \\ \cdots & & \cdots & & \cdots & \cdots & & \cdots \\ 0 & 0 & 0 & 0 & \cdots & \cdots & b & 0 \\ 0 & 0 & 0 & 0 & \cdots & \cdots & 0 & b \end{bmatrix} \tag{18}$$

$$A_{diag} = \begin{bmatrix} a & 0 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & a & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & a & 0 & \cdots & \cdots & 0 & 0 \\ \cdots & & \cdots & & \cdots & \cdots & & \cdots \\ 0 & 0 & 0 & 0 & \cdots & \cdots & a & 0 \\ 0 & 0 & 0 & 0 & \cdots & \cdots & 0 & \mathrm{a} \end{bmatrix} \tag{19}$$

3.3. PID Control

One of common PID structure in discrete domain is in the form [8, 9].

$$G_{PID}(z^{-1}) = \frac{Q(z^{-1})}{P(z^{-1})} = \frac{q_0 + q_1 z^{-1} + q_2 z^{-2}}{(1-z^{-1})(1-\gamma z^{-1})} \tag{20}$$

q_0, q_1, q_2 are controller parameters. In order to achieve the desired characteristic polynomials, the controller's polynomials must satisfy in Diophantine equations.

$$A(z^{-1})P(z^{-1}) + B(z^{-1})Q(z^{-1}) = D(z^{-1}) \tag{21}$$

$D(z^{-1})$ is desired polynomial. This equation is the same as (14), but the degree of controller's polynomial is known. The matrix equation for solving Diophantine equation in this situation is defined as follow:

$$[P_{coff} \quad Q_{coff}]F = C_{coff} \tag{22}$$

$$F = \begin{bmatrix} A_{diag} \\ [0]_{3\times(n-m)} \qquad B_{diag} \end{bmatrix} \tag{23}$$

$$P_{coff} = [1 \qquad \gamma\text{-}1 \qquad \gamma] \tag{24}$$

$$Q_{coff} = [q_0 \quad q_1 \quad q_2] \tag{25}$$

In the equation (23), A_{diag} and B_{diag} are $(3\times(2+n+1))$ and $(3\times(2+m+1))$ matrices, defined as (18, 19). From equation (24) it can be seen that two columns of vector P_{coff} are dependent, so F_i if denote the i th row of matrix F then (22) is abbreviated as follow:

$$[\gamma \quad q_0 \quad q_1 \quad q_2]\begin{bmatrix} F_2 - F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix} = C - F_1 + F_2 \tag{26}$$

By compute the coefficients from above equation, PID parameters are obtained.

4. Simulation Result

The results of designed controllers are presented in this section. The initial conditions for identification progress are chosen same for two controllers. They have been selected as follow; the initial condition for covariance matrix was selected $P(0) = 1000I_6$ .The initial condition for estimated parameters was selected same for all ones and it was 0.9; the value of forgetting factor.

According the (5) the degree of denominator is six. However the PID controller can add 2 degree to system's model. So the reduction order method was used to compute the coefficients of PID controller. It has done with MATLAB "balred" command.

The observer polynomial in Diophantine equation has been chosen $A_o(z^{-1}) = 1$ because the difference between denominator degree and $B^+(z^{-1}) = 1$ is one. $B^+(z^{-1})$ is stable part of nominator polynomial.

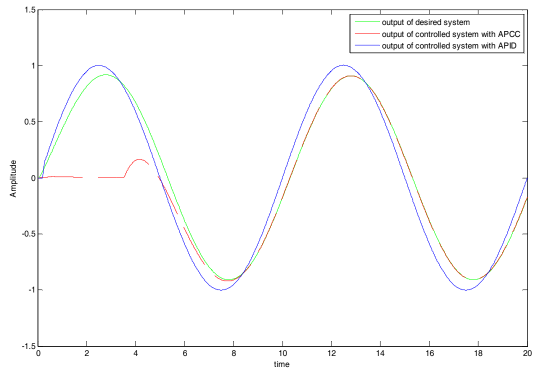

Fig. 3: Output of desired system and controlled system with APPC and APID controllers.

The outputs of controlled system and output of desired system and the signal of designed controllers have been shown in fig.2 and fig.3.

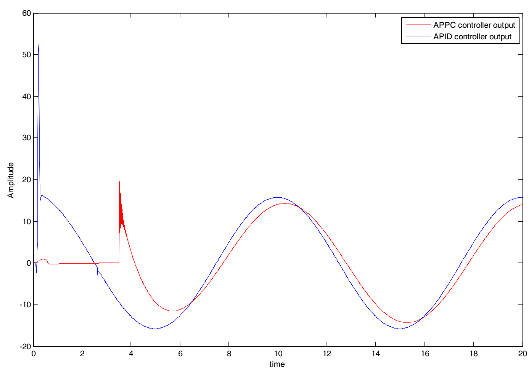

Fig. 4: APPC and APID control signals.

According the fig.2 the APPC controller is able to follow the desired output, however in the first period of time the output is not appropriate. The adaptive PID controller is not able to follow the desired output because it cannot place the system zeros to desire zeros but the parameter estimation convergence is faster than APPC controller.

5. Conclusion

In this paper Adaptive Pole Placement and Adaptive PID controllers was studied on active vibration isolation system. The theory of PPC and PID controller and parameter estimation were expressed. For solving a Diophantine, a matrix equation is described, so algebraic Diophantine equation was changed to matrix equation.

In section 4 simulation results were presented. It has been seen an APPC controller is be able to achieve the desired system's response; however the convergence of estimations parameter is slower than adaptive PID controller.Adaptive PID controller is not being able to achieve the desired response because it can't put the zeros of system in desired place. Also it has been seen controller output in APPC controller is better than adaptive PID controller results of designed controllers are presented in this section. The initial conditions for identification progress are chosen same for two controllers. They have been selected as follow; the initial condition for covariance matrix was selected $P(0)=1000I_6$.The initial condition for estimated parameters was selected same for all ones and it was 0.9; the value of forgetting factor.

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