Proceedings of the Institute of Acoustics

ADAPTIVE ACTIVE CONTROL OF NOISE AND VIBRATION

M O Tokhi and M A Hossain

Department of Automatic Control and Systems Engineering, University of Sheffield, UK.

1. INTRODUCTION

Active noise/vibration control consists of artificially generating cancelling source(s) to destructively interfere with the unwanted source and thus result in a reduction in the level of the noise/vibration (disturbances) at desired location(s). This is realised by detecting and processing the noise/vibration by a suitable electronic controller so that when superimposed on the disturbances cancellation occurs. Due to the broadband nature of these disturbances, it is required that the control mechanism realises suitable frequency-dependent characteristics so that cancellation over a broad range of frequencies is achieved. The dependence of the required controller characteristics on frequency-dependent components within the system makes it possible to estimate/measure the controller transfer function and realise this either as an analogue or digital or hybrid controller [1,2]. In practice, the spectral contents of these disturbances as well as the characteristics of system components are in general subject to variation, giving rise to time-varying phenomena. This implies that the control mechanism is further required to be intelligent enough to track these variations, so that the desired level of performance is achieved and maintained.

This paper presents an investigation into the development of an active control mechanism for noise cancellation and vibration suppression within an adaptive control framework. An active noise control (ANC) system is designed utilising a single-input single-output (SISO) control structure to yield optimum cancellation of broadband noise at an observation point in a linear propagation medium. The controller design relations are formulated such that to allow on-line design and implementation and, thus, yield a self-tuning control algorithm. The algorithm is implemented on an integrated digital signal processing (DSP)/transputer system, using DSP and parallel processing (PP) methods, and its performance assessed.

A flexible beam system in transverse vibration is considered in fixed-free and fixed-fixed forms for vibration suppression. Such a system has an infinite number of vibration modes although in most cases the lower modes are the dominant ones requiring attention. The unwanted vibrations in the structure are assumed to be caused by a single point disturbance of broadband nature. These are detected and suitable suppression signals generated via a point actuator to yield vibration suppression over a broad frequency range along the beam. The self-tuning control algorithm developed within the ANC system is implemented within a SISO vibration control structure using the integrated DSP/transputer system and its performance assessed.

2. ACTIVE NOISE CONTROL

A schematic diagram of the geometrical arrangement of a SISO ANC structure is shown in Figure 1(a). An unwanted primary point source emits broadband noise into the propagation medium. This is detected by a detector located at a distance r_e relative to the primary source, processed by a controller of suitable transfer characteristics and fed to a cancelling (secondary) point source located at a distance d relative to the primary source and a distance r_f relative to the detector. The secondary signal thus generated is superimposed on the primary signal so that to achieve cancellation of the noise at and in the vicinity of an observation point located at distances r_g and r_h relative to the primary and secondary sources respectively.

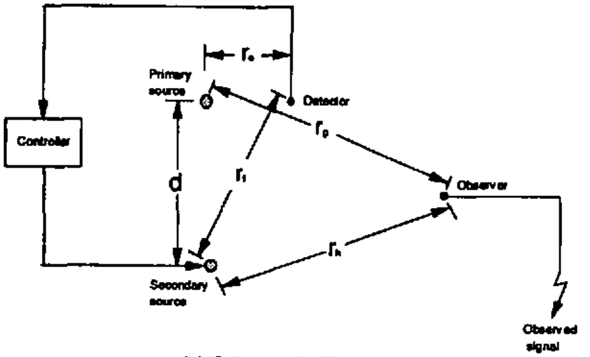
A frequency-domain equivalent block diagram of the ANC structure is shown in Figure 1(b), where E, F, G and H are transfer functions of the acoustic paths through the distances r_e, r_f, r_g and r_h respectively. M, M_o, C and L are transfer characteristics of the detector, the observer, the controller and the secondary source respectively. U_D and U_C are the primary and secondary signals at the source locations, whereas, Y_{OD} and Y_{OC} are the corresponding signals at the observation point respectively. U_M is the detected signal and Y_O is the observed signal. The block diagram in Figure 1(b) can be thought of either in the continuous frequency (s) domain or discrete frequency (z) domain. Therefore, unless specified, the analysis and designs developed in this paper apply to both the continuous-time and the discrete-time domains.

The objective in Figure 1 is to achieve total (optimum) cancellation of the noise at the observation point. This is equivalent to the minimum variance design criterion in a stochastic environment. This requires the primary and secondary signals at the observation point, to be equal in amplitudes and have a phase difference of 180^0 relative to each other. Thus, synthesising the controller within the block diagram of Figure 1(b) on the basis of this objective yields

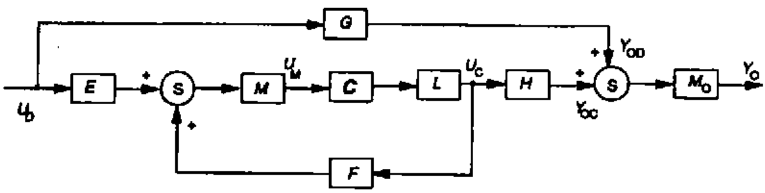
$$C = \frac{G}{ML(FG - EH)} \qquad (1)$$

Equation (1) is the required controller transfer function for optimum cancellation of broadband noise at the observation point.

Note in equation (1) that, for given secondary source and detector the controller characteristics are determined by the geometric arrangement of system components. This incorporates the location of the detector and the observer with respect to the primary and secondary sources.



(a) Schematic diagram.



(b) Block diagram.

Figure 1: Active noise control structure.

Among these, there exist arrangements that will lead to the denominator, *FG - EH,* in equation (1) approaching zero and thus requiring the controller to have impractically large gain. Thus, an analysis of the system on this basis yielding the locus of detection and observation points for which the controller will be required to have an impractically large gain for optimum cancellation is required at a design stage [3]. Moreover, note in Figure 1(b) that the secondary signals reaching the detector form a positive feedback loop that can cause the system to become unstable for certain geometrical arrangements of system components. Therefore, an analysis of the system from a stability point of view leading to a robust design of the system is important at a design stage [4].

2.1. Self-tuning Active Noise Control

Consider the system in Figure 1 as a SISO system with the detected signal, U_M, as input and the observed signal, Y_O, as output. Moreover, owing to the state of the secondary source let the system behaviour be characterised by two sub-systems, namely, when the secondary source is *off*, with an equivalent transfer function denoted by Q_0, and when the secondary source is *on*, with an equivalent transfer function denoted by Q_1. Using the block diagram of Figure 1(b), these can be obtained as

$$Q_0 = \frac{M_e G}{ME} \quad , \quad Q_1 = \frac{M_e G}{ME}\left[1 - \frac{ML(FG - EH)}{G}\right] \tag{2}$$

Note that in obtaining Q_0 and Q_1 in equation (2) the controller block in Figure 1 is replaced simply by a switch; the controller transfer function is not known before an estimation/measurement process. Manipulating equation (2) and using equation (1) yields an equivalent design relation for the controller in terms of Q_0 and Q_1 as

$$C = \left[1 - \frac{Q_1}{Q_0}\right]^{-1} \tag{3}$$

Equation (3) is the required controller design rule given in terms of transfer characteristics Q_0 and Q_1 which can be measured/estimated on-line. An on-line design and implementation of the controller can thus be achieved by obtaining Q_0 and Q_1 using a suitable system identification algorithm (e.g. a recursive least-squares parameter estimation algorithm), using equation (3) to calculate the controller transfer function and implementing this on a digital processor. Moreover, to monitor system performance and update the controller characteristics upon changes in the system a supervisory level control can be utilised. This results in a self-tuning ANC mechanism. The supervisor is designed to monitor system performance on the basis of a pre-specified quantitative measure of cancellation as an index of performance, so that if the cancellation achieved is within the specified range then the algorithm implementation remains at the control level. However, if the cancellation is outside the specified range then self-tuning is re-initiated at the identification level. The supervisory level can also be facilitated with further levels of intelligence such as monitoring system stability, system performance in a transient period, validation of the plant model at the identification level, etc.

2.2. Experimentation

To assess the performance of the self-tuning ANC algorithm a simulation environment characterising the structure in Figure 1 was constructed using practical measurements of noise propagation in a three-dimensional medium. The propagation medium is assumed to be non-dispersive (linear), where a sound wave in propagating through a distance r is attenuated in amplitude inversely with r and delayed in phase directly with the product of r and the frequency of the wave.

The self-tuning ANC algorithm was implemented on an integrated DSP-transputer system incorporating an i860 DSP device and a T805 transputer using DSP and PP methods. To assess the performance of the algorithm a broadband (0-512 Hz) PRBS signal was used as the unwanted primary noise. Figure 2 shows the difference between the autopower spectral densities of the noise before and after cancellation, i.e. the cancelled spectrum. It is noted that an average cancellation level of nearly 40 dB is achieved over the broad frequency range of 0-512 Hz. As compared with previous implementations using DSP devices only this significant level of cancellation over a broad range of frequencies is due to the computing power achieved by the utilisation of DSP and PP methods.

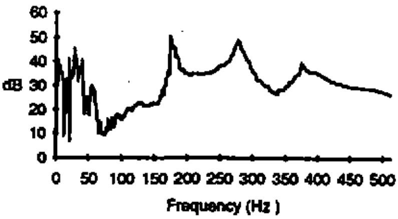


Figure 2: Cancelled noise spectrum.

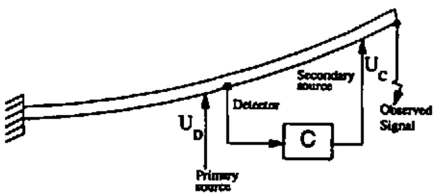


Figure 3: Active vibration control system.

3. ACTIVE VIBRATION CONTROL

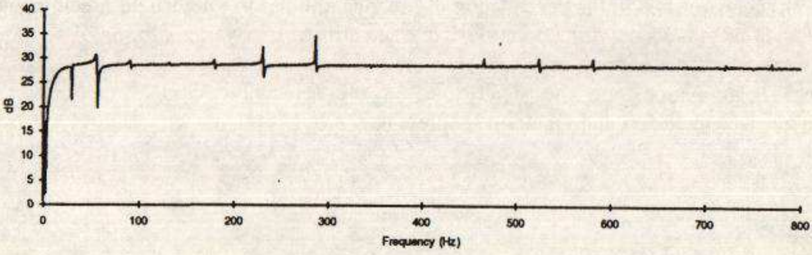
Active vibration control (AVC) is realised in a similar manner as ANC. The design of an AVC system depends upon the complexity of the structure under consideration and the nature of the disturbance process. A schematic diagram of the AVC system, incorporating a fixed-free beam, is shown in Figure 3. The unwanted vibrations in the structure are assumed to be caused by a single point disturbance force (U_D) of broadband nature. These are detected by a point detector, processed by a controller to generate suitable suppression signals (U_C) via a point actuator so that to yield vibration suppression over a broad frequency range at an observation point along the beam. A frequency-domain equivalent block diagram of the AVC system in Figure 3 will give rise to that of the ANC system in Figure 1, with a similar interpretation of the transfer functions and signals involved. In this manner, the required controller transfer function for optimum vibration suppression at the observation point is, therefore, given as in equation (1) with the corresponding equivalent relation suitable for on-line design and implementation as in equation (3). Therefore, a similar formulation of the self-tuning control algorithm developed for noise cancellation applies to vibration suppression in Figure 3, yielding a self-tuning AVC algorithm.

3.1. Experimentation

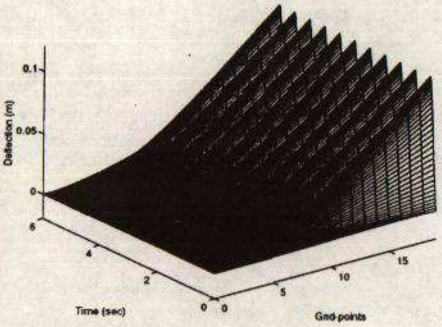
To allow testing of the self-tuning control algorithm in the suppression of vibration of the beam structure an environment simulating a flexible beam of length *0.635 m* in transverse vibration, in fixed-free and in fixed-fixed forms, was developed through discretisation of the governing dynamic equation of motion of the beam using central finite-difference (FD) methods [5]. This involves dividing the beam into a finite number of equal-length sections (segments) and considering the motion of end of each section (grid-point) at equally-spaced discrete instants of time. Investigations were carried out to determine a suitable number of segments the beam under consideration be divided into so that reasonable accuracy is achieved by the simulation algorithm. This was, thus, chosen as 19 sections for both the fixed-free and the free-free forms. To investigate the performance of the self-tuning AVC algorithm in broadband vibration suppression, the beam simulation algorithm, as a test and evaluation platform was implemented on the integrated DSP/transputer system. The investigations here were focused onto a broad frequency range covering almost all the resonance modes of the beam. To assess the performance of the algorithm a fixed (finite-duration) disturbance was used as the unwanted primary disturbance (U_D).

The self-tuning algorithm was first realised within a SISO structure, for the beam in fixed-free form, with the primary and secondary sources located at grid points 16 and 20 respectively, the detector at grid-point 16 and the observer at grid-point 12 along the beam. Figure 4(a) shows the amount of cancellation (cancelled spectrum) achieved at the observation point. It is noted that an average cancellation level of more than 25 dB is achieved over the broad frequency range of the disturbance. The sharp dips/spikes noted in Figure 4(a), correspond to the resonance modes of vibration of the beam. The corresponding time domain descriptions of the beam fluctuation before and after cancellation are shown in Figures 4(b) and 4(c). It is noted that the level of unwanted disturbance is significantly reduced throughout the length of the beam.

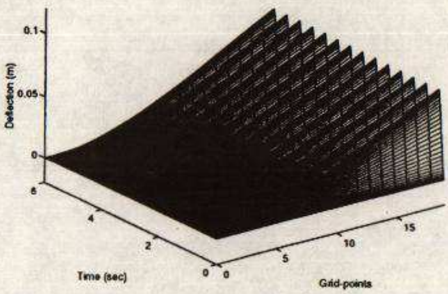
The self-tuning algorithm was secondly realised within an SISO structure, for the beam in fixed-fixed form, with primary and secondary sources located at grid points 10 and 11 respectively, the detector at grid-point 11 and the observer at grid-point 9 along the beam. Figure 5(a) shows the amount of cancellation (cancelled spectrum) achieved at the observation point. It is noted that an average cancellation level of more than 25 dB is achieved over the broad frequency range of the disturbance. The corresponding time domain description of the beam fluctuation before and after cancellation are shown in Figures 5(b) and 5(c).



(a) Cancelled spectrum.



(b) Beam fluctuation before cancellation.

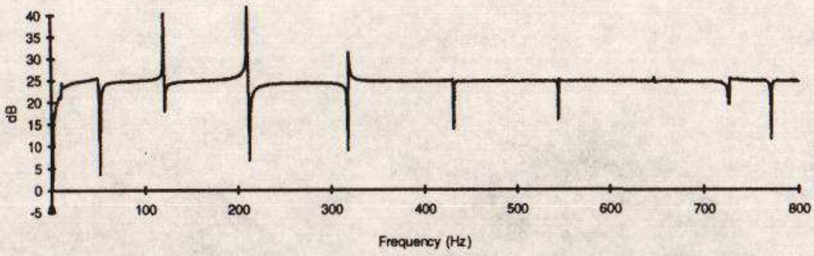


(c) Beam fluctuation after cancellation.

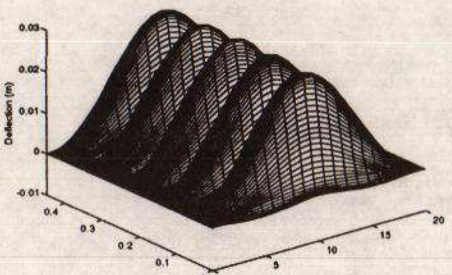
Figure 4: Performance of the self-tuning AVC algorithm (fixed-free beam).

4. CONCLUSION

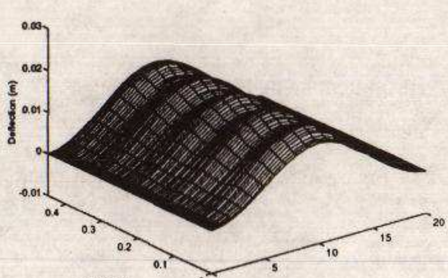
The design and implementation of a self-tuning control algorithm for ANC and AVC have been presented, discussed and verified through experimentation. An active control mechanism for broadband cancellation of noise and vibration has been developed within an adaptive control framework. The algorithm thus developed and implemented on an integrated DSP-transputer system, incorporates on-line design and implementation of the controller in real-time. Moreover, a supervisory level control has been incorporated within the control mechanism which allows on-line monitoring of system performance and controller adaptation. The performance of the algorithm has been verified in the cancellation of broadband noise in a free-field medium and in the suppression of broadband vibration in flexible beam structure of various forms. A significant amount of cancellation has been achieved over the full frequency range of the disturbance in each case. These demonstrate the significance of the self-tuning control mechanism for broadband noise cancellation and vibration suppression.



(a) Cancelled spectrum.



(b) Beam fluctuation before cancellation.



(c) Beam fluctuation after cancellation.

Figure 5: Performance of the self-tuning AVC algorithm (fixed-fixed beam).

5. REFERENCES

[1] R. R. Leitch and M. O. Tokhi 'Active noise control systems', IEE Proceedings, 134, p525-546, (1987)

[2] M. O. Tokhi and R. R. Leitch 'Design and implementation of self-tuning active noise control system', IEE Proceedings-D, 138, p421-430, (1991)

[3] M. O. Tokhi and R. R. Leitch 'Design of active noise control system in a three-dimensional non-dispersive propagation medium', Noise Control Engineering Journal, 36, p41-53, (1991)

[4] M. O. Tokhi and R. R. Leitch 'The robust design of active noise control systems based on relative stability measures', Journal of the Acoustic Society of America, 90, p334-345, (1991)

[5] G. S. Virk and P. K. Kourmoulis 'On the simulation of systems governed partial differential equations', Proceedings of Control-88, Conference, pp. 318-321, (1988)