IMPLEMENTATION OF ADAPTIVE ACTIVE NOISE CONTROL SYSTEMS USING DIGITAL SIGNAL PROCESSING DEVICES

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1. INTRODUCTION

Active noise control (ANC) uses the intentional superposition of acoustic waves to create a destructive interference pattern and thus reduce the level of unwanted sound. This is realised by artificially generating cancelling source(s) through detecting and processing the noise by an electronic controller of suitable frequency-dependent characteristics. Due to the broadband nature of the noise emitted by practical sources the controller is required to realise suitable frequency-dependent characteristics so that to properly adjust the amplitude and phase of every tone of the noise. With a suitable design method, it is possible to measure/estimate and realise the required controller transfer characteristics either as an analogue or digital or hybrid controller [1, 2].

In practice, the characteristics of sources of noise change due to a number of factors such as operating conditions, etc. resulting in time-varying spectra. Moreover, the transfer characteristics of transducers and electronic components used in an ANC system and the geometric set-up of sources and transducers are subject to variation. Thus, the system performance is affected by such variations and an ANC system employing a controller of fixed transfer characteristics will not perform to a satisfactory level. Therefore, it is required to design the system within an adaptive control framework to be capable of updating the controller characteristics in accordance to variations in the system so that the desired level of cancellation is achieved and maintained. This can be realised by a suitable integration of a system identification algorithm with controller design rules to result in a self-tuning ANC algorithm.

The current development in digital electronics producing fast digital signal processing (DSP) devices allows the digital implementation of controllers in real-time. Moreover, these devices are cheap enough to allow dedication to one system. However, influential factors affecting the performance of an ANC system such as processes of A/D and D/A conversion, programming support, data format, speed and dynamic range of computation of the processor are important to be given special consideration in a practical implementation process.

This paper presents the design and implementation of a self-tuning ANC system for compact sources of noise in three-dimensional propagation. The controller is designed within a single-input multi-output (SIMO) realisation structure on the basis of optimum cancellation of noise at a set of observation points. The controller design relations are related to the transfer characteristics of the system model, thus, leading to the formulation of a self-tuning control algorithm. Moreover, to ensure system stability and robustness, a supervisory level control is developed that monitors system performance and initiates self-tuning control accordingly. The real-time implementation of the algorithm on a DSP device is investigated, practical aspects of the implementation process are discussed and performance of the algorithm is verified in practical experimentation.

2. CONTROLLER DESIGN

A schematic diagram of the ANC structure is given in Fig. 1. The primary source emits unwanted signal into the medium. This is detected by the detector, processed by the controller and fed to a set of secondary (cancelling) sources. The secondary signals thus generated are superimposed onto the unwanted noise so that the noise level is reduced at a set of observation points. The objective in Fig. 1 is to reduce the level of noise to zero at the observation points. This is the minimum variance design criterion in a stochastic environment. This requires that the observed primary and secondary signals at each observation point be equal in magnitude and opposite in phase. An analysis of the system in the frequency domain on the basis of this criterion will lead to the required controller design relations in terms of the transfer characteristics of the detector, secondary sources and the acoustic paths between the sources and the sensors [3]. 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, for given sources, sensors and necessary electronics, a study of the dependence of the controller characteristics on the transfer characteristics of the acoustic paths and, hence, system geometry, giving an insight into the complexity and practical realisation aspects of the controller, is important [3].

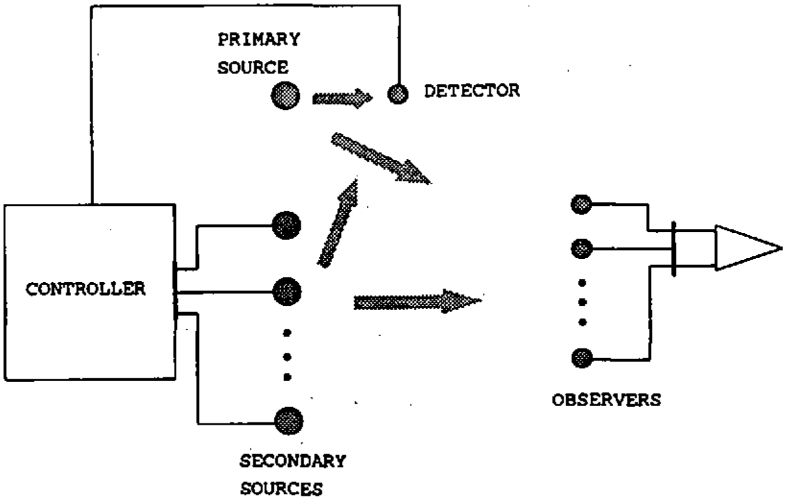

Fig.1: Schematic diagram of the ANC structure.

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The system in Fig. 1 can be considered as a SIMO system with the detected signal as the input and the array of observed signals as the output. Moreover, owing to the state of a secondary source, two distinct situations; namely, either the source being off or on, can be considered. These two situations with regard to a set of k secondary sources lead to characterising the system in terms of a set of $k(k+1)$ equivalent sub-systems. Thus, the design of an adaptive controller can be based on models describing these sub-systems. In this manner, if x_{0j} ($j = 1, 2, \ldots, k$) represents the equivalent 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 equivalent system transfer function between the detector and observer j when all except secondary source i is off then the controller design relations can be expressed by

$$c_n = Q_n \left[\sum_{p=0}^{k} Q_p \right]^{-1} ; \quad n = 1, 2, \ldots, k \tag{1}$$

where c_n is the transfer function of the controller element that drives secondary source n and

$$Q_n = (-1)^n \begin{vmatrix} x_{01} & x_{02} & \cdots & x_{0k} \\ x_{11} & x_{12} & \cdots & x_{1k} \\ \vdots & \vdots & & \vdots \\ x_{(n-1)1} & x_{(n-1)2} & \cdots & x_{(n-1)k} \\ x_{(n+1)1} & x_{(n+1)2} & \cdots & x_{(n+1)k} \\ \vdots & \vdots & & \vdots \\ x_{k1} & x_{k2} & \cdots & x_{kk} \end{vmatrix} \qquad Q_0 = \begin{vmatrix} x_{11} & x_{12} & \cdots & x_{1k} \\ x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & & \vdots \\ x_{k1} & x_{k2} & \cdots & x_{kk} \end{vmatrix} \tag{2}$$

The self-tuning ANC algorithm as combined identification and control is thus the on-line implementation of Eq. (1). To achieve on-line adaptation of the controller parameters, whenever a change in the system is sensed, a supervisory level control is required. The supervisor is designed so that to monitor system performance and, based on a pre-specified quantitative measure of cancellation, initiate self-tuning control. Thus, the actual cancellation achieved is measured and compared with a pre-specified index. If the cancellation is within the desired limit then the controller continues to process the detected signal, generate and output the cancelling signal. However, if the cancellation is outside the desired limit then self-tuning is re-initiated and commenced at the plant identification level. In addition to monitoring system performance, other intelligent features such as controller stability, system behaviour in a transient period, model structure validation, etc. can also be facilitated within the supervisory level control.

3. IMPLEMENTATION OF THE ALGORITHM

The self-tuning ANC algorithm outlined above can readily be implemented on a dedicated DSP device. This, however, requires a careful consideration of the practical issues that affect the implementation process and hence the performance of the system. These 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.

It is important in digital control applications to have a proper conditioning of the input signals. Owing to the aliasing problem associated with the sampling process it is necessary to remove all frequencies above the Nyquist frequency before sampling the signals. The filtering process is also an important consideration in allowing the system be excited only at frequencies where good process models are required. The aliasing problem is commonly solved by a low-pass (anti-aliasing) filter that band-limits the input signal before sampling. In a simulation environment where the signals can be chosen so that to suit the robustness requirements of the control algorithm these problems will not arise. In practice, however, care must be taken to condition the input signal properly before sampling.

A disadvantage of the anti-aliasing filter in ANC applications is the introduction of an additional phase lag in the path of the controller that has to be compensated for within the controller transfer function. The amplitude and phase characteristics of a constant gain controller (CGC) realising a transfer function $H(z) = -a$, where a is a positive real number, as measured after implementation on a DSP device are shown in Fig. 2. The linear phase delay introduced by the A/D and D/A

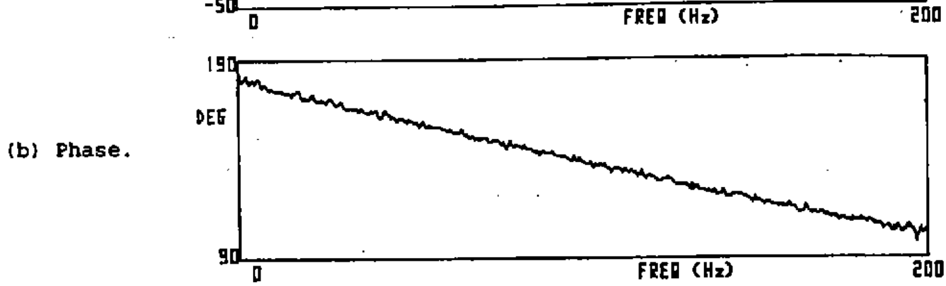


Fig.2: Transfer characteristics of the CGC.

circuitry into the transfer characteristics of the controller can lead to a deterioration in the performance of the system. At low frequencies where the delay is negligible the system performance is not affected significantly. At high frequencies, however, the effect of the delay, if not compensated for, can be pronounced [1].

Two categories of parameters, namely, process related and performance related can be chosen. The process related parameters typically include the order of the plant model and time-delay in the controlled process. These are usually easy to determine. The performance related parameters include performance indices and initial values for the estimation routine. Determination of these parameters require some understanding of the system behaviour and can be chosen such that the performance indices are insensitive of the initial values of the estimator.

The accuracy of the plant model and hence robustness of the control algorithm is influenced by the model order. An underestimation of the model order leads to an inaccurate model. An overestimation, however, will result in redundant parameters which in turn will increase the sampling time and at high sampling frequencies can lead to a wrong model.

Due to the limited number range, with usual processor word-lengths, it is important to make sure that variables fit well into the available range. Numbers are thus required not to exceed the limited range nor they should be so small to lead to undesirable effects due to quantisation. To avoid overflow problems data and results of arithmetic operations that do not fit into the available number range would require either to be truncated or rounded off. This, in turn, introduces quantisation errors into the computation process. However, quantisation errors can be minimised by initially scaling down data values to a suitable level.

The accuracy requirements of the estimated models and consequently of the controller require a signal processor to have a large dynamic range of computation. Thus, a processor supporting floating-point arithmetic will usually be favoured. To increase the dynamic range of computation of a processor supporting fixed-point arithmetic, however, two alternative methods have been suggested: (a) to implement floating-point arithmetic, (b) to split variables into e.g. integral and decimal parts and store accordingly. Either of these will require suitable routines for accessing and algebraic manipulation of variables accordingly which may lead to limitations in sampling time and data memory [4].

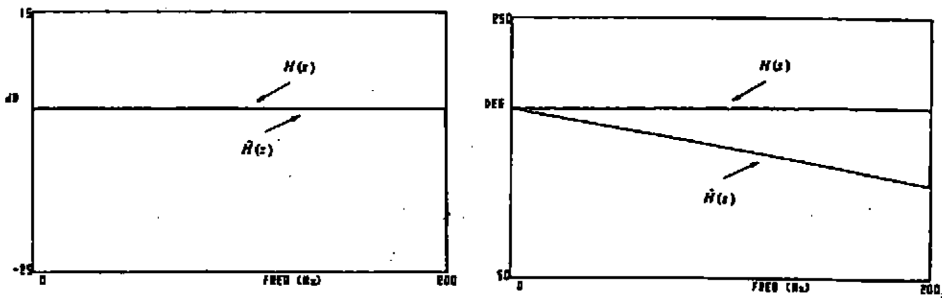
Sampling period is an important parameter influencing the behaviour of the algorithm. Accurate realisation of the controller requires the sampling period to be consistent throughout the processes of identification and control. Moreover, the plant identification process in general requires simultaneous sampling of the input and output signals of the plant. The input and output samples of the plant are subject to delay in the process of A/D conversion. Provided the delay at both input and output ends of the plant are equal, so that simultaneous sampling is achieved, a correct estimate of the plant model can be obtained. Any difference between the two delays will reflect itself as a delay element, realising a transfer function with constant amplitude and linear phase, in cascade with the plant and thus become part of the estimated model transfer function. In this manner, the resulting estimated model transfer function $\hat{H}(z)$ of a plant with transfer function $H(z)$ will be

$$\hat{H}(z) = z^{-\tau} H(z) \qquad (3)$$

where τ is a non-negative real number. To demonstrate this effect, a simple inverter was implemented on an analogue computer and a recursive least squares (RLS) estimation algorithm was used to estimate the transfer characteristics of the inverter. The amplitude and phase characteristics of the inverter, $H(z)$, and of the corresponding estimated model, $\hat{H}(z)$, are shown in Fig. 3. The phase deviation evident in $\hat{H}(z)$ from that of $H(z)$ represents a delay of $z^{-0.8}$ introduced due to the difference in delays through the A/Ds at the input and output ends of the inverter. Such a delay normally results if the A/D converters at the input and output ends are not identical and, in practice, the delay is possible to occur with even identical A/Ds.

The above demonstrates that non-simultaneous sampling of the input and output signals of the plant in an identification process will lead to an estimated model transfer function that is not a true representation of the plant characteristics. Moreover, if the delay $z^{-\tau}$ is a non-integer multiple of the sampling period then this could lead, in general, to further problems in the process of controller implementation. In the self-tuning ANC algorithm, however, as follows from Eq. (1), such a delay, if accurately modelled, will cancel out in the process of controller design and, hence, will not lead to subsequent problems. Thus, the accuracy of the estimation process is an essential consideration in the implementation process.

The accuracy requirements of the phase characteristics of the digital controller are crucial in ANC applications. The phase delay introduced by the A/D and D/A circuitry in the process of implementing the digital controller can have a significant effect on the performance of the system. This requires the use of a compensating transfer function to be implemented in cascade with the controller. The introduction of a delay compensator, however, will increase high-frequency gain and



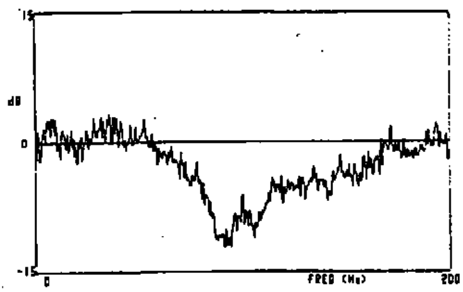
(a) Amplitudes. (b) Phases.

Fig.3: Actual and estimated transfer characteristics of the inverter.

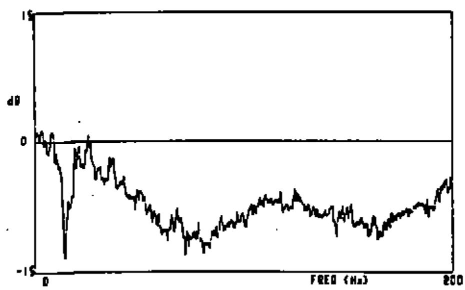
can cause instability in the system. Although, the stability problem can in general be avoided by band-limiting the output of the controller, this problem is not crucial in ANC applications as the system does not operate at high-frequencies. band-limiting the output of the controller, this problem is not crucial in ANC applications as the system does not operate at high-frequencies.

To investigate the performance of the system the algorithm, combining the controller design rules with a RLS estimator and a supervisory level control, was implemented in real-time on a dedicated DSP device to achieve cancellation at an observation point. A synthetic source of noise, using a loudspeaker driven by a $0-200$ Hz PRBS signal, was used as the unwanted primary source. To evaluate the performance of the system on a comparative basis a CGC, realising a phase shift of $180°$, was also implemented. The performance of the system with the CGC is shown in Fig. 4(a), where the 0 dB line partitions regions of cancellation (below the line) and reinforcement (above the line). As expected, maximum cancellation is achieved at only one frequency, f_m, for which the controller meets the required conditions of cancellation for best system performance. The level of cancellation on either side and away from this frequency reduces and eventually reinforcement occurs. The reinforcement at frequencies below f_m results due to the high attenuation in the secondary source (loudspeaker) characteristics, whereas at frequencies above f_m noise is reinforced due the excessive delay in the controller characteristics.

The performance of the system with the self-tuning control algorithm (STC) is shown in Fig. 4(b). As noted, significant cancellation of the broadband noise is achieved from almost the lowest to the maximum noise frequency. The slight reinforcement at frequencies below 20 Hz occurs due to the high attenuation in the secondary source characteristics. This demonstrates that the self-tuning ANC algorithm can perform well and to within practically acceptable requirements. The algorithm is capable of providing the desired amounts of cancellation of the unwanted noise from almost the



(a) With CGC.



(b) With STC.

Fig.4: Performance of the ANC system.

minimum to maximum noise frequency under changes in the geometrical arrangement of the system as well as under time-varying conditions.

4. CONCLUSION

The design and implementation of a self-tuning ANC algorithm has been presented, discussed and verified in practical experimentation. To achieve complete cancellation of an unwanted noise, cancelling source(s) of similar complexity as the unwanted source will be required. In practice, this is realised by artificially generating a finite set of cancelling sources to interfere with the unwanted source so that to result in cancellation of the unwanted noise within a given volume of the medium.

An ANC system can be 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 range of the noise from almost the lowest to the maximum noise frequency. Such a significant broadband cancellation and the ability of the algorithm to track variations in the system and adjust the controller accordingly is a desired feature of an ANC system for practical applications.

5. REFERENCES

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