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ACTIVE NOISE CONTROL IN THREE-DIMENSIONAL PROPAGATION USING SELF-TUNING METHODS

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1. INTRODUCTION

Active noise control (ANC) is realised by artificially generating cancelling source(s) of noise such that to destructively interfere with an unwanted source, thereby, resulting in a reduction in the level of noise. This is achieved through a detection and processing of the noise by an electronic controller.

Due to the broadband nature of noise emitted by practical sources the controller is required to realise suitable frequency-dependent characteristics so that the amplitude and phase of every detected tone of the noise is adjusted properly. The dependence of controller characteristics on a number of frequency-dependent factors within the system makes it possible to measure/identify and realise the required characteristics either as an analogue or digital or hybrid controller [1, 2]. The current development in microprocessor technology provides the opportunity to implement such a controller using digital techniques. In particular, there exist powerful digital processors, specially designed for signal processing and digital filtering applications. These have the capability for the real-time processing of signals within the frequency range suitable for ANC and are cheap enough to allow dedication to one system.

In practice, the characteristics of noise sources drift and vary due to a number of factors, such as operating conditions, leading to time-varying spectra. Moreover, variations in the characteristics of transducers and electronic equipment used occur over time. Furthermore, changes in the geometric arrangement of system components can occur. Thus, in practice, an ANC system employing a controller with fixed transfer characteristics will not be adequate to result in large amounts of cancellation of an unwanted noise. Under such circumstances an alternative is to design an ANC system within an adaptive control framework to be capable of updating the controller characteristics in accordance to changes in the system so that the desired amount of noise cancellation is achieved and maintained. A realisation of this approach can be achieved by a proper integration of a system identification algorithm and controller design to result in a self-tuning ANC system [3].

This paper presents a procedure for the design of self-tuning ANC systems in three-dimensional propagation using single-input multi-output feedforward control structures. The off-line controller design relations are derived on the basis of achieving optimum cancellation at a finite set of observation points. These are then related to the transfer characteristics of models of the system.

thereby, allowing on-line identification of the required controller transfer function. Moreover, a supervisory level control is developed that monitors system performance and activates self-tuning accordingly. The algorithm is implemented in real-time for the special case of single-input single-output structures and experimental results verifying the practical significance of the self-tuning control strategy are presented.

2. CONTROL STRUCTURE

A schematic diagram of the geometric arrangement of the ANC structure is shown in Fig.1a. The (unwanted) primary signal is detected by the detector, processed by the controller and fed to a set of secondary sources. The secondary (cancelling) signals thus generated are superimposed onto the unwanted noise so that the noise level is reduced at a set of observation points. An equivalent block diagram of this structure in the complex frequency, s, domain is shown in Fig.1b where $E(s)$, $F(s)$, $G(s)$ and $H(s)$ respectively represent transfer functions (in matrix form) of acoustic paths between primary source and detector, detector and secondary sources, primary source and observers and secondary sources and observers. Similarly, $M_d(s)$, $M_o(s)$, $C(s)$ and $L(s)$ respectively represent transfer functions of detector, observers, controller and secondary sources including amplifiers and other necessary electronics. $P(s)$ and $S(s)$ respectively represent primary and secondary signals before propagation whereas $P_o(s)$ and $S_o(s)$ respectively represent primary and secondary signals at the observation points. $D(s)$ is the detected signal and $O(s)$ represents an array of the combined (observed) primary and secondary signals.

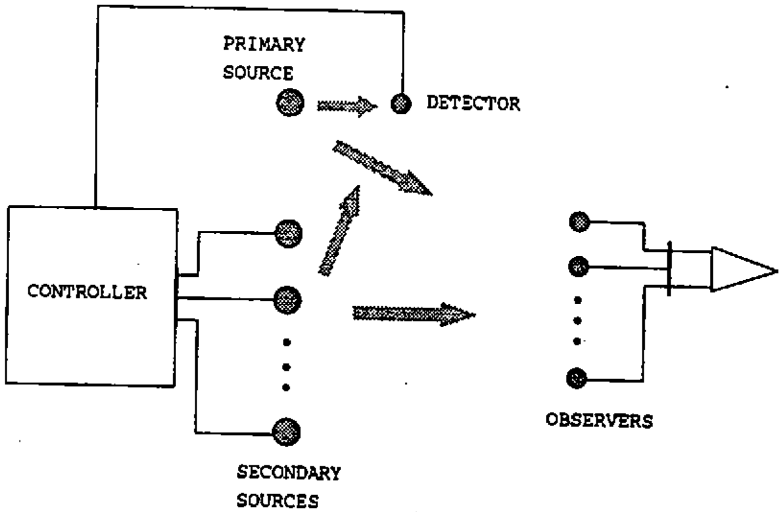
The objective in Fig.1 is to reduce the level of noise to zero at the observation points. This requires that the observed primary and secondary signals at each observation point be equal in magnitude and opposite in phase; i.e.

$$P_o(s) = -S_o(s) \tag{1}$$

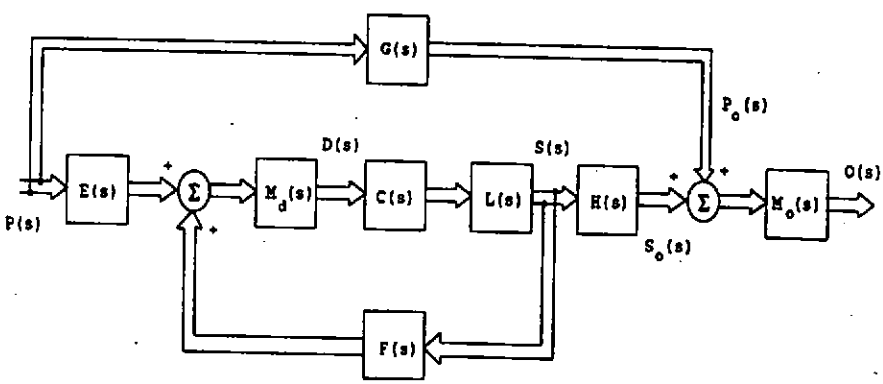
Obtaining $P_o(s)$ and $S_o(s)$ from Fig.1b, substituting into Eq.(1) and simplifying yields the required controller transfer function as

$$C(s) = M_d^{-1} (G H^{-1} F - E)^{-1} G H^{-1} L^{-1} \tag{2}$$

This represents the required controller design relation for optimum cancellation of broadband noise at the observation points. In designing such a controller a careful consideration of the acoustic feedback loops, due to secondary source radiations reaching the detector, that can cause the system to become unstable is required. Moreover, as noted in Eq.(2), for given sources, sensors and necessary electronics the controller characteristics are determined by the transfer characteristics of the acoustic paths and, hence, system geometry. Thus, a study of such a dependence, giving an insight into the complexity and practical realisation aspects of the controller, is important.



(a)



(b)

Fig.1: Active noise control structure;
(a) Schematic diagram,
(b) Block diagram.

3. SELF-TUNING CONTROL

The design of an adaptive controller for use in an ANC system involves two phases. Firstly, of finding a model for the system between its input and output using a system identification algorithm and, secondly, of controller design computation based on this model and the control objectives. Modelling of the system in terms of the ANC structure of Fig.1, will mean considering the primary source signal (as system's input), at the source, and the observed signals (as system's output).

The observed signals can easily be measured by using acoustic sensors, such as microphones, at the observation points. The primary source signal at the point of emission, however, can not be measured easily because no direct access to this signal will, in general, be available. Therefore, to obtain the required information on the system input, measurement of a signal coherent with the emitted noise is required. This can easily be achieved either through a process of direct detection: by measuring the acoustic signal at a distance from the source; e.g. using a, detector, microphone, as in Fig.1 or through indirect detection: by measuring a non-acoustic coherent signal; e.g. source vibration [2]. In either of these situations, the design of the controller will be based on model(s) describing the system between the detected signal (as system input) and observed signals (as system output).

The ANC system of Fig.1 can be considered as having a set of signal generating, or source points; namely, the primary and secondary sources. Among these, the primary source is an independent source of noise whereas the secondary sources are derived from the primary source and hence are dependent sources. Thus, depending on the state of a secondary source two distinct situations; namely, either the source being off or on, are possible under manual/automatic (program) control. These two situations with regard to all secondary sources lead to characterising the ANC system in terms of a set of equivalent sub-systems. Therefore, the design of an adaptive controller will invariably be based on models describing these sub-systems. Thus, with k secondary sources a total of $k(k+1)$ transfer functions can fully characterise the ANC system. In this manner, if x_{0j} ($j = 1, 2, \ldots, k$) represents the system transfer function between the detector and observer j for all the secondary sources switched off and if x_{ij} ($i = 1, 2, \ldots, k$; $j = 1, 2, \ldots, k$) represents the system transfer function between the detector and observer j when all except secondary source i is off then using these transfer functions the controller design relation in Eq.(2) can equivalently be expressed by

$$c_i = Q_i \left[\sum_{p=0}^{k} Q_p \right]^{-1} \quad ; \quad i = 1, 2, \ldots, k \tag{3}$$

where c_i is the ith element of the array $C(s)$ and

$$Q_0 = \det \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1k} \\ x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & & \vdots \\ x_{k1} & x_{k2} & \cdots & x_{kk} \end{bmatrix} , \quad Q_i = (-1)^i \det \begin{bmatrix} x_{01} & x_{02} & \cdots & x_{0k} \\ x_{11} & x_{12} & \cdots & x_{1k} \\ \vdots & \vdots & & \vdots \\ x_{(i-1)1} & x_{(i-1)2} & \cdots & x_{(i-1)k} \\ x_{(i+1)1} & x_{(i+1)2} & \cdots & x_{(i+1)k} \\ \vdots & \vdots & & \vdots \\ x_{k1} & x_{k2} & \cdots & x_{kk} \end{bmatrix} \qquad (4)$$

where 'det' indicates the 'determinant of'.

The self-tuning ANC algorithm as a combined identification and control is merely the on-line implementation of the controller design procedure outlined in Eq.(3); i.e. estimating the $k(k+1)$ model transfer functions and then using Eq.(3) to calculate the controller transfer function. In this manner, the controller design calculation follows the completion of the plant model estimation phase. Therefore, to achieve on-line adaptation of the controller parameters whenever a change in the system is sensed the addition of a supervisory level control is required. The supervisor is designed to monitor system performance and, based on a pre-specified quantitative measure of cancellation, initiate self-tuning control. The actual cancellation achieved at the observation point is measured at each sample time, if this is within the specified limit then the controller continues processing the detected signal, generating and outputting the cancelling signals. However, if the cancellation is outside the specified limit then the supervisor de-activates the controller and re-initiates the process at the level of plant model identification. In addition to monitoring system performance, other levels of intelligence such as controller stability, system behaviour in a transient period, model structure validation, etc. can also be incorporated within the supervisory level control. Fig.2 shows the self-tuning ANC structure realisation where $D(t)$ and $O(t)$ respectively represent the detector signal (as system input) and observed signals (as system output).

The self-tuning ANC algorithm outlined above can readily be implemented on a dedicated digital signal processor. This, however, requires a careful consideration of the practical issues that affect the implementation process and hence the performance of the system. These, that are also common to the implementation of almost all digital controllers, include factors such as properties of the input signal, robustness of the estimation process, initialisation of parameters at the start, sampling time etc. and processor related factors such as signal quantisation, computational power, speed of computation, programming support, data format etc.

4. EXPERIMENTATION

Presented here is an investigation of the performance of the system employing the self-tuning controller implemented in real-time on a dedicated digital signal processor. The performance of the system was investigated with the exhaust noise of a motorcycle as the unwanted primary source. This represents a practical, compact, low-frequency source whose noise spectrum changes with operating conditions (throttle) resulting in a time-varying characteristic. The noise is essentially low-frequency and is composed of harmonics of the fundamental (engine firing) frequency. An increase in the engine speed results a decrease in the spacing between successive harmonics and an increase in the level of noise.

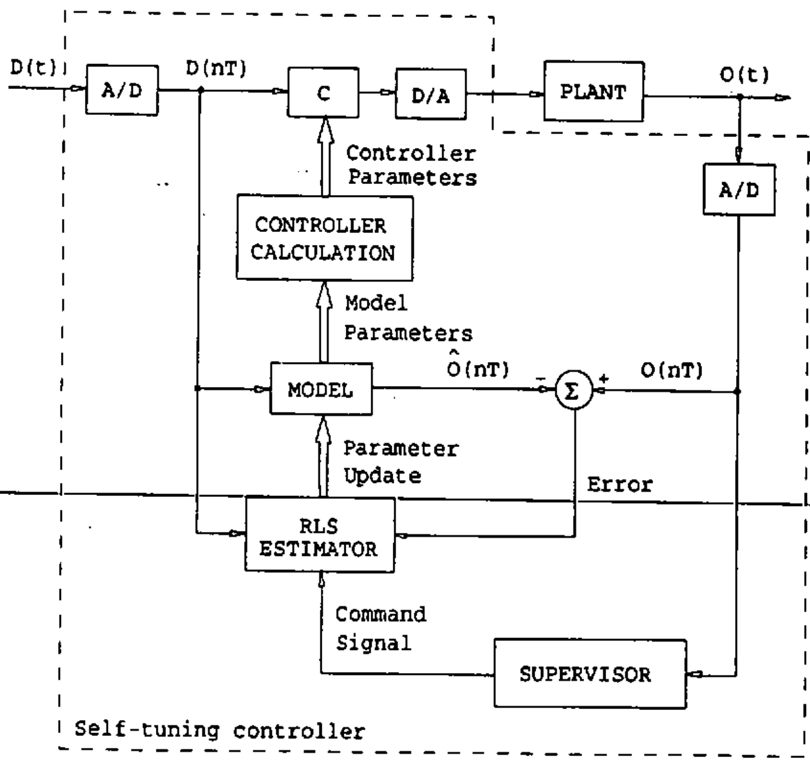


Fig.2: Self-tuning controller.

With the engine running at medium speed the result shown in Fig.3 is obtained, where the 0 dB line partitions regions of cancellation (below the line) and reinforcement (above the line). The cancellation achieved covers a broad frequency range of almost the lowest noise frequency to the 200 Hz maximum measurement frequency. The average amount of cancellation achieved is more than 10 dB (pre-specified).

The self-tuning controller having the ability to alter the controller characteristics in accordance to changes in the noise spectrum and geometry of the system gives cancellation of the noise from almost the minimum to maximum noise frequency. The significant amount of cancellation achieved in each of the above experiments demonstrates and verifies the practical applicability of the self-tuning ANC algorithm for cancellation of time-varying broadband noise emanating from a compact source in three dimensions.

It follows from the results of the above experiments that the self-tuning ANC algorithm as implemented on a dedicated signal processor can perform well and to within practically acceptable requirements. The algorithm is capable of providing the desired amounts of cancellation of the unwanted noise under changes in the geometrical arrangement of the system as well as under time-varying conditions. A change in the system, leading to performance degradation, is automatically detected by the supervisory level which in turn de-activates the controller and re-initialises the self-tuning control so that the desired level of performance is maintained. Due to limitations of the digital signal processor used the range of cancellation achieved is limited to a frequency band of 0 to about 250 Hz. However, the frequency range of cancellation can further be increased by using a more powerful processor with a longer processor word length, faster instruction execution time and supporting floating point arithmetic.

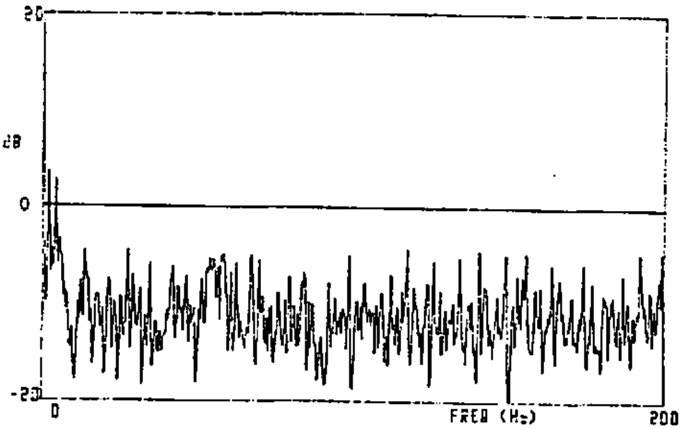


Fig.3: Cancellation of exhaust noise of a motorcycle.

5. CONCLUSION

The design and implementation of a self-tuning ANC algorithm has been presented, discussed and verified through a set of experiments. In practice, the characteristics of sources of noise vary with operating conditions, thereby, leading to time-varying characteristics. Moreover, the geometric arrangement of sources and sensors in an ANC system will, generally, not remain constant, leading to variations in the characteristics of the acoustic paths of the system. These factors result in ANC systems with time-varying parameters. For an ANC system to perform well under such circumstances a design strategy within an adaptive control framework is required.

An ANC system, depending on the state of secondary sources, is characterised by a set of distinct sub-systems' behaviour. The dependence of the required controller characteristics on these sub-systems' behaviour, on the other hand, makes it possible to formulate an algorithm that meets the time-varying requirements of the system. A proper formulation, design and subsequent implementation of such an algorithm, as a self-tuning controller, will result in cancellation of the unwanted noise to a desired level over a broad frequency band of the noise. The cancellation achieved with such a controller is characterised by a flat-shaped cancellation as function of frequency ranging from almost the lowest to the maximum noise frequency. Such a significant increase in the amount of broadband cancellation and the ability of the algorithm to track changes in the system and adjust the controller accordingly makes the self-tuning ANC algorithm practically desirable and superior over an ANC system that employs a controller with fixed characteristics, and proves to be a major step forward in eliminating the numerous practical problems due to low frequency acoustic noise.

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