Abstract - This paper reviews research in the field of active vibration control and describes the most important methods of implementation. Nonadaptive and adaptive systems (feedforward, feedback and hybrid control structures, single and multiple channel case) with adaptive algorithms are outlined. Influence and modeling of secondary path is presented. Major applications and directions for further research are indicated.

Index Terms - active vibration control, feedforward, feedback, adaptive control, LMS, FXLMS

I. INTRODUCTION

Active vibration control (AVC) is the active application of force in an equal and opposite fashion to the forces imposed by external vibration, [1, 2, 3, 4]. Most machines and structures are required to operate with low levels of vibration as smooth running leads to reduced stresses and fatigue and little noise. Vibration is often limiting factor in performance of many industrial systems, [5, 6, 7]. Use of passive damping is effective at higher frequencies, but often of little use at lower frequencies. Passive vibration control treatments are unable to adapt or re–tune to changing disturbance or structural characteristics, over time. Active vibration control systems have emerged as viable technologies to fill this low frequency gap. They do not penalize the weight sensitive structures by adding excessive weight to them.

II. DESTRUCTIVE INTERFERENCE

Active vibration control based on principles of superposition and destructive interference, [2, 3]. It is achieved by application of identical force but exactly reverse in phase to the offending vibration, Fig. 1. As a result vibrations cancel each other. Consider the case when source vibration is sinusoidal:

\[ F_1 = A \sin \omega t \]  (1)

The actuator force is:

\[ F_2 = -(A + a) \sin(\omega t + \theta) \]  (2)

where \( a \) and \( \theta \) represent the amplitude and the phase error between two forces.

Resultant force is given by relation:

\[ F_1 + F_2 = F = A \sqrt{4 + \left(1 + \frac{a}{A}\right) \sin^2 \theta + \left(\frac{a}{A}\right)^2} \]  (3)

Level of the resultant depends on amplitude and phase errors. Great attenuation can be achieved if amplitude and phases are closely matched (3), [3]. In real world source vibration is of more complex waveform that can be represented as a sum of harmonically related components, each with its frequency and phase angle. Efficient AVC system should produce the control signal that will address all these components.

III. ACTIVE VIBRATION CONTROL SYSTEM

Block diagram in Fig. 2 illustrates general idea behind an AVC system, its elements and interactions of system with controlled mechanical structure. Major components of an AVC system are the plant, actuators, sensors, and a controller. Implementation of typical AVC system is illustrated in Fig. 3, [1, 2, 3, 4]. System in Fig. 3 and Fig. 4 is a fully active vibration control system that consists of an actuator which actively reacts on the vibrations of controlled structure. Semiactive vibration control systems are those where passively generated damping or spring forces are modulated according to a parameter tuning policy with only a small amount of control effort, [8]. Properties of a passive device (like stiffness or damping) can be varied in real time with a low power input. As they are inherently passive, they cannot destabilize the system. Such systems fill the gap...
between purely passive and fully active vibration-control systems and offer the reliability of passive systems, yet maintain the versatility and adaptability of fully active devices.

IV. VIBRATION TRANSDUCERS

AVC systems use sensors to measure plant vibration and actuators to introduce control forces, [6, 9].

A. Sensors

Error and reference sensors are employed to measure the motion of the system to be controlled, [5, 6, 9]. Vibration sensors in AVC systems are mostly of piezoelectric type. An electric field is generated due to a change in dimensions of a material. Frequency and phase responses of piezo sensors are quite flat across large frequency range.

B. Actuators

Actuators are used to introduce control forces into the plant in order to modify its behavior, [5, 9]. They can be:

- Piezoelectric
- Electrodynamic
- Hydraulic

Electrodynamic actuators or shakers consist of a moving wire coil mounted inside a permanent magnet. Frequency and particularly phase responses of actuators (with the exception of piezo actuators) change considerably with frequency. Electrohydraulic (often called servohydraulic) shakers are valued for their long stroke and high force commencing at extremely low frequencies.

C. Actuators for Semiactive Control

Particular kind of actuators are electro/magneto-rheological fluids and magnetostrictive actuators, [8]. They change dimensions of a material due to the application of an electric and magnetic field and are used in semiactive vibration control systems for changing parameters of passive systems.

Sensors and actuators are separate entities, but there is interesting use of same piezoceramics both as sensors and actuators as described in [10].
the input of the plant $S$ (secondary path) see Fig. 5. The disturbance observer is used to reconstruct the primary waveform and to generate the secondary cancellation signal (Fig. 6).

![State observer model](image)

Fig. 6. State observer model

The disturbance is modeled as a sum of finite number of sinusoidal signals, which are harmonically related.

$$d(k) = \sum_{i=1}^{n} A_i \sin(2\pi f_i t + \phi_i)$$  \hspace{1cm} (4)

where $n$ is the number of considered harmonics, $A_i$ and $\phi_i$ are the amplitude and the phase of $i$-th harmonic, $f_i$ frequency of single harmonic and $t$ time. The disturbance attenuation is achieved through producing an estimate of the disturbance $d$ and using this estimate, with a sign reversal, as a control signal $u$:

$$u(k) = -\hat{d}(k)$$  \hspace{1cm} (5)

The observer is designed off-line assuming time-invariance and investigating the property of robustness over a certain frequency range for a single observer. Disturbance model is described in (6) and (7), [11]:

$$x(k+1) = Ax(k) + Bu(k)$$ \hspace{1cm} (6)

$$y(k) = Cx(k)$$ \hspace{1cm} (7)

B. Adaptive Approach

Adaptive approaches generally use adaptive digital filters and algorithms for adjusting parameters of these filters, [12]. General feedforward system is illustrated in Fig. 7. System identification viewpoint of AVC is illustrated in Fig. 8.

1. Adaptive Feedforward Control Structure

![Block diagram of feedforward system](image)

Fig. 7. Block diagram of feedforward system

![System identification viewpoint of AVC](image)

Fig. 8. System identification viewpoint of AVC

The Filtered-X LMS (FXLMS) algorithm is the form of the LMS algorithm that considers transfer function of the secondary path following the adaptive filter. Instead of $x(n)$, algorithm uses $x(n)$ filtered by $\hat{S}(z)$, hence the name 'Filtered-X LMS', [1]. Coefficient updating is given by the following equation:

$$W(n + 1) = W(n) + 2\mu\hat{x}'(n)e(n)$$ \hspace{1cm} (11)

Determination of the secondary path can be accomplished in off-line and on-line mode:

Feedforward is preferred method when designer has direct access to information about the disturbance signal to the system, [1, 2]. The objective of adaptive FIR filter is to minimize the residual error signal. Most popular algorithm for adjusting adaptive FIR filter is LMS algorithm, [12, 3].

Filter output is defined:

$$y(n) = x^T(n)W(n)$$ \hspace{1cm} (8)

Error signal is:

$$e(n) = d(n) - e(n)$$ \hspace{1cm} (9)

and coefficient updating is:

$$W(n + 1) = W(n) + 2\mu X(n)e(n)$$ \hspace{1cm} (10)
Off-line modeling determines the secondary path when AVC system is not operating. Such system has a calibration phase when the secondary path estimate is determined. White noise signal \( x(n) \) is supplied to the actuator and error signal is picked by the nearby sensor. These two signals are used by the LMS algorithm to estimate a copy \( \hat{S}(z) \) of the transfer function \( S(z) \).

On-line modeling determines and continually adapts the secondary path estimate together with the normal operation of an AVC system. This is achieved by injecting additive random noise as illustrated in Fig. 12, [1].

Two important requirements regarding the secondary path modeling are:
1. Accurate estimate \( S(z) \) should be produced regardless of the controller transfer function \( w(z) \).
2. Estimation of \( S(z) \) should not intrude operation of AVC system.

Tradeoff between these two requirements can be solved by the Additive Random Noise Technique. Estimation of \( S(z) \) is accomplished by injected zero-mean white noise that is added to a secondary signal, as illustrated on Fig. 12. The higher the noise level, the better the convergence of \( S(z) \). On the other hand there always remains residual error that equals at least to injected noise. The secondary path modeling increases complexity of control system. Variants of FXLMS algorithm with improved convergence properties are described in [14].

2. Adaptive Feedback Control Structure

Feedback control is suitable when the disturbance signal cannot be observed directly [1, 2]. Adaptive feedback AVC system synthesizes its own reference signal based only on the adaptive filter output and the error signal. Block diagram of general feedback system is presented in Fig. 13. [1, 2, 3]. Feedback system with secondary path modeling is illustrated in Fig. 14. The synthesized reference signal \( x(n) \) is given by:

\[
x(n) = \hat{d}(n) = c(n) + \sum_{k=0}^{K-1} \hat{s}_k y(n-k)
\]

Weight updating of coefficients \( w_m \) of filter \( W \) is given by:

\[
w_m(n+1) = w_m(n) + \mu x'(n)e(n)
\]

where filtered signal \( x'(n) \) is:

\[
x'(n) = \sum_{k=0}^{K-1} \hat{s}_k x_m(n-k)
\]

and \( K \) is a length of FIR filter for \( \hat{S}(z) \) with coefficients \( \hat{s}_k \).

### TABLE I

<table>
<thead>
<tr>
<th>Type of control</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Feedback</td>
<td>- simple to design</td>
<td></td>
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<tr>
<td>Adjust for errors as they take place</td>
<td>- no process model required</td>
<td></td>
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<tr>
<td>Method: model based (LQG, ( H_\infty )) or adaptive filtering (FX-LMS)</td>
<td>- guaranteed stability when collocated</td>
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<td></td>
<td>- global method</td>
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<td></td>
<td>- attenuates all disturbances within ( \omega_c )</td>
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<td>- only corrects for errors after they happen</td>
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<td></td>
<td>- generally takes input from one sensor</td>
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<td>- limited bandwidth (( \omega_c &lt; \omega_s ))</td>
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<td></td>
<td>- disturbances outside ( \omega_c ) are amplified</td>
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<tr>
<td>Feedforward</td>
<td>- requires reference signal</td>
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<tr>
<td>Anticipate and correct for errors before they happen</td>
<td>- local method</td>
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<tr>
<td>Method: adaptive filtering (FX-LMS)</td>
<td>- response may be amplified in some part of the system</td>
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3. Adaptive Hybrid Control Structure

![Fig. 15. Hybrid AVC with combination of feedback AVC and feedforward AVC](Image)

The hybrid method for vibration suppression use synergy between feedforward and feedback control, Fig. 15, [1]. The feedforward control extends the bandwidth of the controller for steady state disturbances with a correlated reference, while the feedback control reduces drastically the impulse response of lightly damped structures, avoiding the problems associated with truncation.

4. Multiple Channel Control Structure

It is possible to design AVC system with several error sensors, several actuators and even several reference sensors.

![Fig. 16. Multichannel AVC system](Image)

The goal of multichannel system is to minimize kinetic energy of vibrating structure. An estimate proportional to the kinetic energy of the structure is given by

\[ E = \sum_{m} |\dot{w}_m|^2 \]  

(15)

where \( N \) is the total number of accelerometers and \( \dot{w} \) is out-of-plane velocity obtained by integrating the accelerometer signal. Adaptive algorithms are matrix extensions of single channel systems. Following variations of multichannel control structure are common in AVC: Single Reference/Multiple-Output, Multiple-Reference/Multiple-Output and Multiple Channel Adaptive Feedback System.

VII. SMART STRUCTURES

![Fig. 17. Smart structure](Image)

A Smart Structure is a structure that can sense an external disturbance and respond to that with active control in real time. It typically consists of a host structure incorporated with sensors and actuators coordinated by a controller, Fig. 17, [4]. The integrated structured system is called smart because it has the ability to adapt to environmental change. Promising applications are the control and suppression of structural vibrations, [15,16,17].

VIII. APPLICATIONS

Vibration control can be applied to various kinds of engineering systems to obtain the desired dynamic behavior, improved accuracy and increased reliability during operation. Applications are related to control of structures vibration isolation, control of vehicle dynamics, noise control, control of machine mechanisms as well as control of fluid-structure-interaction. Practical applications employ Active and Semiactive Vibration Damping, Active and Semiactive Vibration isolation and Active Structural Acoustic Control. Some of more important fields are:

A. Engines and Vehicles

Weight saving are achieved due to replacement of heavy passive absorbers. Secondary benefits are improved mission performance and enhanced passenger comfort. Main examples are listed bellow:

1. Active vibration control in large diesel engines
2. Engine-induced vibration in automotive vehicles
3. Gearbox vibrations, [18]
4. Aircraft Engine
   - Active engine mounts: Controlling vibration at low frequencies in a passive mount requires soft materials, which are impractical to use for statically maintaining the engine in position.
   - Fan/Rotor active balancing
5. Power Generations
   - Shaft active balancing
   - WT tower vibration control
6. Active magnetic bearings (SKF)
7. Active Vibration Control in Light Weight Vehicles
   - In order to allow the future use of lighter materials, it is necessary to reduce the vibration and radiated noise of components in the car by AVC
8. Vibration suppression of rotating machinery, [19]
9. Active vibration control for reducing vibration in helicopters, offering better comfort with less weight than traditional passive technologies, [20]

B. Precision Instruments

High-precision machines typically suffer from small but annoying vibrations. Modern technologies, e.g. in the field of high-resolution measurement, high-precision manufacturing processes and super lightweight construction, require effective anti-vibration solutions to achieve maximum performance. Some examples are:

1. Precision working surfaces
2. Active Vibration Control in Fabs
- Many processes in fabs are highly sensitive to vibrations (optical and electron beam tools).
3. Medical Instruments
- Active balancing and damping, accurate suspension
4. Instruments for precise physical experiments (e.g. Michelson interferometer)
5. Computer hard disk drives track-following control for high density data recordings. [21]

C. Buildings and Architecture

Vibration control of buildings subjected to seismic excitation can be achieved by AVC. Some examples are:
1. Active tendon control of bridges
2. Earthquakes
   - Structural control against earthquakes is becoming increasingly important, [22, 23]
3. Wind loads - main sources of structural vibrations
4. Telescope vibration control [24]
5. Active Control of Power Flow in Beams
6. Floor vibration control, [25]

IX. DIRECTIONS FOR FURTHER RESEARCH

Topics of future research are the choice of the optimal control strategy, optimal sensor and actuator locations and the selection of appropriate sensors and actuators, [26]. There is still room for improvement of control strategies to include nonlinear characteristics of actuators. In active vibration control of structures, some parameters such as the location of actuators and sensors have a major influence on the performance of the control system. There is also a need for actuators capable of performing in harsh environments (high temperature, pressure, humidity and greasy/corrosive environment) and high energy density actuators (system miniaturization, high force and high stroke applications).

X. DISCUSSION AND CONCLUSION

AVC cancels unwanted vibration by introducing vibration of equal amplitude but opposite phase through the actuators. Active control of vibration has become an important area of development in recent years. The variations in the type and nature of the source and disturbance have led to the exploration of different control structures and design criteria. For simple problems analog feedback control system suffice, for more complex problem there exist various adaptive digital control solutions. Many of traditional problems can be treated more efficiently with AVC than with passive approaches of the past.

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