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VIBRATION SUPPRESSION USING MECHATRONIC SYSTEMS

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Abstract- Vibration suppression has always been an important issue in developing efficient motion control systems. Traditionally, in a mechanical system, the vibrations are suppressed by adding more material to the system in order to increase the rigidity. However, recent advancements in mechatronics, has provided with many alternative solution that avoids excess material addition and increased performance. This paper attempts to summarize various methods that are being developed for vibration detection and suppression. The techniques included in this paper are motion control strategies based on sensors, sensor-actuator and sensorless controllers.

Keywords*-Vibration suppression; Sensorless control technique; piezoelectric; shape memory alloy;PID; Input shaping*

I. INTRODUCTION

The vibration in machine structure has a significant effect on machine's performance. There is a need to develop systems for damping and control of vibrations in order to have high precision and speed. Due to the global demand for mass production, automation systems have to be consistently efficient to meet the requirements. An important issue for such systems is the jerk and vibration caused by the inappropriate acceleration or deceleration motion, which results in decreased accuracy and increased settling time to the motion control systems in the equipment. Moreover, motion induced vibration also occurs in such systems. The occurrence of vibration leads to an additional settling time before the new maneuver can be initiated. Therefore, in order to achieve a fast system response, it is imperative that this vibration is reduced.

Traditional method to suppress vibrations was to increase the rigidity of the system in order to resist the vibrations. Recent advancements in mechatronics have given rise to alternate solution in the form of a smart structure which would suppress the vibrations without significant increase the overall weight of the equipment. A smart structure used in vibration control can be defined as a structure of structure's component with bonded of embedded sensors and actuators as well as an associated control system, which enable the structure to respond simultaneously to external stimulus exerted on it and then suppress undesired effects of enhance desired effects. Various approaches have been proposed to reduce vibration in flexible systems. They can be broadly categorized based on control system used as feed-forward, feedback or a combination of both methods.

This paper talks about various smart materials and control strategies, used in passive and active vibration control. Smart materials like piezo-ceramics and shape memory alloys are extensively being studied for vibration suppression. However, there are other methods where the various control strategies are used in order to achieve the optimum damping characteristics with and without these smart materials. Few such methods are discussed in this paper.

II. PIEZOELECTRIC VIBRATION SUPPRESSION SYSTEMS

A. Bonded Piezoelectric Sensors and Actuators

Piezoceramics are well known smart materials for being lightweight, low-cost. They offer sensing and actuation capabilities that can be utilized for passive and active vibration control. Active vibration control (AVC) is well known nowadays as an optimum technique in vibration suppression of flexible structures. In AVC, constrained viscoelastic damping layers are usually used to attenuate the vibration of vibrating bodies. Gou Xinke Tian Haimin [1] presented a numerical study on the active vibration control of piezoelectric cantilever beam. In his study, he analyzed optimum position for placement of piezoelectric actuators on a cantilever beam.

In AVC, a controller receives the information about the induced vibration and supplies suitable control signals to actuators in order to suppress the vibration. From the results of Gou Xinke Tian Haimin's work it was evident that controlled dynamic response of displacement at the free end of the piezoelectric cantilever beam had significant less compared to uncontrolled dynamic response.

It was further observed that application of LQR optimal control algorithm suppresses excessive vibration when sensors and actuators are placed at fixed end of the cantilever beam as shown in figure 1.

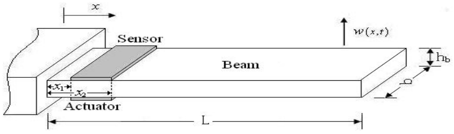

Figure 1 Cantilever Smart Sensor [1]

B. Active Force Control Strategy

In Active Force Control (AFC), a controlled varying force is applied by the actuators in order to suppress the vibrations. In AFC, it has been shown that the system subjecting to a number of disturbances remains stable and robust via the compensating action of the AFC control strategy [2]. The main concern in the AFC scheme is regarding the estimation of mass of the dynamic system to ensure correct estimation of total force to be applied by the actuator. This mass being estimated is virtual mass that represents mass of dynamic system. There are several methods to find correct value of mass matrix such as genetic algorithm, iterative learning algorithm, fuzzy logic and etc.

Zahidi Rahman's [3] experimental study of the vibration control of flexible structure using AFC method is chosen for discussion. He used heuristic method to estimate the mass matrix of flexible system along with an assumption that transfer function of actuator is unity. In this study, collocation of sensor and actuator was implemented. Thus an accelerometer was placed at the opposite side of piezoelectric patch actuator at the same flexible plate.

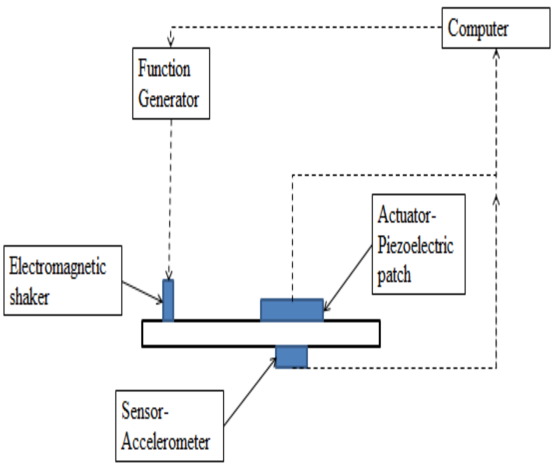

Figure 2 Schematic diagram of Active Force Control System [3]

Piezoelectric patch transducer was chosen to attenuate the disturbance vibration force from the plate. The transducer contracted when voltage is applied to create counter force.

The results of above mentioned study clearly indicates that AFC possessed the ability to attenuate the unwanted vibration of flexible system as long as a proper method is chosen to estimate the mass matrix of the system to ensure correct estimation of counter force subjected to the system.

III. CONTROL STRATEGIES FOR VIBRATION SUPPRESSION

C. Input-Shaping with PID

The command shaping technique is widely employed in control of flexible manipulators and aircraft [4, 5]. The design method involves convolving a desired command with a sequence of impulses known as an input shaper. The shaped command that results from the convolution is then used to drive the system. The method has been effective in reducing motion-induced vibration [6, 7].The performance of the feedback control can be improved by adding the feed forward control component, by achieving reduction in the system vibration. This is important for the fast maneuvering platforms, where the command signals change rapidly.

However, when the feed-forward control component is augmented with feedback component it causes additional delay in the system response. To resolve this issue, an objective function is created to tune the PID controller within the augmented strategy that gives the smallest overshoot, fastest rise time, quickest settling time and very small steady state error. In order to combine all these objectives, multiple objective functions are used to minimize the output error of the controlled system. To get optimum performance of a PID controller its parameters were tuned using GA optimization process by Fareg Aldebrez [8]. The population is represented by real valued numbers or binary strings each of 16 bits called a chromosome. Each chromosome consists of three separate strings constituting a Kp, Ki and Kd terms, as defined with in specific range, which can ensure stability.

The response due to shaped step input is stored and error is assessed taking the difference between the desired and actual response. This error signal is processed based on different criteria to evaluate the performance and assign a fitness value to that individual. Using the fittest individuals, the next population is generated through a process of shuffle crossover with reduced surrogate and mutation operation [9].

This method was experimentally implemented on a 4-impulse input shaper, designed on the basis of vibration frequency and damping ratio of the main rotor system. The designed input shaper was used for pre-processing the reference signal. It was observed that oscillation in the system response has been significantly reduced due to the shaped reference signal.

The system performance after GA tuning process recorded further reduction in settling time. This study has proven that with proper tuning, a PID controller can be used to controls an augmented feed-forward control component combined with feedback control component to achieve significant improvement in the dynamic system response with satisfactory level of vibration reduction.

D. Acceleration Profile Control

An important issue in high precision and high speed automatic equipment is the jerk and vibration caused by inappropriate acceleration or deceleration motion, which results in decreased accuracy and increased settling time to the positioning table. To solve such problems and reach a high production efficiency level, the motion control must have the capability to plan trajectory and generate motion profile in such a way that the accelerating and decelerating phases become much smoother to reduce inertia force and decrease residual vibration of point-to-point motion. A typical point-to-point motion profile can be divided into three phases: accelerating, constant speed and decelerating.

To improve the performance, the velocity profile is modified to have an s-shape during the acceleration and deceleration periods to reduce the residual vibrations caused in a mechanical system by a moving mass. In such s-curve velocity profile, the trajectory ramps up to peak acceleration and ramps down to constant speed. Though s-curve motion profile gives faster and more precise motion compared to trapezoidal velocity profile, it is noted that s-curve profile still exhibits a sudden jerk profile, and the finite jerk spreads out over a period of time [10].

A method proposed by H.Z.Li [11] smoothens the acceleration profile using sine wave function to achieve smoother jerk profile. The main objective of this method was to minimize the high acceleration induced jerk in high-speed and high-precision motion control. The DSP controller performs the servo motion control by providing motion profile generation, position determination, position error calculation, and motion commands creation in real time. In this method, the profile data was calculated using Matlab script and the values for the constant velocity and deceleration parts are calculated by the DSP. The results showed that it is possible to reduce the motion-induced transient vibration of a structure by using a sine wave profile.

E. Sensorless Control Technique

When vibration in a flexible system has to be suppressed, using motion control system with sensors, multiple sensors will be required. Multiple sensors require multiple wiring along with their associated electronic setups. Moreover, using certain sensors increases the mechatronic products' cost tremendously, especially if force/torque feedback is required. In addition, control of flexible systems requires using sensors with certain specifications such as fatigue resistance to withstand the everlasting fluctuations due to simplest maneuvers. To overcome most of such issues sensorless control techniques are being developed. Sensorless techniques reduce the hardware sophistication that is added when sensors are utilized.

Action-reaction event normally occurs at the actuator-plant's point of interface. Actuator's action on any given dynamical system is naturally followed by an instantaneous dynamical system reaction. The actuator's action and dynamical system's reaction are related. Therefore, one can get the information about the plant's dynamics and parameters through measurement taken from the other system that imposes the action. Gulnihal Cevik [12] discusses about one such sensorless technique where based on the measurements from system imposing action, an estimation algorithm combined with regular LQR is capable of achieving motion control and vibration suppression without taking any measurement from the flexible plant. The correctness of the whole analysis discussed in [12] shows that almost zero variation of the estimated displacement and real ones and the vibration is significantly decreased in comparison to a PID control. However the estimation algorithm will not compensate for unknown or sudden effects on the system. The unknown parameters can be the masses of peripherals, springs, parts of the setup etc. These external effects can be minimized be more experience and thus finding equivalent gains for these unknowns.

IV. VIBRATION CONTROL USING SHAPE MEMORY ALLOYS

Shape memory alloys (SMAs) have been widely employed as actuators and sensors in applications including smart structures, biomedical devices, and robotics. When heated above the transformation temperature, the SMAs undergo a change in the crystal structure, thereby generating large forces that can be used to actuate the control systems. However, due to the inherent nonlinear and complex dynamic behavior of the SMA actuators, it is generally difficult to design a controller that guarantees closed loop stability within the performance bounds [13, 14].

There are comparative merits and demerits of the SMA actuators with respect to the piezoelectric actuators. The SMA actuators are capable of producing large forces, withstanding large stresses and recovering large strains, unlike piezoelectric actuators, which are brittle, and when subjected to large stresses, can become depolarized and ineffective. The SMA actuators are attached to each flexible link for the vibration suppression.

The SMA actuators are wires that act in pairs to provide a bidirectional control i.e., the actuators tend to counteract. The slow response of the SMAs is a major limitation in practice, and thus, loses effectiveness at high frequencies of vibration, whereas the piezoelectric actuators can operate at frequencies, of the order of 10 kHz [15]. The slow response of SMA can be partially circumvented by reducing the size of the actuators to increase the rate of heat transfer. However, the force production decreases with size, thus diminishing the advantage of the SMAs in delivering large forces. For successful implementation of the SMAs, engineers need to balance the force requirements of the application in concern with the rate of cooling that can be achieved in the operating environment.

V. CONCLUSION

This paper discusses various options available to suppress the vibrations using mechatronics system. The methods discussed serve as an alternate option to material addition which has been traditional practice to increase rigidity. It is clear from our discussion that SMAs are only limited to low frequency vibrations and is a long way from being effective in active vibration control. Though control techniques discussed were very effective in certain applications, they're limited to those applications. However, their applications can be extended by combing with an actuator and sensor. Hence it can be said that actuator-sensor based control strategies can achieve optimum vibration suppression. And as discussed, piezoelectric actuators, because of their high frequency response, can be the best option for such control strategies, as it can be easily augmented with variety of control strategies.

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