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Real Time Vibration Control of Active Suspension System with Active Force Control using Iterative Learning Algorithm

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Abstract

This paper presents concurrent vibration control of a laboratory scaled vibration isolator platform with Active Force Control (AFC) using Iterative Learning Algorithm (ILA). The work investigates the performance of the traditional Proportional Integral Derivative Controller (PIDC) with and without AFC using ILA for vibration suppression. The physical single degree of freedom quarter car has been interfaced with a personal computer using a National Instruments data acquisition card NI USB 6008. The controllers are designed and simulated using LabVIEW simulation software. The results infer that the PIDC with AFC using ILA works superior than the PIDC.

Keywords

PID Controller, Active Force Control, Iterative Learning Algorithm, LabVIEW, Vibration Control

1. Introduction

The tremendous growth of road vehicle made the research on vibration control [1] more important, because the vibration will lead to unwanted noise in the vehicle, damage to the fittings attached to the vehicle and cause severe health problems to the passengers. In reality a vehicle undergoes random vibration as it moves on a rough road and the magnitude of vibration depends on the road condition. Repeated and prolonged exposure of the human being to vibration leads to many health problems such as increase in heart rate, spinal problems etc. Even less magnitude and continuous exposure to vibration can lead to passenger discomfort and eventually exhaustion.

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Hence the vehicle body has to be isolated from the sources of vibration. The conventional passive vibration isolation system consists of a spring and a damper. In 1995, Kashani, [2] pointed out that the performance of the passive systems is highly system dependent as they are unable to adapt or re-tune to changing disturbances or structural characteristics over time. An active suspension is the associative adaptation potential where the suspension characteristics can be adjusted while driving to match with the profile of the road being traversed. The active system uses sensors, actuators and control techniques within mechanical structures which allow higher degree of vibration isolation to be achieved. The suspension system of an automobile plays a vital role in vehicle handling and ride comfort.

Numerous control approaches such as optimal state feedback control by Hrovart in 1993 [3] and by Esmailzadeh et al. in 1996 [4], nonlinear adaptive control in 1997 by Alleyne et al. [5], finite frequency H_∞ control in 2011 by Sun et al. [6], robust H_∞ control in 2012 by Li-Xin et al. [7], fuzzy control in 2008 by Cao et al.[8] and in 2011 by Rajeswari [9], Proportional Integral Derivative (PID) control in 2011 by Rajeswari [9], proportional – integral sliding mode control in 2004 by Yahaya et al. [10], adaptive fuzzy sliding mode control in 2003 by Shiuh-Jer et al. [11], active force tracking control in 2010 by Rajeswari et al. [12] skyhook control in 2009 by Gopal Rao et al. [13], neural network in 2007 by Jyh-Chyang et al. [14] and adaptive robust control in 2013 by Weichao Sun et al. [15] have been proposed in the past for the control of active suspension system. In 2010, Hassan et al. [16] demonstrated a simulation study involving the application of an Active Force Control (AFC) strategy to suppress vibration on the rear handle of a handheld tool. The paper investigates the performance in terms of vibration reduction capability of a feedback controller employing AFC-based schemes on a selected powered portable machine. In 2010, Rajeswari et al. simulated the intelligent AFC scheme [12] with a fuzzy logic controller (FLC) applied to the vehicle suspension system of a quarter car model with actuator dynamics. Even though the intelligent methods are available, by considering the ethics, in order to make the system human controllable, they are limited to simulation works in laboratories. An attempt is made to apply a new simpler method to control an active suspension system in real time based on the AFC. AFC using an Iterative Learning Algorithm (ILA) which is discussed in 2002 by Zhihua et al. [17] is applied to the active suspension system setup and the experimental results proved the effectiveness of the proposed AFC control scheme in suppressing the undesirable effects of the suspension system.

Organization of the paper is as follows. Active Vibration Isolator (AVI) test rig is explained in section 2. Two control schemes are briefly explained in section 3. Controller simulation with real-time test rig is presented in section 4. Experimental results are presented and discussed in section 5. Conclusion and scope for future work are summarized in the final section of the paper.

2. Active vibration isolator

The design of an AVI experimental test rig [9] is based on the concept of active vibration control using sensors, actuators and control techniques within the mechanical structures. Figure 1 shows the block diagram for control of the AVI test rig using digital controller and the experimental test rig developed for test purpose is given in Figure 2. Experimental set up is an integration of the mechanical parts, electric/electronic devices and computer control to make the rig functional as an AVI.

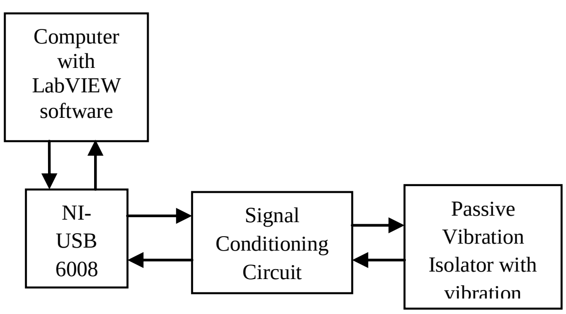

Figure 1: Block diagram for control of AVI test rig

The actuator plays a main role in active control of the dynamic system. An easy handled, maintenance free pneumatic actuator is used in this work, for rapidity of response and safety reasons. The components used to build this actuator are pneumatic cylinder of double acting type, electro-pneumatic positioner, an electronic positioner, air-filter and regulator. Electro-pneumatic actuator is chosen

Figure 2: Experimental setup

because it matched the demand, control configuration and cost. Random vibrations are produced by the electric motor rated 220 V, 50 Hz which is placed on top of the mass table [9] is shown in Figure 2. With the help of LabVIEW software and the use of a data acquisition card, NI USB 6008 with the input and output devices connected, the practical AVI rig that integrates both the software and hardware elements has been developed.
Force balance equation for the above system is given as:

$$M\frac{d^2x}{dt^2} = F(t) - C\frac{dx}{dt} - Kx - F_a \quad (1)$$

$$F(t) = F_0 \sin\omega t \quad (2)$$

where
- $x(t)$ Displacement of the mass
- K Spring constant
- C Damper constant
- F_a Actuator force
- $F(t)$ Force due to external vibration source (disturbance).
- F_0 The amplitude of the applied force
- ω The frequency of applied force

3. Control schemes

Active vibration control is electronic monitoring and control of system in harmony with the external vibration by the application of force provided by the external actuator. With this type of control, an industrial component can be maintained on a vibration free stage. The actuator will provide a force or displacement to the

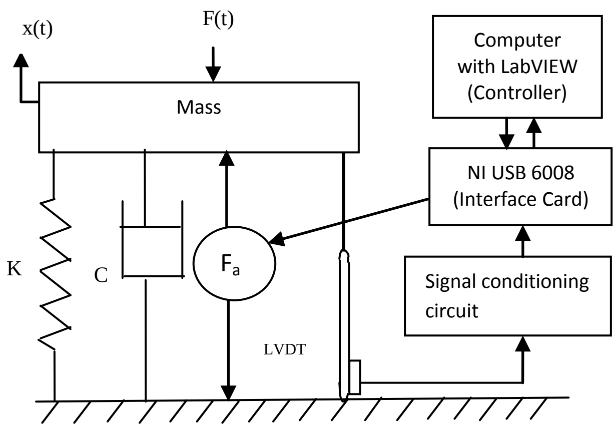

Figure 3: Active vibration control

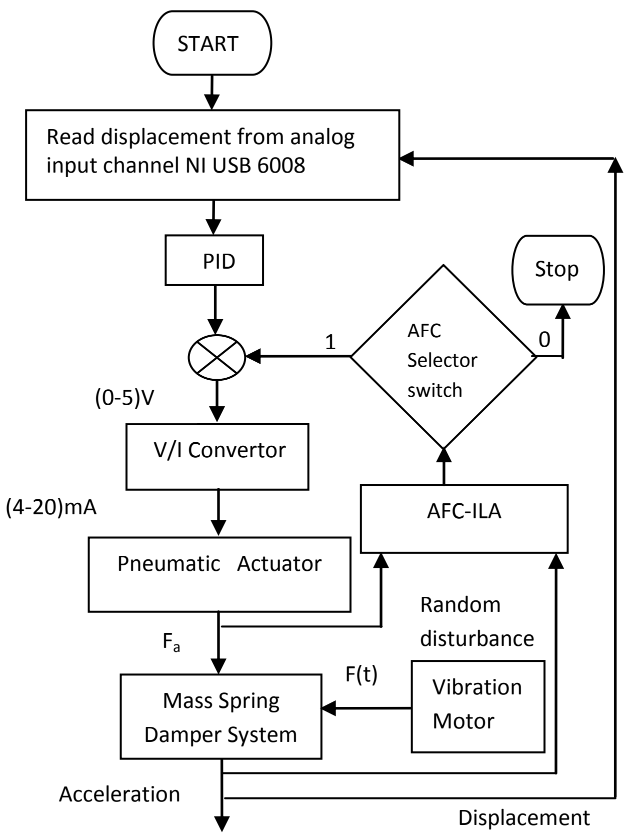

Figure 4: Flow chart for vibration control of mechanical suspension system

system based on the measurement of the response of the system using feedback control system. Based on Figure 3, an active vibration control system starts working with measuring the response of the system using suitable sensors. The displacement of the mass is detected by a LVDT displacement transducer. Then, the electronic circuit reads the sensors output and converts the signal appropriately and send it to the control unit. Based on the control law used, the calculated force signal is sent to the actuator and the controlled force is correspondingly applied to the system. The actuator force will actually compensate the vibration force in the system. PID and AFC-ILA are the two algorithms used in this experimental study. The selection of control scheme is revealed in the flow chart Figure 4. If the AFC selector switch is at '1' both PID controller output and AFC-ILA based control output are given to the actuator. Otherwise only PID controller output is available for control action. As a result of such feedback control system, stronger suppression of vibrations is achieved as compared to ordinary damper.

PID controller

A classic PID controller which is a combination of proportional, integral and derivative controller that can improve the total performance of the system ie. both the transient response and steady state response is used for controlling the vehicle active suspension system. PID controller transfer function that can be used for vibration control of active suspension system is given below.

$$G_c(s) = k_c[1 + \frac{1}{\tau_i s} + \tau_d s] \tag{3}$$

where is $G_c(s)$ the controller output

k_c is the proportional constant

τ_i is the integral time constant

τ_d is the derivative time constant

The gains such as k_c , τ_i and τ_d of PID controller are tuned with the method proposed by Ziegler-Nichols [18]. PID controller takes the present, the past and the future of the error into consideration. Tuned PID parameters are k_c = 1500, τ_i = 6.89 and τ_d = 0.036.

Active Force Control

AFC is introduced by Hewitt and Burdess in 1981 [19] and has been applied effectively to a number of dynamical systems as a two-Degree-Of- Freedom compensation action of AFC involves direct measurement or estimation of a number of identified parameters. Hence, a large portion of mathematical and computational burden can be reduced significantly. AFC can be shown to complement the basic Newton's second law of the essence of the AFC strategy is to obtain the estimated disturbances force, F^* via the measurement of mass acceleration, ' a '

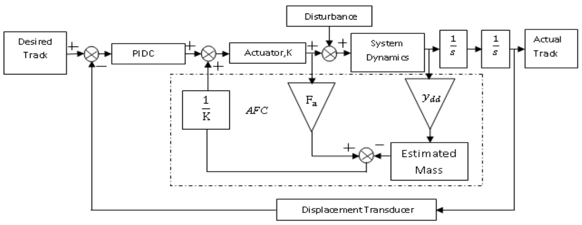

Figure 5: Block diagram of system with Active Force Control strategy

and actuator force, ' F_a ' together with an appropriate estimation of the estimated mass, M^* as described in the following equation.

$$F^* = F_a - M^* a \qquad (4)$$

It has been proved that the usage of AFC makes the system to remain in the stable state, robust and effective in the presence of known or unknown disturbances, uncertainties and various operating conditions [20] and [21]. Rajeswari et al. in [12] designed the AFC loop that compensates for the disturbance force obtained from the error between the ideal and actual force vector (Figure 5). The efficiency of the AFC strategy relies on the mass estimator as the body acceleration and the actuator force are easily obtained. A tracking control method ILA which has the ability to learn from earlier error on repetitive tasks is used for the estimation of mass. The estimated mass is multiplied with the acceleration to yield the estimated force and is used to cancel out the disturbance force. An Arimoto-type ILA [22] employs a combination of constant learning parameters very similar to the conventional PID controller gains which are directly related to the proportional, integral and derivative terms. Iterative learning control technique is applied to a class of flexible material transport system to damp out any string oscillation during transportation [17]. In [23] optimum PID parameters are achieved with the ILA. A simple control law is of the form

$$u_{p+1} = u_p + (\varphi + \psi \frac{d}{dt}) + e_p \qquad (5)$$

where u_p is the current value of output

u_{p+1} is the next value of output

e_p is the current tracking error

φ is the proportional learning parameter

ψ is the derivative learning parameter

From successive test runs, the learning parameter values are found to be $\varphi = 6.82$ and $\psi = 5.9$.

4. Experimental work

The AVI test rig parameters [9] are given below:
1. size of the frame
length : $600 * 10^{-3}$ m
breadth : $400 * 10^{-3}$ m
2. mass of the table 6 kg
3. spring constant 300 N/m
4. pneumatic actuator
cylinder diameter : $25 * 10^{-3}$ m
cylinder height : $140 * 10^{-3}$ m
pressure limit : 1 bar
maximum travel : $25 * 10^{-3}$ m

The analogue signals from the accelerometer and displacement sensor are given to a Personal Computer (PC) by using DAQ card NI USB 6008. PC after performing calculations generates a signal to be given to the pneumatic actuator for nullifying the effect of disturbance on the mass. Voltage signal is taken through the output ports of the DAQ card and is converted into a current signal by a suitable V/I converter. This current signal is given as the input to the electro pneumatic actuator which produces the control force to suppress the vibrations. Controllers are implemented using LabVIEW software. Simulations are conducted for passive mode, active mode with PID and AFC-ILA. All the relevant parameters and conditions are maintained the same for all the schemes to ensure a realistic and a fair one-to-one comparison.

5. Experimental results and discussion

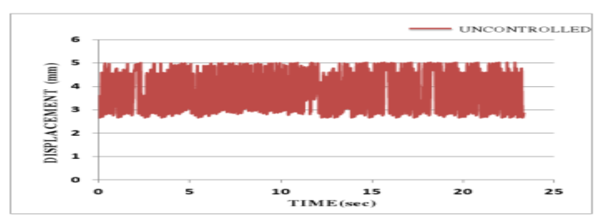

Figure 6: Displacement in passive mode

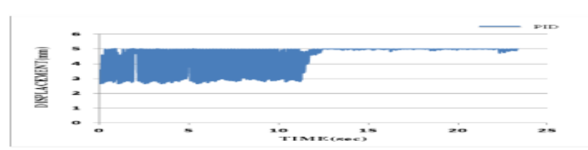

Figure 7: Displacement in active mode (PID without AFC-ILA)

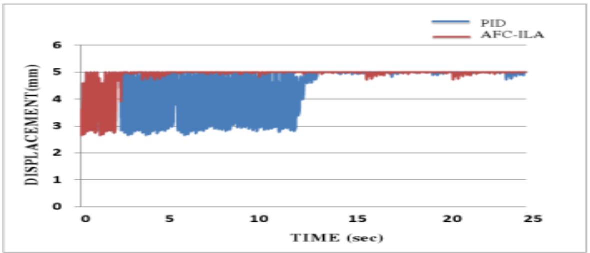

Figure 8: Displacement in active mode (PID with AFC-ILA)

Table 1: Performance comparison of control scheme with and without AFC-ILA

Control Scheme PID	**Settling time (sec)**
Without AFC-ILA	11.5
With AFC-ILA	2.9

Vibration isolation of the mechanical suspension system is achieved experimentally with the help of feedback controllers in an active mode. One of the main objectives of the experimental study is to obtain the best responses of each controller PID and AFC-ILA by tuning the respective parameters of the controllers. The position and acceleration of the rig with the input excitation have been measured using sensors installed at a suitable position in the rig. The experiment has been carried out for the random frequency generated by the vibration motor. Random vibrations have been generated by an electric motor with an unbalanced mass on its drive shaft. Figure 6 to Figure 8 shows the displacement response of the mechanical suspension system for passive, PID and AFC-ILA based controller respectively. Figure 6 shows the displacement response for the passive mode of operation is continuous. It is obvious from Figure 8, by using AFC-ILA technique the mass is brought to the equilibrium position in a faster time. It is demonstrated by both active modes vibrations are completely brought down and at the same time AFC-ILA performs better than only with PID in terms of settling time. AFC-ILA based control produces faster settling compared to the PID scheme without AFC-ILA (Table 1). It clearly shows that working of AFC-ILA is very efficient than PID with quick response action. Thus, both the PID and AFC-ILA schemes have shown the capability to suppress the vibration up to 98%. It is demonstrated from the experimental results, that provided better performance than its counterpart.

6. Conclusion and Future Work

AVI test rig has been developed in real time and control of vibrations using PID, with and without AFC-ILA with the help of the LabVIEW software have been experimented. From the results obtained, it is clear that the AVI using either PID or AFC-ILA based controller gives much better performance than the passive isolator. Overall, the AFC-ILA scheme gives an excellent performance in compensating the disturbances (vibrations at random) introduced into the suspension system. This clearly demonstrates the potential of the practical AFC-ILA scheme in that it can be readily implemented in real time arising from the fact that the control algorithm is mathematically simple and computationally not intensive.

In future, optimal intelligent based AFC can be designed so that the controller can work well irrespective of the system dynamics.

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