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ACTIVE NOISE AND VIBRATION CONTROL LITERATURE SURVEY: CONTROLLER TECHNOLOGIES

U.O. Akpan – D.P. Brennan – T.S Koko – O. Beslin – P. Masson – S. Renault

Martec Ltd.

DEFENCE RESEARCH ESTABLISHMENT ATLANTIC

Contractor Report

DREA CR 1999-177

November 1999

National Defence Défense nationale

Canada

National Defence — Research and Development Branch
Défense nationale — Bureau de recherche et développement

DREA CR 1999-177

ACTIVE NOISE AND VIBRATION CONTROL LITERATURE SURVEY: Controller Technologies

U.O. Akpan[1], D.P. Brennan[1], T.S. Koko[1],
O. Beslin[2], P. Masson[2], and S. Renault[2]

[1] Martec Ltd.
Suite 400
1888 Brunswick Street
Halifax, NS, Canada
B3J 3J8

[2] G.A.U.S.
Université de Sherbrooke
Sherbrooke, PQ, Canada
J1K 2R1

Scientific Authority N. C. Sponagle

W7707-8-6156/001/HAL
Contract Number

November 1999

CONTRACTOR REPORT

Prepared for

Defence Research Establishment Atlantic
Centre de Recherches pour la Défense Atlantique

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ABSTRACT

This study has been motivated by the need to control noise in naval vessels in order to reduce their detectability and hence vulnerability to enemy attack. In this report, a detailed review of controller technologies, methodologies and algorithms that could be used for active noise, vibration and structural acoustic control in ship structures has been provided. The review focused on a wide range of controller technologies, methodologies and algorithms such as feedforward control; feedback control; adaptive control; control of tonal noise; control of broadband noise; decentralized control; neural network control; active engine mounts; active noise cancellation; active vibration control and active structural acoustic control. The steps involved in the design of an active control system have been exhaustively reviewed and documented. The diesel engine noise problem was the focus of the study and consideration was given to the control of low frequency noise from the engine. All the noise and vibration transmission paths associated with the engine problems namely, the engine mount, the exhaust stacks and piping systems, the drive shaft, the mechanical couplings and the airborne radiated noise have been considered in the review. Based on factors such as robustness of controller technology, the characteristics of the disturbance, the operating environment and experience in other applications detailed recommendations on controller technologies for the various vibroacoustic paths have been provided. In particular for the engine mounting system, the active vibration control based on adaptive feedforward control technology was recommended. For the drive shafts and coupling, active structural acoustic control that uses the adaptive feedforward control technology has been recommended and an active noise cancellation technique which employs adaptive feedforward control was recommended for the exhausts stack and piping system. It was also recommended that the engine radiated noise be controlled with an active noise cancellation technique that uses the adaptive feedforward control technology. It is concluded from the review that the adaptive feedforward controller technology that uses an external reference signal is best the controller technology for all the vibroacoustic paths associated with the engine noise problem. Since it is well known that the control of one vibroacoutic path might lead to amplification of noise in other paths, it has also been suggested in this study that global control of external radiated noise based on ASAC technology be explored. For fail-safe design, it was advocated that the active strategy be combined with passive treatment whenever possible. A systematic and pragmatic program, based on combined experimental and numerical investigation, was suggested in order to implement the controller technologies recommendations made in the study.

Résumé

La présente étude a été motivée par le besoin de contrôler le bruit dans les navires afin de réduire leur détectabilité et par le fait même leur vulnérabilité face aux attaques ennemies. Le présent rapport comprend un examen détaillé des technologies, méthodes et algorithmes relatifs aux contrôleurs qui pourraient être utilisés pour le contrôle actif du bruit, des vibrations et des problèmes d'insonorisation des structures de navires. L'étude vise une vaste gamme de technologies, méthodes et algorithmes relatifs aux contrôleurs comme la réaction positive, le contrôle de rétroaction, le contrôle adaptatif, le contrôle du bruit tonal, le contrôle du bruit à large bande, le contrôle décentralisé, le contrôle du réseau neuronal, les supports de moteur actifs, l'élimination active du bruit et le contrôle actif des vibrations et des problèmes d'insonorisation. Les étapes de la conception d'un système de contrôle actif ont été examinées et documentées à fond. L'étude se concentre surtout sur le problème du bruit causé par les moteurs diesel mais traite aussi du contrôle des bruits à basse fréquence émis par les moteurs. L'examen traite de tous les trajets de transmission du bruit et des vibrations reliés aux problèmes de moteurs comme les supports de moteur, les cheminées et les canalisations d'échappement, l'arbre d'entraînement, les raccords mécaniques et les bruits transmis par rayonnement dans l'air. À partir de facteurs comme la robustesse du contrôleur, les caractéristiques des perturbations, le milieu de fonctionnement et l'expérience dans d'autres domaines, des recommandations détaillées sur les technologies de contrôle pour les divers trajets vibroacoustiques ont été fournies. Pour le système de support de moteur plus particulièrement, le contrôle actif des vibrations fondé sur la technologie de la réaction positive adaptative a été recommandé. Pour les arbres d'entraînement et les raccords, le contrôle actif des problèmes d'insonorisation faisant appel à la technologie de la réaction positive adaptative a été recommandé et une technique d'élimination active du bruit faisant appel à la réaction positive adaptative a été recommandée pour les cheminées et les canalisations d'échappement. Il a aussi été recommandé que le bruit provenant des moteurs soit contrôlé au moyen d'une technique d'élimination active du bruit basée sur la technologie de la réaction positive adaptative. L'examen permet de conclure que la technologie de réaction positive adaptative faisant appel à un signal de référence externe est la meilleure technologie de contrôle pour tous les trajets vibroacoustiques reliés aux problèmes de bruits des moteurs. Comme il est bien connu que le contrôle d'un trajet vibroacoustique peut mener à l'augmentation du bruit sur un autre trajet, il a aussi été suggéré dans l'étude que le contrôle global des bruits transmis par rayonnement à l'extérieur basé sur la technologie de l'ASAC soit étudié à fond. Pour un système à sécurité absolue, il est proposé que la stratégie active soit combinée au traitement passif le plus possible. Un programme systématique et pragmatique basé sur une combinaison d'examens expérimentaux et numériques a été conseillé pour mettre en œuvre les recommandations sur les technologies de contrôle mises de l'avant dans la présente étude.

Active Noise and Vibration Control Literature Survey: Controller Technologies

U.O. Akpan, D.P. Brennan, T.S. Koko, O. Beslin, P. Masson, and S. Renault

EXECUTIVE SUMMARY

Background
Reducing or controlling the underwater acoustic signatures of naval ships and submarines has historically meant the use of "passive" techniques. Components such as rubber engine mountings, flexible pipework couplings and joints, vibration isolators, and interior acoustic absorbers can be used to prevent acoustic energy from being coupled into the structure of the vessel. While these methods have proven to be effective in general, there are usually low frequency limitations that cannot be overcome by passive means. Active noise and vibration control methods, when used in combination with more conventional passive techniques, show promise for good noise control over the full frequency range. This report presents a comprehensive survey of literature pertaining to the controller component of an active system. The study was conducted as part of a Technology Investment Fund sponsored project entitled "Warship Underwater Signature Reduction by Active Means".

Principal Results
The report reviews a wide range of controller technologies, methodologies and algorithms, together with the steps involved in the design of an active control system. The most likely significant noise and vibration transmission paths associated with marine engines was also considered. Based on factors such as robustness of controller technology, characteristics of the disturbance, the operating environment, and experience in other applications, recommendations on controller technologies for the various vibroacoustic paths have been provided. The study concludes that adaptive feedforward control using an external reference signal is the best controller technology for all the vibroacoustic paths associated with the engine noise problem. Furthermore, since the control of one vibroacoustic path may lead to amplification of noise in other paths, a combination of smart structure and active structural acoustic control technologies has been recommended for the global control of externally radiated noise.

Significance of Results
This report, along with a companion review on sensors and actuators, provides a good starting point for research and development in the area of active noise control in ship structures.

Future Work
Future work in this area will include proof of concept studies to demonstrate the potential benefits of active noise reduction technologies in naval ships, using a laboratory environment and/or CFAV Quest as demonstration platforms.

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES - Continued

1 INTRODUCTION

1.1 Background

The success of surface warships and submarines in combat may depend significantly on how difficult it is for them to be detected by enemy vessels. One of the ways by which enemy ships can detect the vessels is through sound or noise that is radiated from the vessels. The dominant sources of noise radiation into water from ships are the ship engine and machinery, the propeller cavitation noise, the noise radiation from propeller blades, and the hydrodynamic pressure fluctuations induced by turbulent water flow along the ship hull. At speeds below propeller cavitation inception, a ship's acoustic signature is generally dominated by structurally transmitted noise from on-board machinery.

In order to reduce the detectability and hence the vulnerability of surface ships and submarines to enemy attack, it is necessary to reduce their acoustic signatures. Reducing or controlling ship noise has traditionally been implemented by passive means, such as the use of vibration isolation mounts, flexible pipe-work and interior acoustic absorbing materials. However, these passive noise control techniques are effective mostly for attenuating high frequency noise and are generally ineffective for controlling low frequency noise. On the other hand, active noise control methods have proven to be effective in controlling low frequency and tonal noise. Consequently, active control methods may be used as replacements for, or in combination with, passive techniques, for controlling or reducing ship noise.

Active noise control (ANC) involves the purposeful reduction/elimination of noise, either by modification of the dynamic properties of the system, or by active noise cancellation through linear superposition of a secondary noise field of equal but opposite strength. An active noise control system will typically consist of all or some of the following ingredients:

(i) Sensors, which provide information on the primary noise source;
(ii) Actuators, which provide means of modifying the system characteristics or providing secondary noise cancellation excitation; and

(iii) Controllers that determine the manner in which the secondary excitations are applied to the system to reduce the noise.

This study arose from a need by the Defence Research Establishment Atlantic (DREA) to investigate the applicability of active noise control methodologies for reducing or controlling the underwater acoustic signatures of Canadian naval ships and submarines. To do proper justice to the subject, it is necessary to have a proper understanding of all three ingredients of ANC listed above.

1.2 Objectives and Scope

The objective of this study is to conduct a comprehensive literature review on the subject of active control of ship engine noise, with emphasis on controller technologies. A review of sensor and actuator technologies is provided in a companion study (Koko et al., 1999).

To put the study in proper perspective, a brief overview of the fundamental concepts of ship noise control is first presented in Chapter 2. Then a review of adaptive digital control and neural network algorithms is presented in Chapter 3. Chapter 4 contains a review of control methodologies and applications. This detailed overview covers feedforward control, feedback control, decentralised control, control of tonal noise, control of broadband noise, robust control, active engine mount and the emerging technology of active structural acoustic control with smart structures. Chapter 5 covers the steps involved in the design of control systems. Recommendations on control technologies for the engine noise problem are discussed in Chapter 6.

2 FUNDAMENTAL CONCEPTS ON SHIP NOISE CONTROL

2.1 Noise Sources and Transmission Paths in Ship Structures

There are many sources of noise in a ship structure. These include propulsion systems, exhaust stacks, and various types of on board equipment. In the present study the engine system has been identified as the principal noise source of interest. A typical ship engine along with its mounting system is schematically depicted in Figure 2.1. This figure shows the various vibro-acoustic paths through which the engine vibration is transmitted to the ship structure and eventually radiated into the surrounding medium. The ship structure transmits noise after it has been excited by mechanical motion (engine vibration). The engine vibration is due primarily to unbalanced rotating or oscillating parts, bearing noise, gear meshing and combustion. In general the spectrum of the excitation is broadband but exhibits spikes at frequencies corresponding to the shaft rotational speed and its harmonics. The various vibro-acoustic paths transmit noise in different ways. For example:

- The noise from the exhaust stack and the fuel intake and the cooling systems can be viewed as duct and piping noise. In this mechanism the pressure wave in the duct is excited and transmitted as noise;
- The mounting systems, which consist of the engine cradle, isolation mount, raft and foundation are mechanical connections between the ship hull and the machine. Vibration is transmitted from the engine motion to the ship hull through these connections. The induced hull vibration is transmitted to the surrounding medium and is radiated as acoustic noise. This noise transmission mechanism is referred to as structural acoustic radiation; and
- The engine vibration leads to airborne radiation within the enclosure, which may induce an acoustic load on the ship hull. This resulting excitation is radiated to the surrounding medium as acoustic noise.

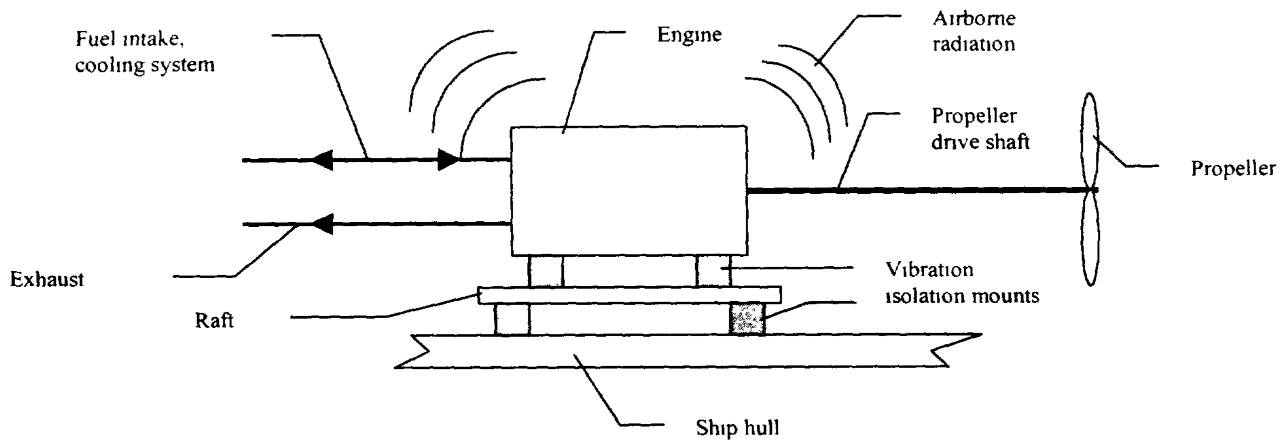


Figure 2.1. Schematics of a Ship Diesel Engine Mounting

2.2 Objective of Ship Noise Control

There are many reasons why ship noise is undesirable. These include:

- Significant levels of radiated noise could constitute a potential threat because of the higher susceptibility to detection by enemy naval vessels such as submarines and surface ships;
- High levels of ship noise may cause discomfort to crew; and
- High levels of noise and vibration in the vicinity of the engine mounts could cause localized acoustic fatigue.

The objective of ship noise control is the minimisation of the acoustic radiation from the piping systems, the ship hull and appendages to the surrounding water.

2.3 Prediction and Assessment of Noise Levels

Once the noise sources and transmission paths have been identified, it is essential to have capabilities to accurately assess the noise and vibration levels either experimentally or computationally. Typically, acoustic sensors can be installed to measure the noise levels at different locations. The deployment and maintenance of such sensors throughout the service life of the ship structure has several practical difficulties and challenges. Some of these include disconnection after some time of operation, resistance to water and environmental conditions (for submerged locations) and the difficulty of taking far field measurements.

Because of the challenges associated with full reliance on experimental measured acoustic levels, it is very important to have capabilities to accurately predict the acoustic fields pertaining to different ship noises and transmission paths. Several proprietary and commercial computer programs are available for vibro-acoustic modelling. Examples in the connection include SYSNOISE (LMS Technologies, 1997) and AVAST (Brennan, 1998).

In particular, a general-purpose code called AVAST (acronym for Acoustic Vibration and Strength Analysis Program) has been developed over the years by Martec Limited under the sponsorship of the Defence Research Establishment Atlantic (DREA). AVAST is a vibro-acoustic modelling/analysis program that utilizes a coupled boundary element and finite element modelling strategy. The finite element method is used to model the structure and the boundary element method is used for the acoustic medium (fluid). AVAST capabilities have been specifically targeted at ship structure modelling. As a result, we believe it is an appropriate and logical starting point for further development of noise modelling and predictive capabilities that are needed to support the design of adequate control strategies.

In general, there are two distinct methods that are used for the reduction of acoustic noise and radiation. These are passive and active control methods. The methods are briefly described in the next sections.

2.4 The Concept of Passive Noise Control

Passive noise control is essentially the process of reducing unwanted noise by utilising the absorption property of materials. In this approach, sound absorbent materials are mounted on or around the primary source of noise or along the acoustic paths between the source and the receivers of noise. Traditional methods for reducing acoustic noise and vibration have employed passive techniques and these techniques have been shown to be very effective at high frequencies (Harris, 1991; Barenik and Ver, 1992). At low frequencies, however, passive control techniques are not effective because the long acoustic wavelength of the noise requires large volumes of the passive absorbers (Fuller and von Flotow, 1995). Furthermore, at low frequencies it is difficult to stop the transmission of noise from one space to another (Elliot and Nelson, 1993). Attempts to overcome the limitation of passive control led to the development of active noise control by Lueg in 1933.

2.5 The Concept of Active Noise Control

Active noise control can be viewed from two perspectives:

- System dynamical properties modification; or
- Active cancellation.

In system dynamic properties modification the active control system changes the physical characteristics of the overall acoustical system such as the input impedance presented to the external disturbance; the impedance of the modes or the nature of the boundary conditions. The changes in the dynamical characteristics, in turn, reduce the response of the system to the external excitation. This reduction may be due to a variety of mechanisms such as reduction of transmissibility across discrete connections or other identifiable transmission paths. This approach includes the emerging technology of Active Structural Acoustic Control (ASAC) which uses smart structures.

In active noise cancellation the system actuators inject sound which by linear superposition is additive to the field. It operates on the principle of superposing waveforms, by generating a cancelling waveform whose amplitude and envelope match those of the unwanted noise, but whose phase is shifted by 180° (Leitch and Tokhi, 1989). The source of the unwanted noise is referred to as the primary source. The source of the cancelling noise is referred to as the secondary source and is usually driven by a controller. The cancelling noise is sometimes referred to as anti-noise or secondary noise. The concept of active noise cancellation is shown in Figure 2.2. Elliot and Nelson, 1992, have shown that the process of generating a stable destructive noise can only be achieved at low frequencies, that is, the effectiveness of active noise cancellation is restricted to low frequencies. Since passive noise cancellation techniques are effective at high frequencies, then active and passive noise control methods can be combined together to minimise both high and low frequency noise. Therefore, the best solution to a noise control problem is a combination of passive and active control.

A great amount of literature has been published on the origin and development of active noise control. Several studies, (Warnaka, 1982; Leitch and Tokhi 1989; Stevens and Ahuja 1989; Elliot and Nelson 1990, 1993; Fuller and von Flotow, 1995), have chronicled the progression and historical development of active noise control from its inception with Lueg's idea in 1933. These studies demonstrated that practical implementation of active noise control has been driven primarily by the development of modern electronics. Furthermore, Elliot and Nelson, 1993, emphasised that an understanding of both the acoustic principles of the physical system and the control system is essential for successful application of active noise control technology.

The present study is concerned with the review of active controller technologies that have found practical applications particularly in the marine environment. Emphasis is placed on active control methodologies that have been found to be effective in noise and vibration control. For clarity of presentation, the main features of an active control system are illustrated in Figure 2.3. The basic components are the physical system (this encompasses the plant, the sensors and the actuators) and the electronic control system (Nelson and Elliot, 1992). The main features are:

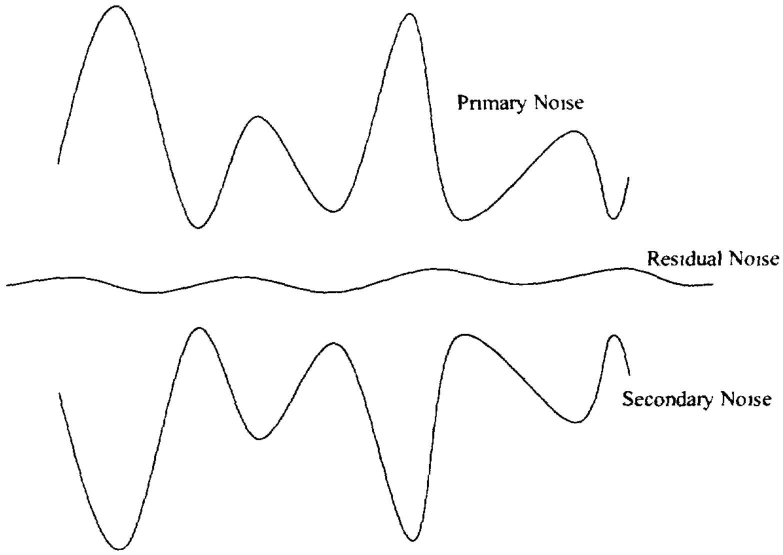


Figure 2.2. The Concept of Active Noise Cancellation

1. The primary source of noise/disturbance and the system to be controlled. This is usually referred to as the plant.

2. The input and error sensors: The input sensors are the electro-acoustic (microphones) or electro-mechanical (accelerometers, tachometers) devices that measure the disturbance from the primary source and communicate it to the controller. They are often referred to as reference sensors. The error sensor monitors the performance of the active controller.

3. The Actuators: These are the electro-acoustic or electro-mechanical devices that generate the secondary noise or anti-noise in order to reduce or cancel the primary noise. In some cases, the actuators modify the dynamic properties of the system in order to reduce their noise radiation efficiencies. Examples of actuators include speakers, piezoelectric material and vibration shakers. The actuators, plant and the sensors are collectively referred to as the physical system.

4. The Active Controller: This is the signal processor (usually a digital electronic system) that gives command to the actuators. The controller bases its output on sensor signals (primary noise sensor/error sensor) and usually on some knowledge of how the plant responds to the actuator.

The performance of an active controller depends on several factors. They include causality condition, acoustic feedback, and the physical arrangement of the actuators and sensors (Nelson and Elliot, 1992).

Causality condition relates the acoustic delay to the electrical delay. In a practical active control system, there is an acoustical delay between the primary noise and the secondary noise (see Figure 2.3). This delay depends on the speed of propagation of the primary noise in the medium. Also, there is an electrical delay between the primary noise sensor (commonly referred to reference sensor) and the actuator. The electrical delay depends on the time it takes the controller to process the input signal. An active control system is said to be causal when the controller produces the anti-noise at a downstream location at the same time that the primary noise arrives. Causality condition requires that, for effective control, the acoustic delay must be longer than the electrical delay, that is, the maximum response time of the sensor-controller-actuator system should be less than the sound propagation time.

When the actuator generates the anti-noise, it travels downstream to generate a zone of quietness. The anti-noise also travels upstream towards the primary source of noise. The secondary noise that moves upstream corrupts the primary noise that is measured by the reference input sensor. The secondary noise that propagates upstream is referred to as secondary effect or acoustic feedback. Acoustic feedback must be taken into consideration in the design of active controllers because it has the potential to undermine the effectiveness of the controller.

The physical arrangements of the control sources (actuators) and the sensors play an important role in determining the effectiveness of the control system. Moving the location of the control sources and sensors can affect the controllability, maintainability and the stability of the control system.

Active Noise Control Methodologies (ANC) can be classified into two main categories:

- Feedforward Control (FFC) and;
- Feedback Control (FBC).

A summary of the description of the two methodologies is given in Chapter 4. The controllers that have been used in active noise control methodologies (FFC and FBC) have evolved over the years from analogue to digital designs. Elliot and Nelson, 1992, have noted that progress in active noise control has been tied to advancement in digital electronics. Therefore a review of digital control technologies is undertaken in the next chapter.

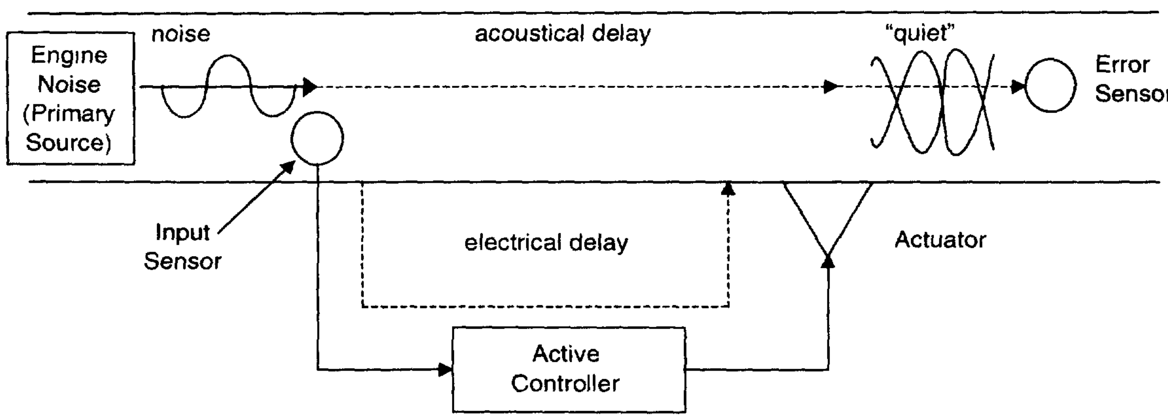


Figure 2.3. The Main Features of an Active Noise Control System

3 DIGITAL CONTROL TECHNOLOGIES

This chapter is concerned with the concept and implementation of digital control technologies in active noise control. Algorithms that constitute the state-of-the-art and the state-of-practice in the practical execution of active noise control are reviewed. An emerging algorithm, namely, neural network is also presented.

3.1 Description of Digital Controllers

Most active noise controllers (ANC) that are currently in use or that are being proposed for use in practical problems are digital controllers. They are commonly referred to as digital filters (Eriksson, 1996). A filter is a linear process that alters the spectral content of an input signal in a specified manner (Nelson and Elliot, 1992). A digital filter operates on a sequence of signals (for example digitally measured reference noise, $x(t)$) to produce another sequence of signals (digital output of secondary noise, $y(t)$). The block diagram for the ANC system of Figure 3.1 is shown in Figure 3.2. The acoustic system is the duct length from the input sensor to the actuator. It is referred to as the plant and it has transfer function $P(z)$. The electronic digital controller, that is, the filter has transfer function $M(z)$. Perfect cancelling of the primary noise, $d(t)$, by the secondary noise, $y(t)$, occurs when the response from the electronic controller model, $M(z)$ matches the response of the plant, $P(z)$. The objective of digital control design is digital construction of the control model, $M(z)$, which results in perfect elimination of the unwanted noise.

Figure 3.3 shows other transfer functions that must be included in a practical design. These are the transfer function of the actuator that follows the controller, $H_s(z)$, and the transfer function from the actuator to the error sensor, $H_e(z)$. In most active control design formulations, it is usually assumed that the sensors have ideal transfer functions. The transfer function, $H_e(z)$ may be readily combined with $H_s(z)$ to form a new plant, $P'(z)$, and a new model, $M'(z)$. Perfect cancellation of the primary noise is obtained when $P'(z) = M'(z)$. This implies that $P'(z) = M(z)H_s(z)$.

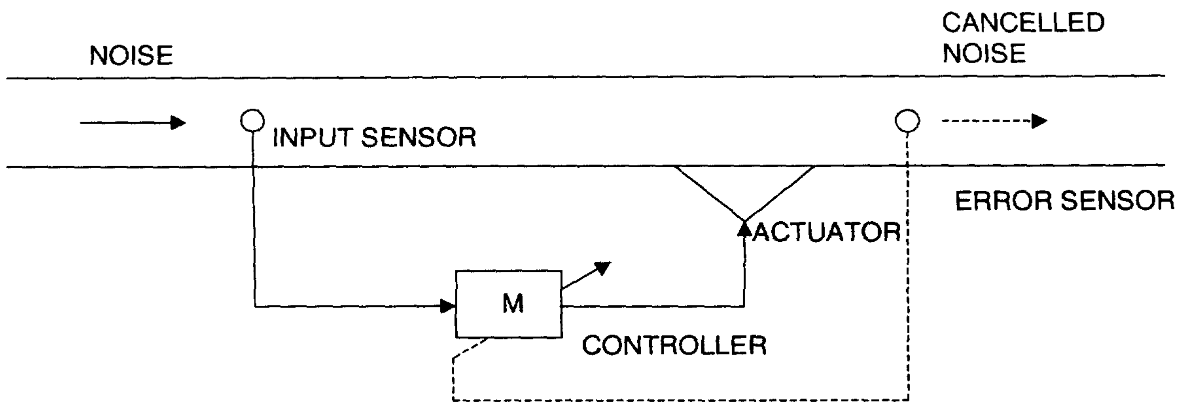


Figure 3.1. An Active Duct Noise Control System

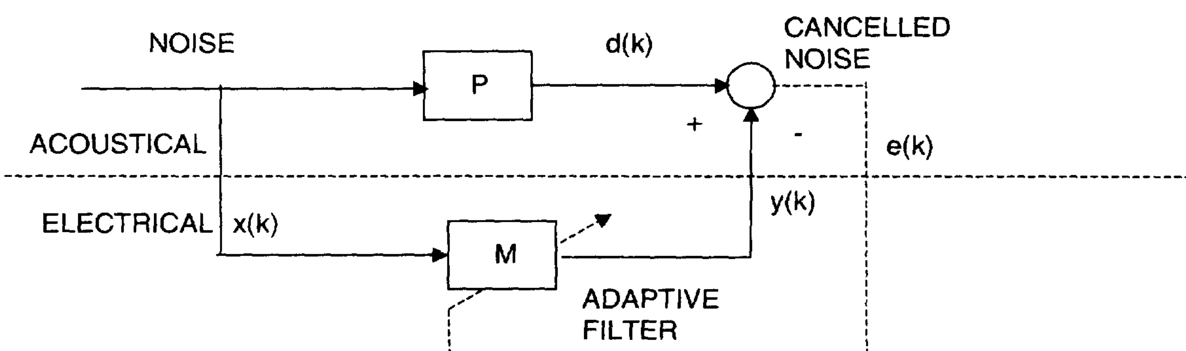


Figure 3.2. Block Diagram for the Active Noise Control System

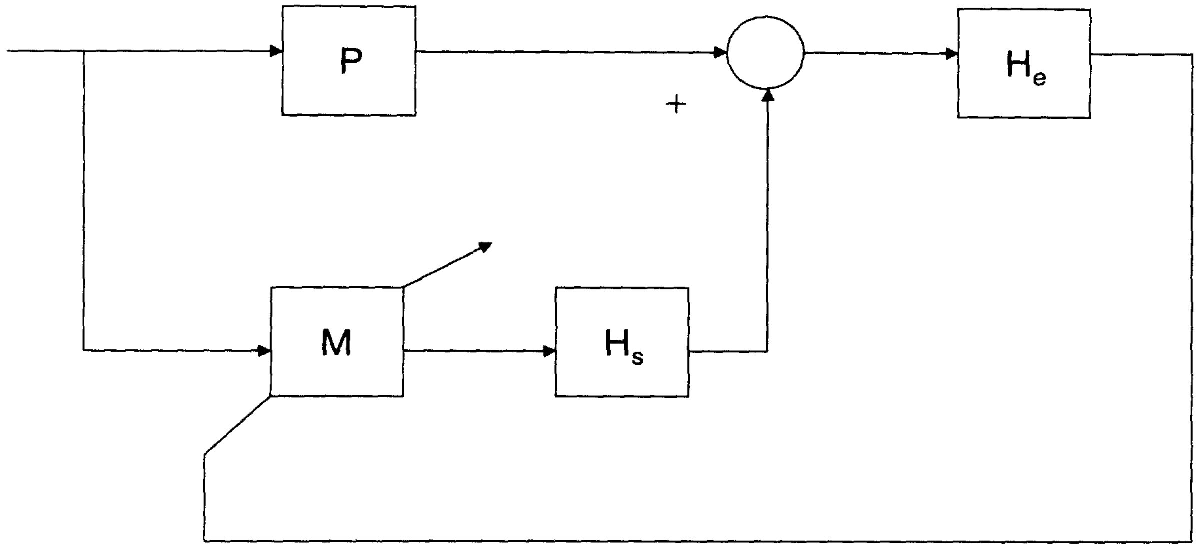


Figure 3.3. Transfer Functions for an Active Noise Control System.
M-Controller, H_s-Actuator, H_e-Error Path, P-Plant

Digital filters are used in the design of the active control, *M(z)*, because they operate with high speed, flexibility, adaptability and also the availability of low-cost hardware in the form of digital signal processor (*DSP*) makes them inexpensive (Nelson and Elliot, 1992). The two types of digital filters that are commonly used are non-recursive filters (*FIR*) and recursive filters (*IIR*).

A digital filter with a zero impulse response function after some finite number of input samples is called non-recursive. This type of filter is commonly referred to as all zero, moving average or transversal. Mathematically, a non-recursive filter is represented by

$$y(k) = \sum_{l=0}^{L-1} a_l x(k-l) = \mathbf{w}^T(k)\mathbf{x}(k) \tag{3.1}$$

where

L = number of coefficient of the filter;

$\mathbf{w} = [a_1, a_2 \ldots a_{k-1}]$ =weight or coefficients of the filter;

$\mathbf{x}(k) = [x(1), x(2), \quad x(n)]$ input acoustic noise formed from discrete measurements by the input sensor;

$y(k)$ - acoustic noise generated by the actuator at discrete time *(k)*

In practice either dedicated shift registers or digital multipliers or general purpose *DSP*, with the coefficient values stored in memory locations, is used to implement equation (3.1), Nelson and Elliot, 1992.

A digital filter with an impulse response function that never decays to zero is said to have an infinite impulse response, (*IIR*) and is called a recursive filter. Recursive filters are also called pole-zero, and auto-regressive moving average filters (*ARMA*). Mathematically this filter is represented by

$$y(k) = \sum_{l=0}^{L-1} a_l x(k-l) + \sum_{n=1}^{K} b_l y(k-n) = \mathbf{w}^T(k)\mathbf{u}(k) \tag{3.2}$$

where

$\mathbf{w} = [a_1, a_2 \ldots a_{k-1}, b_1, \; b_n]$ =generalised weight or coefficients of the filter;

$\mathbf{u}(k) = [x(1), x(2), \quad x(k-1), y(1), y(2). \quad y(n)]$ = generalised input.

The advantages of IIR filter over FIR filters are given in Table 3.1 and the advantages of FIR filters over IIR filters are presented in Table 3.2, Kuo and Morgan, 1996.

Table 3.1. Advantages of IIR filter over FIR filter, Kuo and Morgan, 1996

1.	The. Poles of IIR filters achieve the same performance (resonance, sharp cut-off) as FIR filters, but with much lower order. Therefore IIR filters may require less computation per sample than FIR filters.
2.	IIR filters with sufficient order can exactly match poles as well as zeros of physical systems, whereas FIR filters can give only rough approximations to poles. Therefore, IIR filters can further minimize the error signal thus improve performance.

Table 3.2. Advantages of FIR filter over IIR filter Kuo and Morgan, 1996

1.	FIR filters are conditionally stable, but IIR filters are not conditionally stable because there is a possibility that some poles will move outside the unit circle during adaptation leading to instability.
2.	The performance of an IIR filter is general non-quadratic and multi-modal, therefore IIR filter may converge to a local minimum.
3.	FIR adaptive algorithms generally converge faster than IIR algorithms.

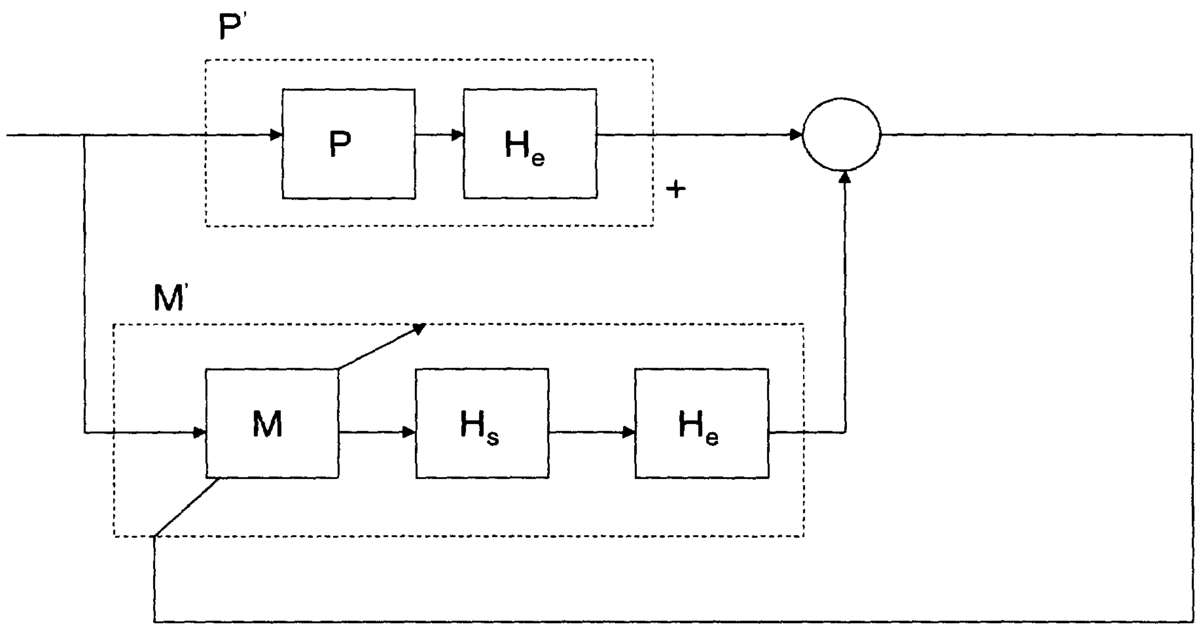


Figure 3.4. Transfer Functions for an Active Controller using FIR Filter.
P' New Plant, M' New Active Model

3.2 Types of Digital Active Controllers

There are basically two types of digital active controllers:

1. Fixed Digital Controllers
2. Adaptive Digital Controllers

A fixed digital controller is a controller with fixed values of the weight vector. They are also commonly referred to as non-adaptive filters. A fixed filter (controller) requires accurate knowledge of all the transfer functions present in the system to be controlled. Unfortunately, in practical *ANC* problems, there are changes in temperature, flow velocity and other system parameters that make the system transfer functions time-varying and difficult to precisely determine, Nelson and Elliot, 1992. Therefore, there is a need for continual adjustment of the filter coefficients. A filter whose coefficient vector is continually adjusted is called an adaptive filter. A schematic diagram of an adaptive filter is shown in Figure 3.5.

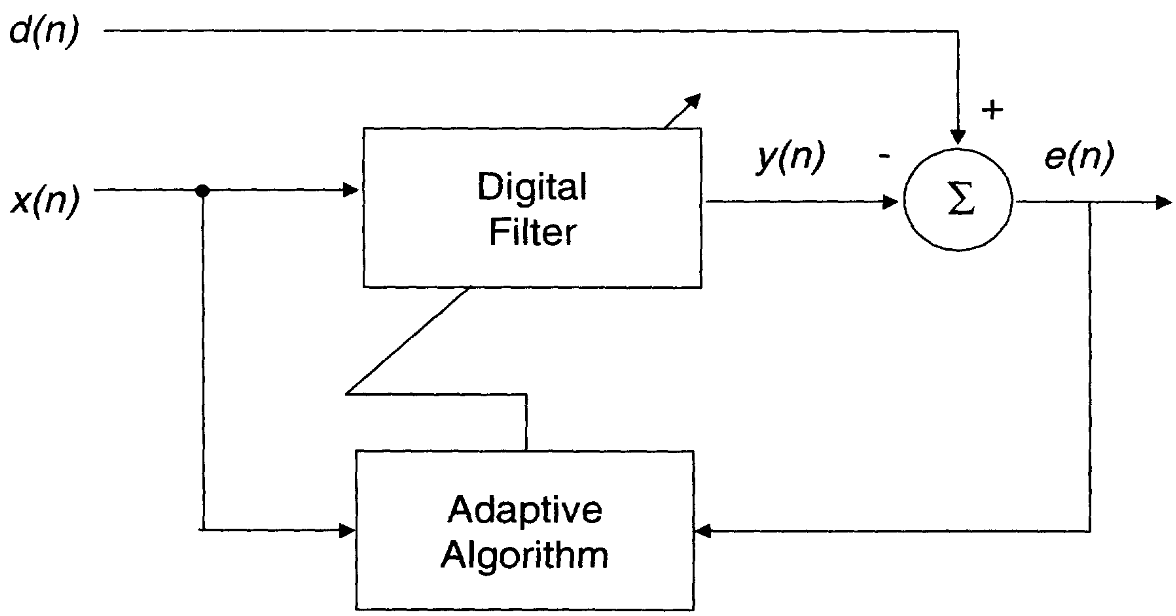


Figure 3.5. Block Diagram of Adaptive Filter

An adaptive digital filter consists of two distinct parts:

1. The digital filter which performs the desired signal processing (*IIR* and *FIR*).
2. An adaptive algorithm for adjusting the coefficients or weights, w, of the filter.

Most of the research work in *ANC* controller technologies has been directed toward the determination of efficient algorithms for adjusting the coefficient or weight, w, of adaptive filters. Many algorithms have been developed for this purpose. A review of some of the practical algorithms is presented next.

3.3 Algorithms for Implementing Adaptive Digital Control

The most common and the most widely used algorithm in adaptive digital control is the least mean square algorithm, *LMS*, Alves et al, 1995; Bender and Beckman, 1997; Snyder and Hansen, 1992. The *LMS* algorithm seeks to minimise the residual noise or error noise in a mean square sense. In particular, the *LMS* algorithm gives the equation for the new weight as

$$w(k+1) = w(k) + \alpha x(k)e(k) \tag{3.3}$$

where

$\mathbf{x}(k)$ – input acoustic pressure vector formed from discrete measurements $x(k)$ by the input sensor;

w - weight vector for transversal adaptive filter;

$y(k)$ - acoustic pressure generated by the actuator at discrete time (k);

$d(k)$ – acoustic pressure to be reduced;

$e(k)$ - acoustic pressure measured by the error sensor, $e(k) = d(k) - y(k)$; *and*

α - a constant factor.

The weight updating process described by equation (3.3) is shown in Figure 3.6. Equation (3.3) states that coefficients of the FIR filter are updated by terms proportional to the product of the input signal associated with each coefficient, $x(k)$, times the error signal $e(k)$. The *LMS* algorithm is essentially a transversal filter. Variant versions of *LMS* algorithms, namely Normalized *LMS*, Correlation *LMS*, Leaky *LMS*, Partial Update *LMS*, Variable Step *LMS*, Signed *LMS*, Complex *LMS* have been developed for active noise control applications. The formulae for the various versions can be found in Nelson and Elliot, 1992. The motivation for the development of the different versions of *LMS* algorithms is the need for a faster rate of convergence, implementation simplicity and robustness of operations. Kavita and Kuo, 1994, have conducted a performance analysis on the different types of *LMS* algorithms. In their study, they demonstrated that there is often a trade-off between convergence rate performance and the steady state attenuation performance. Furthermore, they showed that the best steady state attenuation is obtained with either the correlation, the variable step or the gradient step filter and that the basic *LMS* algorithm has a good attenuation but is the slowest to converge.

Because the *LMS* algorithm is the most widely used algorithm in active noise control, extensive studies have been conducted on the stability, robustness and the convergence of the algorithm in practical applications (Snyder and Hansen, 1992; Nelson and Elliot, 1992). Widrow and Stern, 1986, have demonstrated that the convergence rate of the *LMS* algorithm is unaffected by transfer functions that are placed in the input path of the

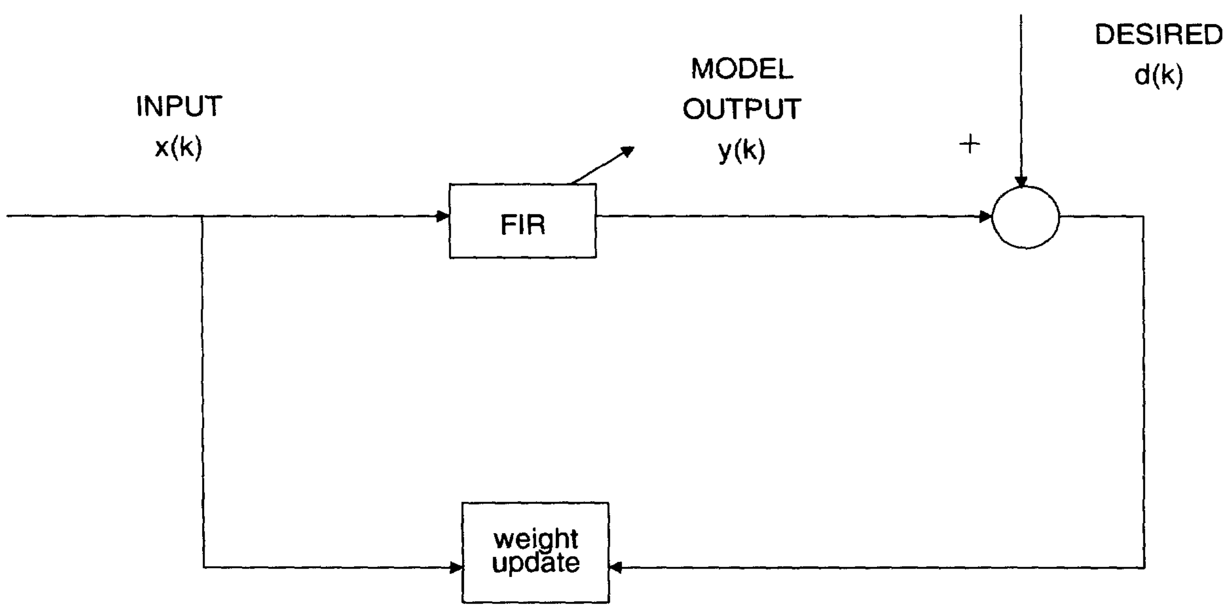


Figure 3.6. Weight Update Processing an LMS Adaptive Filter

adaptive filter (that is, transfer functions associated with the input sensor and error sensor). However, Widrow and Stern, 1986, have also proved that transfer functions that are placed in the output path of an adaptive filter (that is, transfer functions associated with the actuator) will prevent the adaptive filter from converging properly. They suggested that in order to guarantee convergence, when a transfer function is placed on the output path of the adaptive filter (commonly referred to as secondary path), the basic *LMS* adaptive filter should be modified by adding a transfer function, *H(z)*, at the model input. Widrow and Stern 1986, have referred to the *LMS* algorithm that is modified in this manner as the filtered-*X* algorithm (*FXLMS*). This is the most popular algorithm that is used in practical active noise control. Figure 3.7 shows the application of the filtered –*X* algorithm to *ANC* control.

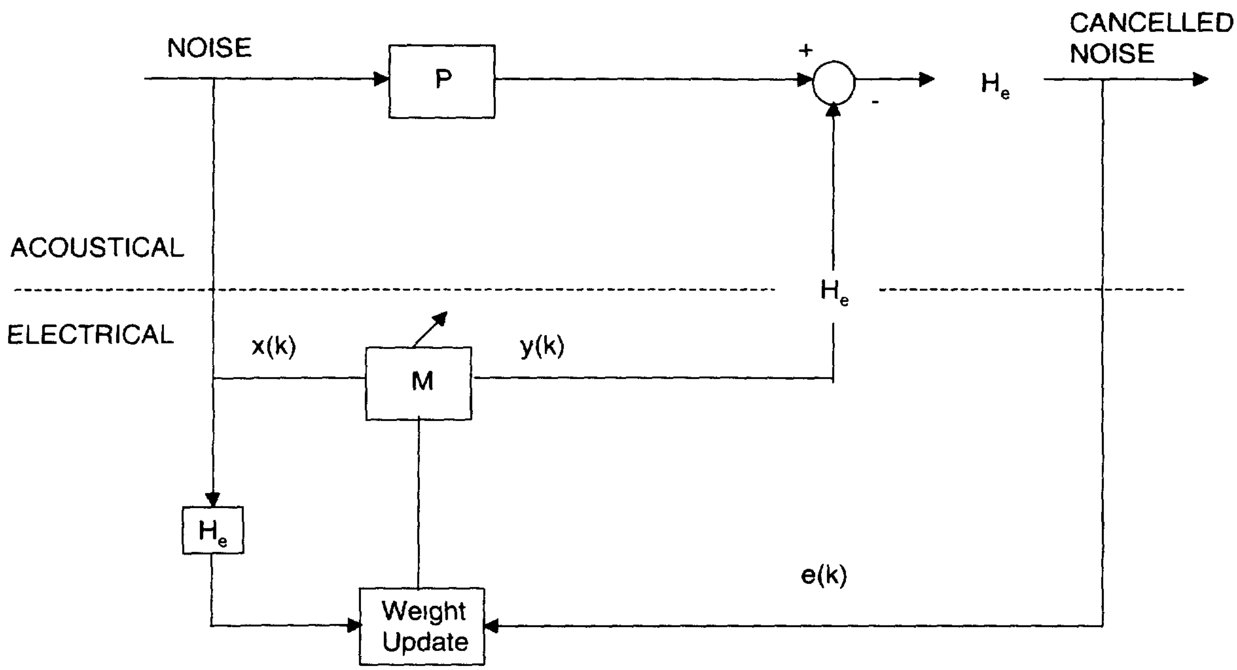


Figure 3.7. Application of Filtered X-Algorithm to ANC

The *LMS* algorithm that has been described so far uses non-recursive (*FIR*) filter structure. This filter is characterised by an all zero transfer function. An alternative structure, shown in Figure 3.8, is the *IIR* recursive filter that has a transfer function that is capable of representing poles and zeros. The IIR controller model, *M(z)*, consists of a *FIR* filter, *A(z)*, followed by a recursive or feedback *FIR* filter, *B(z)*. The output of this filter structure, *y(k)*, is formed by the product of the generalised weight vector, ***w****(k)*, with the generalised input vector, ***u****(k)* = *(x(k), y(k-1)*. It is noted that A(z) feedforwards the reference noises x(k), while B(z) feedbacks previous secondary noises y(u-1). A weight updating algorithm, similar, to *LMS* has been developed for recursive filters. This algorithm is known as the recursive least mean-square algorithm *RLMS.* A simplified version of *RLMS* that is commonly used, Widrow and Stern, 1986, gives the weight update equation as

$$w(k+1) = w(k) + \alpha u(k)e(k) \tag{3.4}$$

where $w(k+1)$ is the new weight.

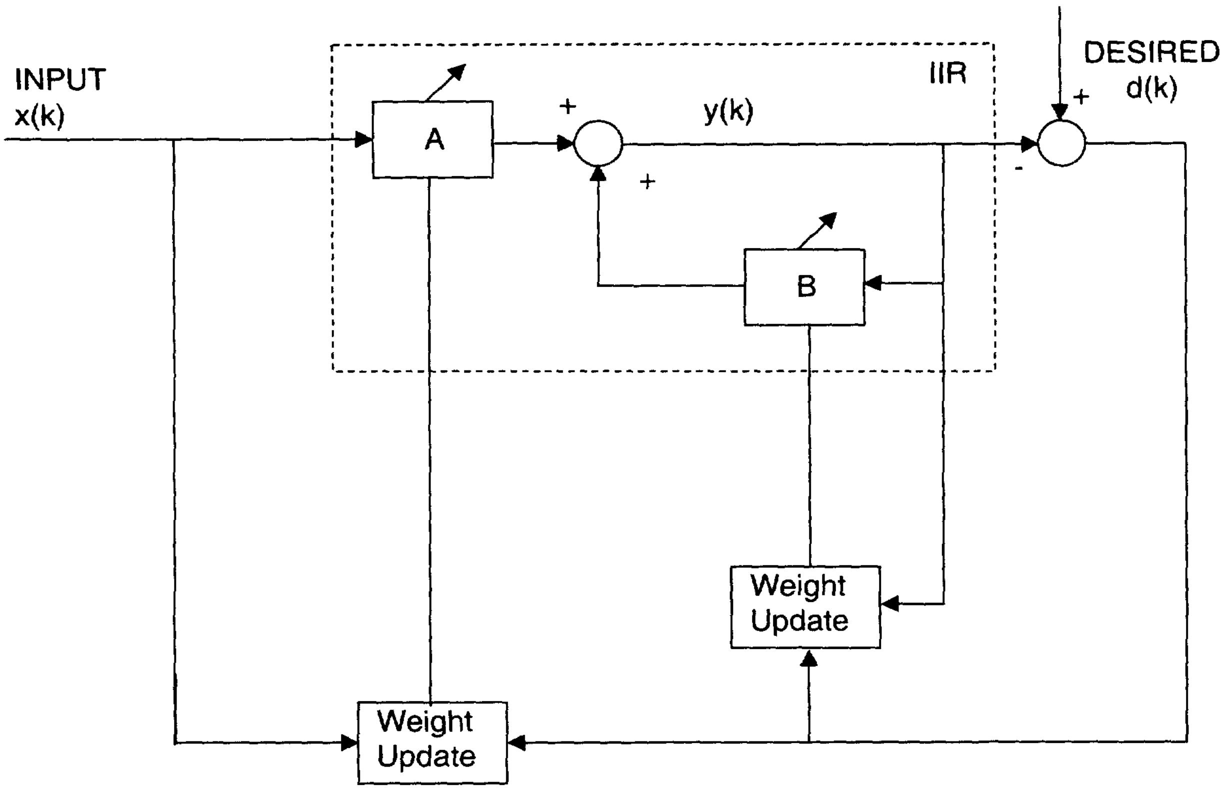


Figure 3.8. Weight Updating Process of an IIR Filter

Eriksson, 1989, showed that the IIR filter structure with its ability to directly model transfer functions with poles and zeros is particularly useful for active control system in which acoustic feedback, $F(z)$ is present (Figure 3.9). The presence of acoustic feedback results in a system model that is different from the simplified model presented in Figure 3.1. However, if a new model is defined that includes the acoustic feedback, the transformed result is similar to Figure 3.1. The new model contains poles associated with the acoustic feedback. An *IIR* filter structure with its pole-zero transfer function has the ability to simultaneously compensate for these poles while cancelling the undesired noise.

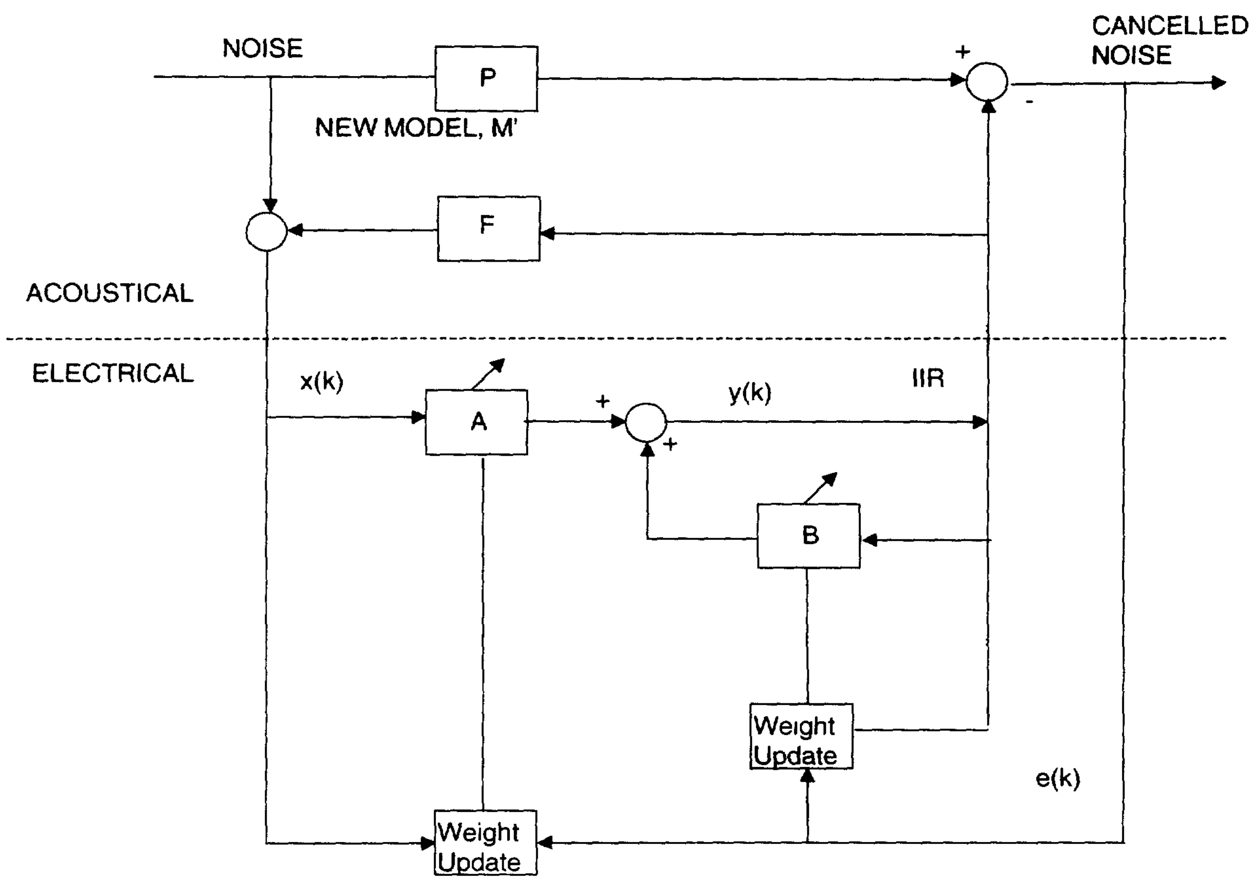


Figure 3.9. Transfer Functions for Active Noise Control using IIR Filter

Just as the *LMS* algorithm must be changed to account for the effect of secondary path, the *RLM*S algorithm must also be changed to account for these transfer functions (acoustic feedback). The modified version of the *RLMS* algorithm is commonly referred to as filter-*U* algorithm, Eriksson, 1985, 1996. The application of filtered –*U* algorithm to an active noise control is illustrated in Figure 3.10. The filtered-U algorithm is also extensively used in adaptive control design.

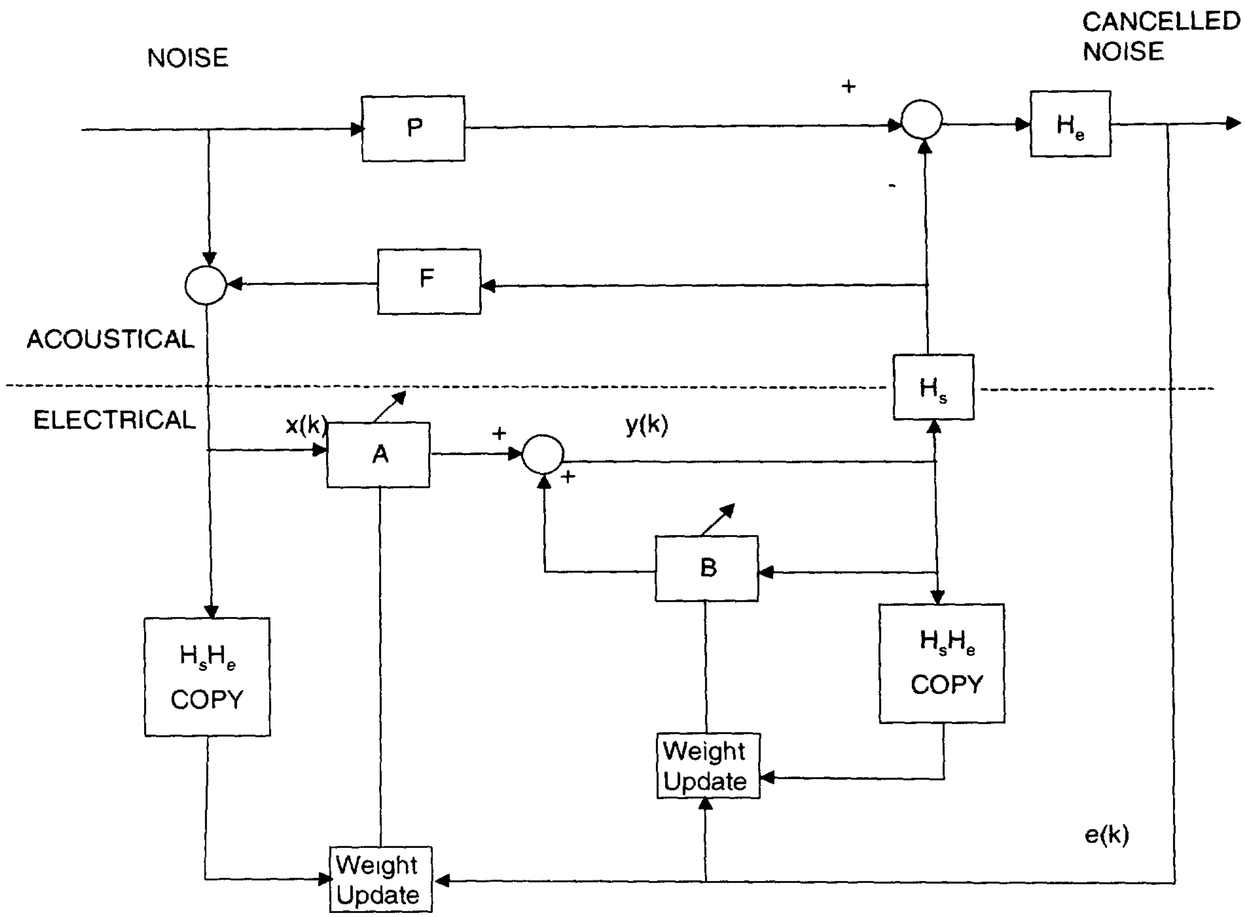


Figure 3.10. Application of Filtered U Algorithm to ANC

The filtered-*U* and filtered-*X* algorithms require knowledge of the transfer functions present in the auxiliary path following the model (H_S) as well as in the error path following the secondary sound source (H_e). Various schemes have been developed for this. They include off line modelling, modelling with actual noise source and modelling with filtered *U* random noise, Eriksson 1989. The random noise technique has been found to be the most powerful, general and is, therefore, the most commonly used. It is shown in Figure 3.11 (Morgan and Kuo, 1996).

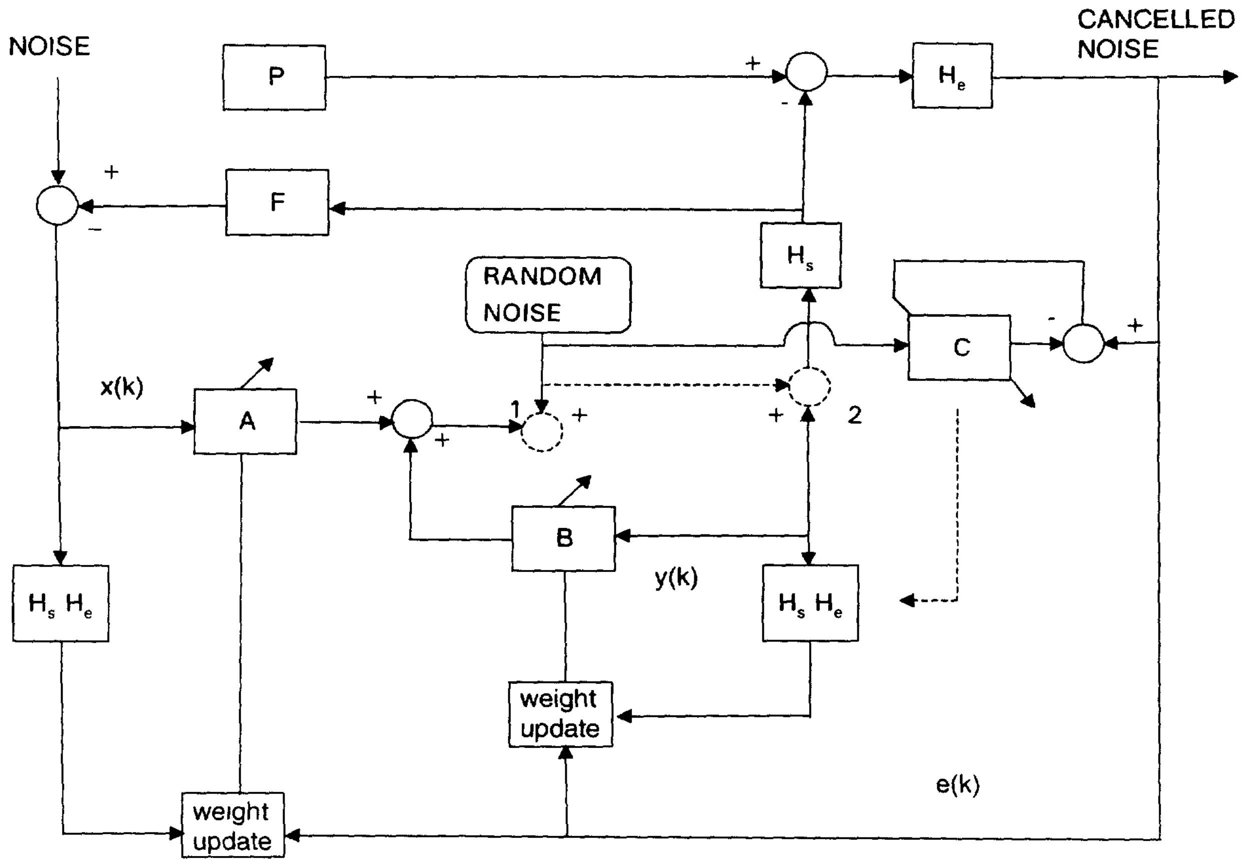


Figure 3.11. The Use of an Independent Random Noise Source for On-line Determination of $H_s(z)$ and $H_e(z)$ for use in Filtered-U Algorithms

The *LMS* and *FLMS* algorithms that have been presented have been discussed in the context of single input and single outputs (*SISO*) control systems. They are the most practical methods used in controller technologies (Kuo and Morgan, 1996). When the control system has multiple input and multiple output *MIMO*, multiple input multiple output versions of *LMS* have been developed, Elliot, 1987. The basic structure of the *MIMO LMS* algorithm is essentially the same as the *LMS* algorithm. Details on the robustness, stability and performance of *MIMO LMS* algorithm can be found in Sydner and Hansen, 1992.

The various versions of *LMS* algorithms that have been described are based on linear theory. Although, they are the most widely used models in ANC, recent efforts have been directed towards the use of nonlinear models in the control design. In particular, the neural network approach is emerging as an alternative model in the design of active controllers. A brief review of the neural network approach is presented in the next section. A more detailed exposition can be found in the book by Haykin, 1994.

3.4 Neural Network Algorithms for Digital Control

Neural networks are made up of neurons. The basic components of a neuron are shown in Figure 3.12.

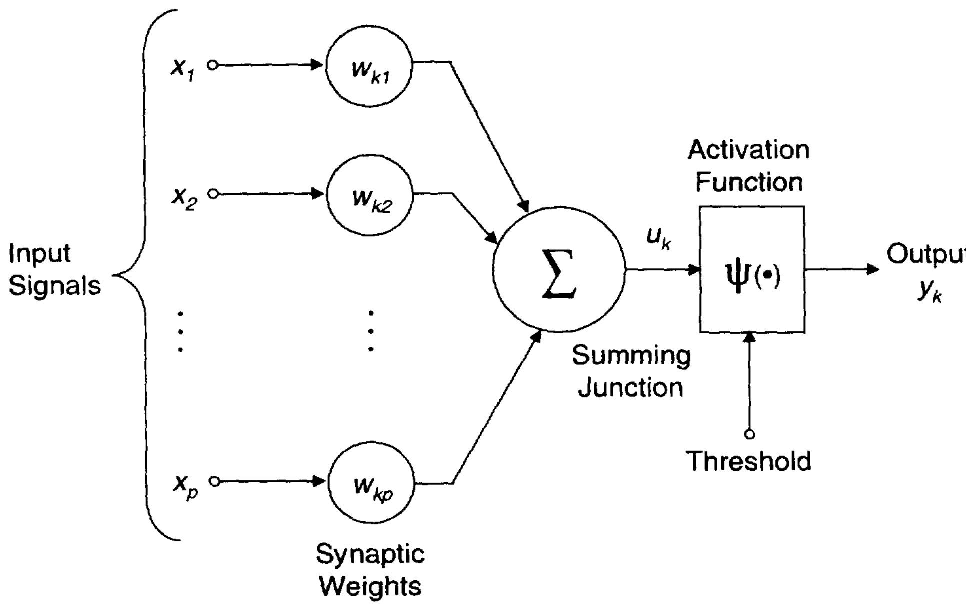


Figure 3.12. Classical Model of Artificial Neuron

The three basic elements in a neuron are:

1. A set of *synapses* or *connecting links*, each of which is characterised by a *weight* of its own. Specifically, a signal x_j at the input of synapse j connected to neuron k is multiplied by the synaptic weight w_{kj};
2. An *adder* for summing the input signals, weighted by the respective synapses of the neuron (*linear combiner*); and
3. An *activation function* for limiting the amplitude of the output of a neuron. An example of a widely used activation function is the *sigmoid function.*

The relations between input signals and the output for the k neuron can be summarised by the following equations:

$$u_k = \sum_{j=1}^{p} w_{kj} x_j \tag{3.5}$$

$$y_k = \varphi(u_k - \theta_k) \tag{3.6}$$

θ_k is a *threshold* allowing an *affine transformation* (transformation of the type: "*y=ax+b*", *b* being a possible shift, in contrast with a simple *linear transformation* "y=ax" which do not allow a shift) to the output of the linear combiner. The other terms are defined in Figure 3.12.

There are basically two kinds of neural network architectures: *recurrent networks* and *feedforward networks*, Haykin, 1994, 1999. A *recurrent network* distinguishes itself from a *feedforward network* in that it has at least one feedback loop. For example, a recurrent network may consist of a single layer of neurons with each neuron feeding its output signal back to the inputs of all the other neurons.

There are two classes of *feedforward networks*: the *Multi-layer Perceptrons* (MLP) and *Radial Basis Functions networks*.

Radial basis functions networks: The design of a neural network can be seen as a curve fitting problem in a high dimensional space. According to this view point, learning is equivalent to finding a surface in a multi-dimensional space that provides a best fit to the training data, with the criterion for "best fit" being measured in some statistical sense. Correspondingly, generalisation is equivalent to the use of this multi-dimensional surface to interpolate the test data. Such a viewpoint is indeed the motivation behind the method of radial-basis functions in the sense that it draws upon research work on traditional strict interpolation in a multi-dimensional space. In the context of neural network, the hidden units provide a set of "functions that constitute an arbitrary "basis" for the input patterns (vectors) when they are expanded into the hidden-unit space; these functions are called *radial-basis functions.*

Multi-layer perceptrons networks (MLP). The MLP is illustrated in Figure 3.13. In the MLP network, three kinds of layers must be considered:

(i) The input layer which contains the synapses of the first neurons hidden layer and on which the input signals are connected;
(ii) One or more hidden layers.
(iii) The output layer from which the output signals come out.

Signals flow through the network from left to right in a forward direction and on a layer-by-layer basis. The function of the hidden neurons is to intervene between the external input and the network output. By adding one or more hidden layers, the network is unable to extract higher-order statistics, for the network acquires a global perspective despite its local connectivity by virtue of the extra set of synaptic connections and the extra dimension of neural interactions The ability of hidden neurons to extract higher-order statistics is particularly valuable when the size of the input layer is large.

The *Multi-layer perceptrons network* has been used in active noise control but the radial basis function network have not be used, probably, because it is very slow.

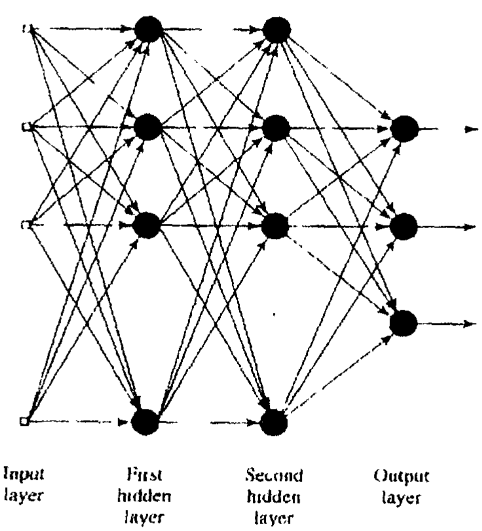


Figure 3.13. Multi-layer Perceptrons (MLP) network

In order for the neural net to perform, it must be trained. Prior to application in active noise control, a large number of couples (input data, desired output data) is presented to the network which adapts its weights in order to generate output data as closely as possible to the desired output data. The most popular learning algorithm is the back-propagation algorithm. This algorithm is based on the *error-correction learning rule*. As such it may be viewed as a generalisation of the least mean square (LMS) algorithm. Basically, the back-propagation algorithm consists of two passes through the different layers of the network: a forward pass and a backward pass. In the forward pass, an activity pattern (input vector) is applied to the sensory nodes of the network and its effect propagates through the network, layer by layer. Finally, a set of outputs is produced as the actual response of the network. During the forward pass the synaptic weights of the networks are all fixed. On the other hand, during the backward pass the synaptic weights are all adjusted in accordance with the error correction rule. Specifically the actual response of the network is subtracted from a desired (target) response to produce an error signal. This error signal is then propagated backward through the network, against the direction of synaptic connections. The synaptic weights are adjusted to make the actual response of the network closer to the desired response.

Through literature it is shown that neural net can be used in active noise and vibration control in three different tasks:

(i) System identification;
(ii) State estimator; and
(iii) Controller.

In particular, for active noise control, Snyder et al., 1995, have developed a neural network controller for use in a feedforward control scheme. This controller has been experimentally implemented and compared with a classic linear controller. Both controllers provided equal performance for a linear control problem. However, the neural net controller was able to compensate for nonlinearity introduced by the control actuator. Also, the neural controller was able to compensate for a distorted reference signal in a manner superior to the linear controller.

Toki et al., 1997, have simulated MLP networks with back-propagation learning algorithms in both modelling and control contexts. A feedforward active noise controller was simulated for cancellation of broadband noise in a three-dimensional propagation medium. An on-line adaptation and training mechanism was also developed. It was shown that with a suitable choice of the input data, the system response could faithfully be predicted by a neural-net. It was also demonstrated that the proposed neural-net provides an effective optimal controller. All results were simulated.

Yang et al., 1997, proposed a method using neural networks to control vibration of smart structures. The method was demonstrated experimentally. Three neural networks where used simultaneously for the following three tasks: (i) system identification, (ii) on-line state estimation and (iii) vibration control. Accurate modelling of composite smart structures is plagued by difficulties in the interfaces between composite materials and embedded piezoelectric transducers. This problem can be answered by the utilisation of an identification neural network for identifying the structural dynamic vibration. The neural state estimator allows one to use only one piezoelectric sensor instead of a velocity and a displacement sensor. The neural controller with a closed loop control was asymptotically stable for all feedback gains within the actuators saturation limit. The robustness of this controller has been successfully tested for parameter variations.

Chen et al., 1994, proposed the application of a neural network for state estimation of the modal parameters in the MIMSC (Modified Independent Modal Space Control) algorithm (Baz 87). This approach is interesting since it allows the control of several modes with a limited number of piezoelectric actuators. Additionally, the MIMSC method contains a procedure for determining the optimal locations of the actuators. Only simulations are considered in this article.

Bryant et al., 1993, have used an MLP neuron network and a proportional-integral derivative controller (PID) experimentally to minimise vibration of a three legged table. Rods of magnetostrictive terfenol were used in the dual capacity of passive structural supports and actuators. The neuron network was trained using a back-propagating algorithm. In order to accelerate the training time, the PID controller was used for setting the initial values of the MLP synapse weights instead of starting with random values. This procedure keeps the back-propagation algorithm from getting stuck in a local minimum.

Nagaya et al., 1997, have used a neural network based procedure to optimise a passive noise control configuration. Optimal parameters for vibration absorbers were found to control the sound radiated from a rectangular plate. Simulation results were validated experimentally on a clamped clamped rectangular plate.

Ma et al., 1996, proposed a method to suppress steady state vibration in a flexible structure due to periodic excitation, by using a multi-layer, neural network based, active vibration absorber. The efficiency of the method was demonstrated with the numerical simulation of a single degree of freedom spring mass system. This neural network based controller seems to be highly robust when subjected to variations in excitation frequencies. This approach could be useful for noise/vibration reduction of variable speed rotating machinery.

Smyser et al., 1997, have simulated, using the finite element method, a robust vibration neural net controller of composite beams with piezoelectric sensors/actuators. Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR, Athans, 86, Stein, 87) was used to design a robust controller on the basis of the state space model of the system. The state space model was obtained using the finite element method and modal superposition. Then a neural net controller was trained using a back-propagation algorithm to emulate the LQG/LTR controller. The performance robustness characteristics of both controllers were studied under various different initial conditions, for structural parameter variations and the loss of one or more sensors in a multiple input system. Both controllers exhibit excellent (and comparable) robustness. One advantage of the neuron net controller could be that less computer resources would be required for a real life implementation.

Huang et al., 1996, have proposed the simulation and experimental implementation of a dynamic absorber incorporating active vibration control. The absorber is a two degree-of-freedom spring-lumped mass system sliding on a guide pillar, with two internal vibration disturbances sources. A hybrid control approach is proposed by combining a fuzzy logic controller and a neuron net controller. The fuzzy logic controller was deigned to control the main influence part of the MIMO system, while the neural net controller was employed to take care of the coupling effect and refine the control performance of the MIMO system. Experimental results show that the control system effectively suppresses the vibration amplitude with good position tracking accuracy.

Konishi et al., 1995, have compared experimentally the performance of a neural net controller versus a classical X-LMS controller for controlling the noise generated by a rotating machine. Experimental results shown that in this case, both approaches lead to comparable performances.

In this chapter, some of the algorithms that have been used for practical implementation of active noise and vibration control have been reviewed. The algorithms are usually implemented with control philosophies that are feedforward, feedback or hybrid. These control methodologies and their applications to active noise control are the subject of review in the next chapter.

4 REVIEW OF ACTIVE CONTROL METHODOLOGIES AND APPLICATIONS

4.1 Feedforward Control Methodology

The basic features of a feedforward control system are shown in Figure 4.1. The block diagram representation is presented in Figure 4.2. The undesired noise, which is measured by the input sensor, is referred to as the reference signal *x(t)*. The reference signal is passed through the adaptive filter (controller) *M(z)*, to generate the output *y(t)*. The output is used to drive the actuator to cancel the unwanted noise *d(t)*. The objective of feedforward control is the minimisation of the residual noise signal *e(t)*.

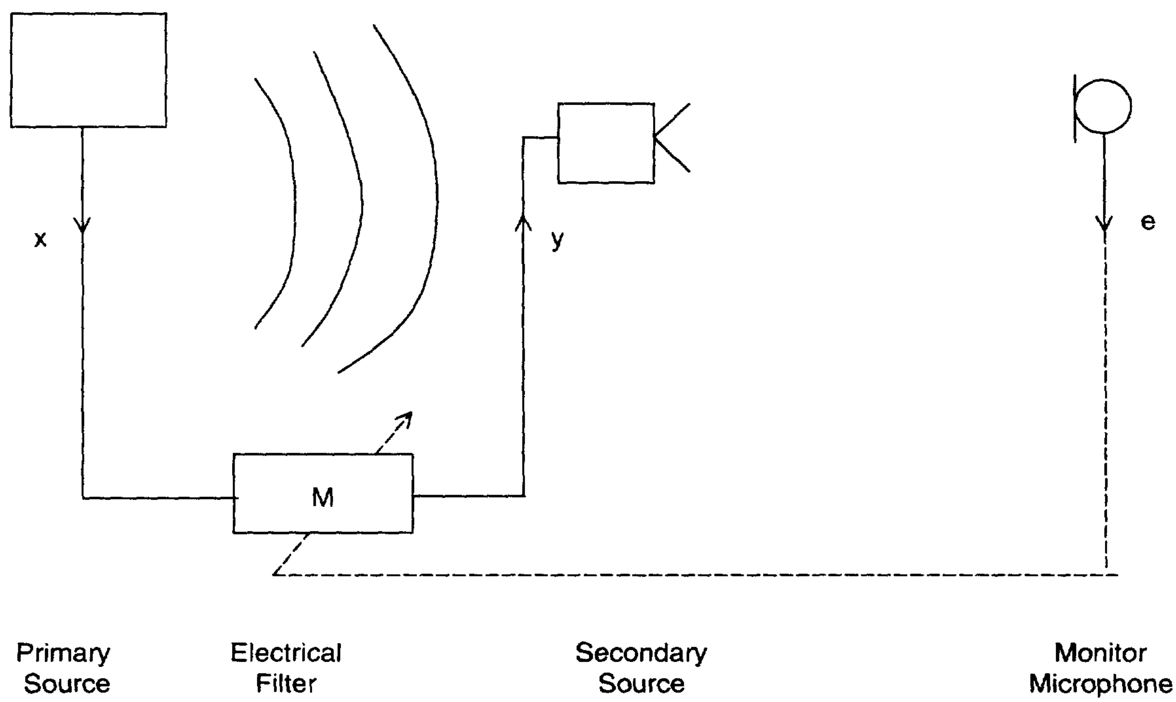


Figure 4.1. An Active Feedforward Control System

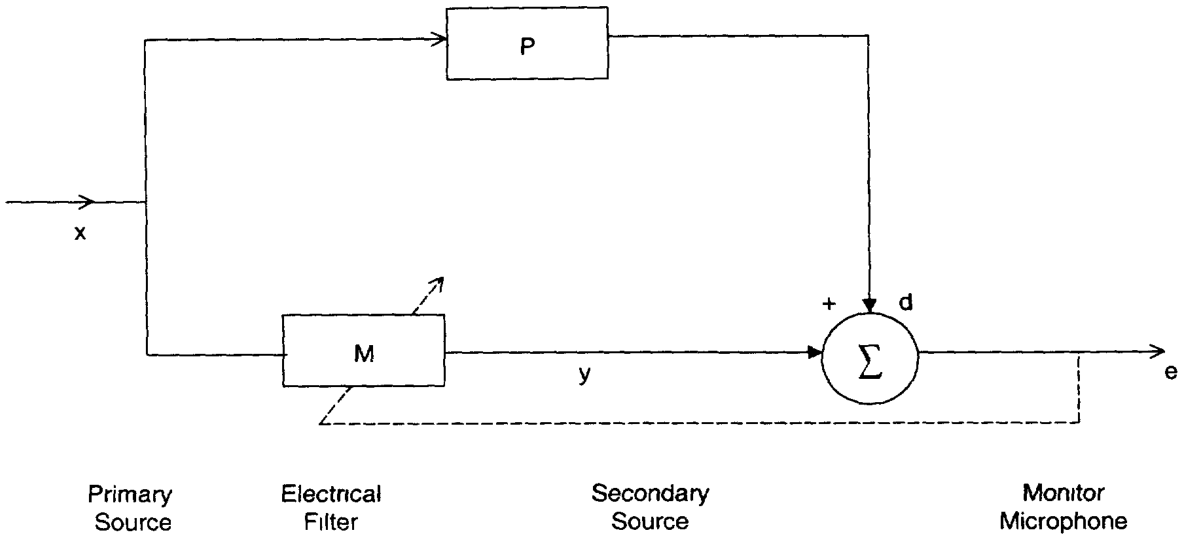


Figure 4.2. Electrical Block Diagram for Feedforward Control

The performance of a feedforward controller, *M(z),* is quantified by the magnitude of the residual noise. The smaller the residual, *e(t)*, the better the performance. In general, the performance of the controller depends on the coherence between the reference signal, *x(t),* and the output from the plant, *d(t).* Higher coherence between the two signals results in better performance. Two types of sensors are used to obtain the reference signal, Kuo and Morgan, 1996. These are:

- Acoustic sensors (microphones); and
- Non-acoustic sensors (example accelerometer, tachometers).

An acoustic sensor is used when the noise to be controlled is broadband or random. Unfortunately, the use of an acoustic sensor for the measurement of reference noise implies that the measured noise can be contaminated by the effect of acoustic feedback. This could result in instability. This problem can, however, be overcome by the use of an adaptive recursive filter to model the plant, Eriksson, 1996.

When a periodic noise is to be controlled then a non-acoustic sensor should be used to generate the reference signal. This is achieved by synchronising a sensor with the noise source.

The generated signal contains the fundamental frequencies and all the harmonics of the primary noise. This situation is applicable to the marine engine noise problem under consideration. The technique has several advantages, including:

1. Elimination of undesired acoustic feedback;
2. FIR filters that are more stable can be used for the controller design;
3. Removal of causality requirement. This allows for flexibility in the positioning of the secondary source;
4. The ability to selectivity control each harmonic independently is enhanced; and
5. Nonlinearities and ageing problems associated with the reference microphone are avoided, Morgan and Kuo, 1996.

In general, two types of reference signals are used: An impulse train with a period equal to the inverse of the fundamental frequency of the periodic noise and sinewaves that have the same fundamental frequencies as the corresponding harmonic tones to be controlled, Hansen and Sydner, 1997.

The impulse train approach, also known as the waveform synthesis method, is the most commonly used technique and was proposed by Chaplin, 1980. Elliot and Darlington, 1985, demonstrated that a feedforward control methodology that employs the waveform synthesis method for the reference signal is equivalent to an adaptive *FIR* filter with an impulse train reference input. Furthermore, they showed that the order of the *FIR* filter is equal to the period of the impulse train. Detailed description of the waveform synthesis method can be found in Kuo and Morgan, 1996; Hansen and Snyder, 1997, and Elliot and Nelson, 1992.

The sinewave approach, Kuo and Morgan, 1996; Hansen and Snyder, 1997; and Elliot and Nelson, 1992, represents the reference signal with sinusoidal components. When sine waves are employed as reference inputs. The *LMS* algorithm is referred to as an adaptive notch filter. Therefore, the second technique is commonly known as an adaptive notch filter.

4.2 Feedback Control Methodology

The basic features of a feedback control system are shown in Figure 4.3. The block diagram representation is presented in Figure 4.4. The signal, *e(t)*, is the residual noise obtained from the error sensor. It is due to a combination of the primary disturbance, *d*(t), and the feedback loop. This error signal is passed through the controller *M(z)*. The transfer function of the error path or secondary path, that is, the transfer function between the actuator input and the residual sensor output, is denoted as the plant *P(z*). The reduction in response due to the closing of the feedback control loop is given by

$$\mathbf{y(t)} = \frac{\mathbf{e}}{\mathbf{d}} = \frac{\mathbf{1}}{\mathbf{1+P(z)M(z)}} \qquad (4.1)$$

In order to make the control response small compared to the uncontrolled response then the magnitude of $|P(z)M(z)|$ must be very large compare to 1. That is $|P(z)M(z)| >> 1$. The product $|P(z)M(z)|$ is termed the loop gain. Therefore, a basic principle of feedback control is to make the loop gain large over the frequency band where noise control is desired. This band is often termed the regulation. However, complexity arises when the frequency is high, because the gain required cannot be sustained, causing the system to become unstable. Thus, the stability requirement imposes a limitation on the extent to which the loop gain can be increased. Further exposition on this subject can be found Kuo, 1987.

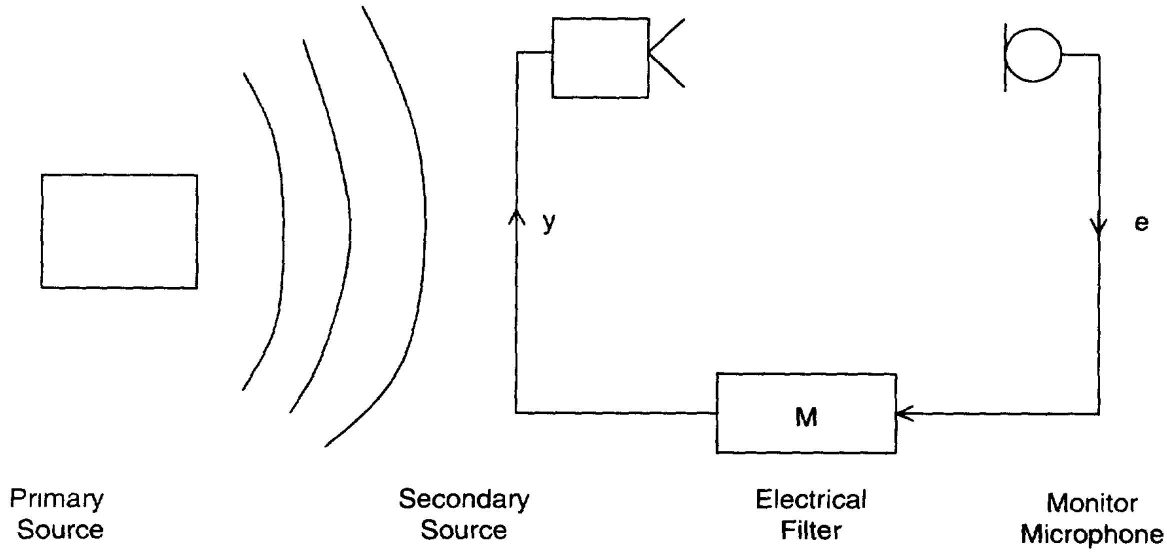


Figure 4.3. An Active Feedback Control System

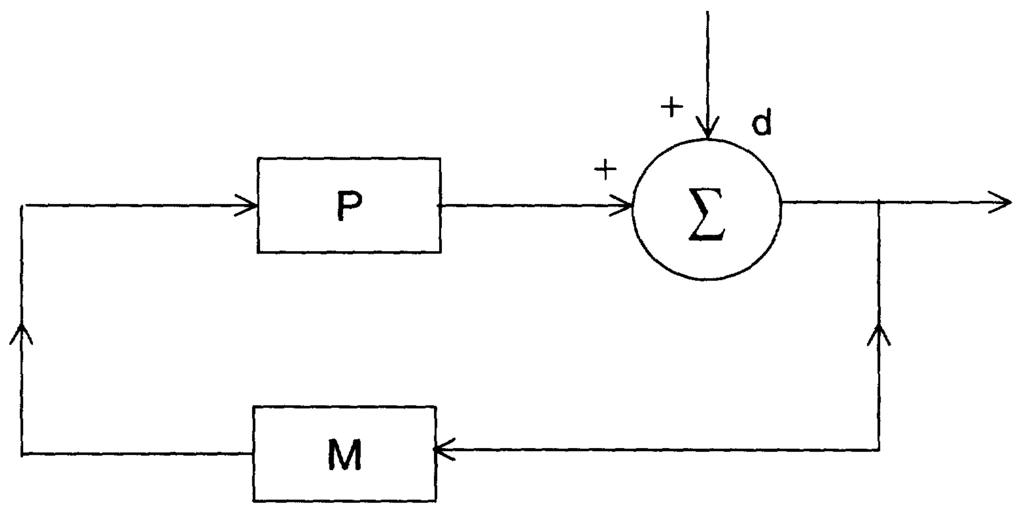


Figure 4.4. Electrical Block Diagram For Feedback Control System

There are a variety of methods for designing the feedback controller, *M(z)*. These include a collection of methods known as modern optimal control theory – Linear Quadratic Regulator, (LQR), Independent Modal Space Control, (IMSC), Koko et al., 1998, Pole Placement and Minimum Variance, Shoureshi, et al., 1993. These methods seek to minimise some weighted norm of the error signal, *e(t)*.

Both feedback and feedback control strategies have been successfully used for active noise and vibration control. The differences between the feedback control and the feedforward control methodologies are presented in Table 4.1. Table 4.2 summaries the advantages and disadvantages of adaptive feedforward and non-adaptive feedback control methodologies. Table 4.3 summaries the advantages of the various control methodologies including hybrid control methodology that seeks to exploit the different strengths of the two control methodologies.

The basic framework for using feedforward or feedback or a combination of both feedforward and feedback control methodologies depends on the number of inputs and outputs to the control system and the complexity of the control problem. The different combinations that are possible in practical problems are given in Table 4.4. It should be noted that the different combinations do not alter the basic philosophies of the two control methodologies as presented in preceding discussions. The essential difference for the various combinations is in the implementation details. The implementation details are discussed in standard texts, Nelson and Elliot, 1992; Kuo and Morgan, 1996; Snyder and Hansen, 1997.

Table 4.1 Difference between Feedforward and Feedback Control

FEEDFORWARD CONTROL	FEEDBACK CONTROL
A reference signal that is coherent with the primary noise is required.	Does not require a reference signal
It derives control by filtering a reference and an error signal	It derives control by filtering an error signal
Regions of detection and attenuation are separated	Region of detection and attenuation is the same
Performance affected by acoustic feedback	
The physical system and the controller can be designed separately	The physical system and the controller must be designed as a coupled system

Table 4.2: Comparison of Adaptive Feedforward ANC and Non-adaptive Feedback ANC, Kuo and Morgan, 1996

CONTROL ALGORITHM	ADVANTAGES	DISADVANTAGES
Adaptive feedforward ANC	Error signal is typically driven to zero Large stability bounds Precise modelling not required	Transient suppression is difficult Coherent reference signal required
Non-adaptive feedback ANC	Active damping provides transient signal suppression Relatively simple control algorithm	Modelling uncertainty reduces robustness Limited cancellation over limited bandwidth

Table 4.3: Comparison of the Behaviour of ANC Systems, Kuo and Morgan, 1996

	FEEDFORWARD ANC	ADAPTIVE FEEDBACK ANC	HYBRID ANC USING FIR FILTER	HYBRID ANC USING IIR FILTER
Filter order	Moderate	High	Low	Low
Spectral capability	Broadband and Narrowband	Narrowband only	Broadband and narrowband	Broadband and narrowband
Primary noise	Not cancelled	Good cancellation	Good cancellation	Good cancellation
Coherence of measured and primary noise	Coherent only	Coherent or incoherent	Coherent or incoherent	Coherent or incoherent

Table 4.4. Different Combinations of Feedback and Feedback Control

TYPE OF CONTROL	NUMBER OF INPUT SENSORS	NUMBER OF OUTPUT ACTUATORS
Single Input and Single Output (SISO)	1	1
Single Input and Multiple Output(SIMO)	1	>1
Multiple Input Single Output (MISO)	>1	1
Multiple Input Multiple Output (MIMO)	>1	>1

4.3 Decentralised Active Noise Control Methodology

In active noise control, centralised feedforward techniques are most often used, Elliott, 1987, Nelson, 1992, Melton, 1992, Popovich, 1992. In the case of active systems designed for the global control of sound over a region of space, employing multiple secondary actuators and multiple error sensors, a multi-channel feedforward controller that drives all of the secondary sources can be implemented. The controller is typically adapted continuously to minimize the sum of the squared outputs from all the error sensors. Such a controller could be described as being fully coupled since the part of the controller driving each secondary source is being adjusted in response to the output of all the error sensors. The algorithm that adjusts the controller typically uses a model of the system under control, i.e., an internal representation of the response from each secondary source to each error sensor. In order to implement such a fully coupled controller, the signals from all the error sensors must be routed to each part of the controller driving each secondary source.

For very large systems, with numerous secondary actuators and numerous error sensors, the fully coupled controller may require considerable processing power and memory. In fact, with N secondary actuators and N error sensors, the processing power and the memory allocation are proportional to N^2. Notice, however, that it is not always necessary to have only one central controller to implement a fully coupled control strategy. If the control algorithm can be written in a form in which the input to one secondary source does not depend on the inputs to the other secondary sources, as is the case with the multiple error LMS algorithm, multiple distributed processors can be used to implement the fully coupled controller. There are, however, two main remaining disadvantages with any such fully coupled system. First, the degree of data communication between the error sensors and the controller may require a great deal of wiring, particularly for a system with large number of error sensors distributed over a wide area. Second, the fully coupled control algorithm that accounts for all the interactions between each of the secondary sources and each of the error sensors is generally a complicated model. This model may be time consuming to identify if the number of secondary sources and error sensors becomes large.

One way of avoiding these problems is to use a number of independently operating control systems in which each individual controller drives a small number of secondary sources and is adjusted to minimize the sum of the squared outputs of a small number of error sensors. This is the decentralised control approach. The limit of this approach is when there are as many secondary sources as error sensors, and the input to each secondary source is adjusted to minimize the output of only one error sensor.

In the case of active noise control in free space with a large number of loudspeakers and microphones, the system to be controlled cannot be subdivided into independent subsystems. This may limit the effectiveness of a fully decentralised approach, especially in terms of its stability and performance when compared to a centralised controller. There have been several studies published recently related to both the stability and improving performance of decentralised controllers in which a number of stability criteria were defined (Siljak, 1991, Date, 1994, Sourlas, 1995, Gong,

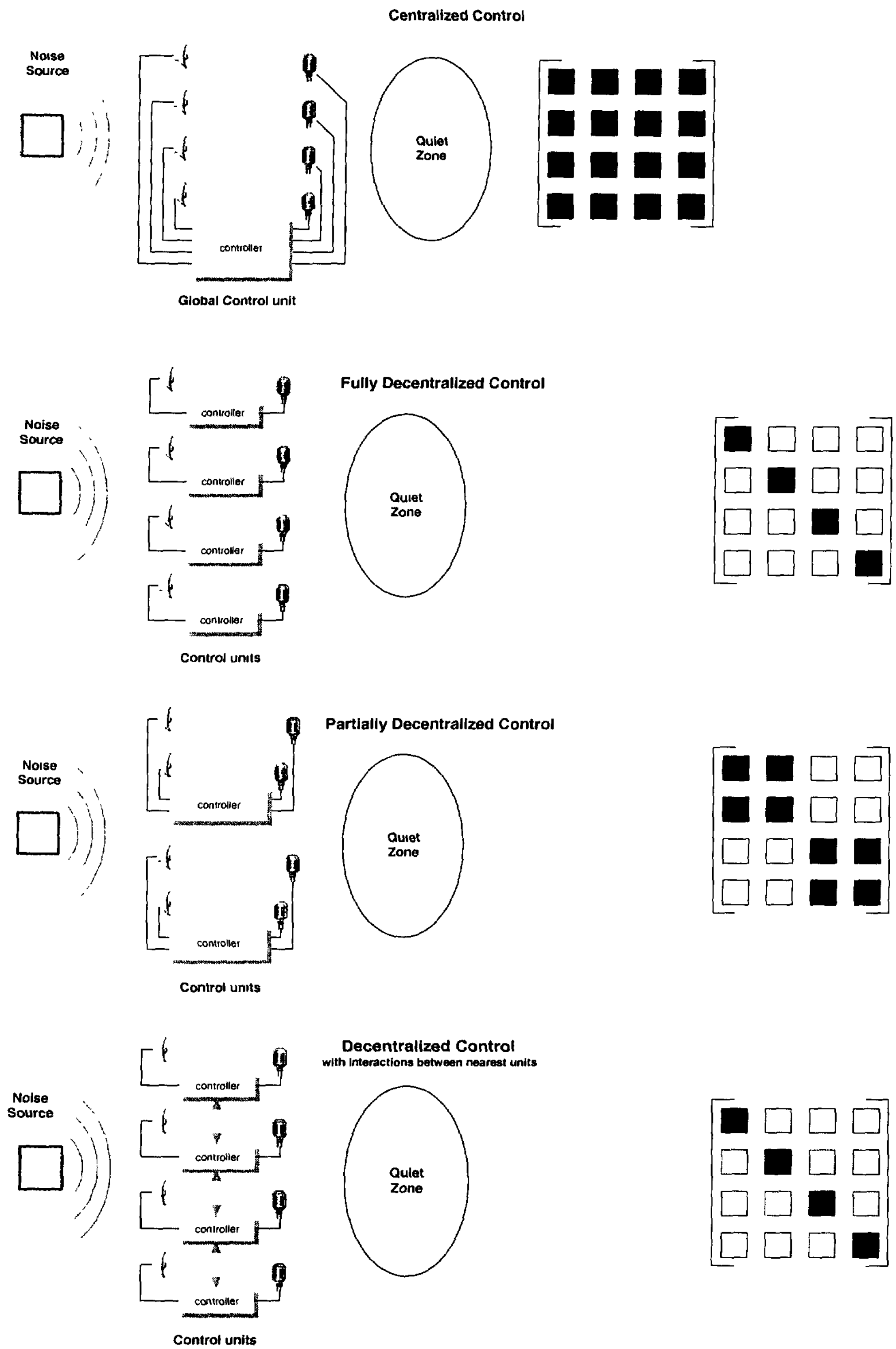


Figure 4.5. Different strategies for feedback MIMO control.

For each case, the interaction scheme between the four sensors and the four control sources are presented in a matrix (black = interaction, grey = possibility of interaction, white = no interaction)

1997). In a related study, Elliot (1994) has published a report dealing with decentralised feedforward active control systems. In addition, research is being conducted at GAUS related to independent feedback controllers to achieve active noise reduction in free space Leboucher, 1999. Huang 1996, discusses the potential utilisation of a MIMO system improved by coupling a fuzzy controller for each degree-of-freedom and a neural net controller to solve coupling effects (see Figure 4.5). This can be interpreted as a partial decentralised control.

For each case, interactions scheme between the four sensors and the four control sources are presented in a matrix (black = Interaction, grey = possibility of interaction, white = no interaction).

An example of a decentralised system used for the control of the humming noise emitted by large power transformers is presented in Figure 4.6 [L'Espérance, 1999]. A total number of 24 single-input/single-output channels were used to control the noise at 120 Hz. The control units consist of single microphone and loudspeaker pairs.

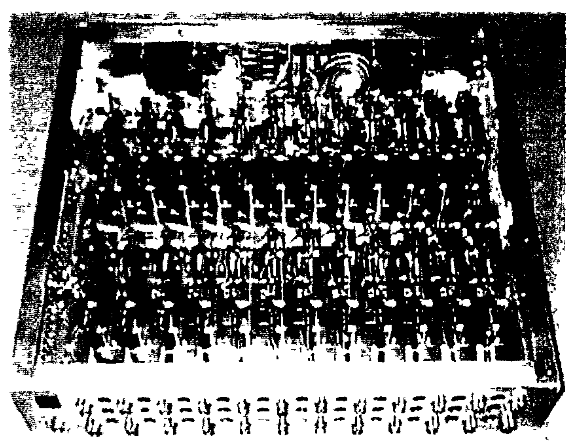


Figure 4.6. Practical implementation of a decentralised control system using 24 single-input/single-output channels. Each of the control units are composed of a microphone, a loudspeaker and a C50 DSP.

4.4 Control of Tonal Noise

Tonal noise can be defined as periodic noises that are mainly generated by rotating or repetitive machines. Because the noise source operates in a repetitive cycle, the noise frequencies are multiples of the basic rotational cycle of the machine, Denenberg, 1992. The basic noise that is generated by marine diesel engines falls into this category.

Most of the successful applications of active noise controller technologies have targeted tonal noises. In most reported works, the feedforward control technique with non-acoustic reference sensors has been employed. A non-acoustic sensor that is synchronised with the noise source is used to generate a reference signal and all the harmonics of the primary noise, Kuo and Morgan, 1996.

The waveform synthesis method highlighted in Section 4.1 has been successfully applied to the control of noise that originates from engines. For example, successful applications to exhaust noise generated by internal combustion engines have been reported by Crocker, 1983, Chaplin, 1984, Eghtesadi et al, 1985, Eghtesadi and Chaplin, 1991, Denenberg, 1992, Ziegler and Gardener, 1993. Figure 4.7 illustrates the application of filtered -X feedforward control methodology in an exhaust system.

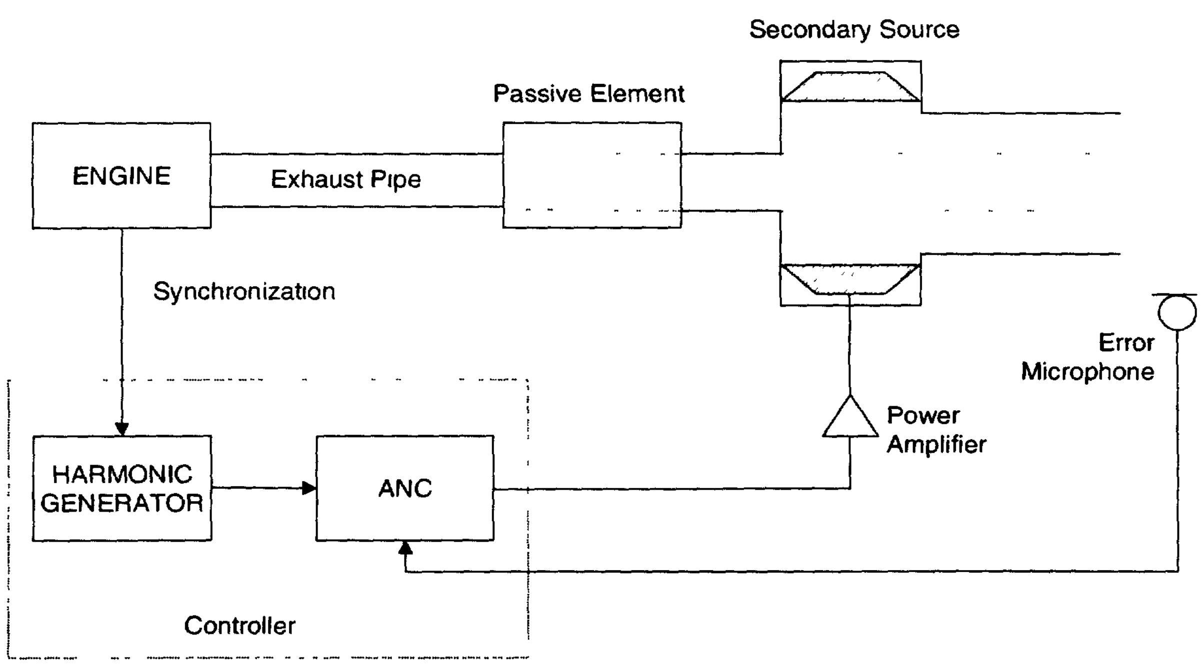


Figure 4.7. Back Diagram of Electronic Muffler

Tests performed by Crocker, 1983, on several diesel engines showed that an active noise control approach could attenuate the steady state engine exhaust noise in the far field by more than 20dB with no measurable deterioration in engine performance. Ziegler and Gardener (1993) obtained a similar result. An average reduction of 20 dB in noise was recorded at the cylinder firing frequency of 90 Hz and an average reduction of 10 to 16 dB for 10 harmonics over a frequency range from 90-360 Hz was observed. The sensors that were employed in all cases of exhaust control were speakers. Nishimuri, 1991, proposed an optimum physical arrangement and cooling method to ensure the durability of transducers used in exhaust tonal noise control.

Kuo and Morgan, 1996, Hansen and Sydner, 1997, have noted that the best methodology for controlling engine related tonal noise problems (exhaust stacks, engine mount etc.) is a feedforward approach that employs non-acoustic sensors to synthesise the reference noise either by waveform or sinewave techniques.

However, Berkman and Bender, 1997, have noted that the primary detriment of feedforward control which uses synthesised reference noise is a lack of guarantee of system stability or avoidance of significant noise amplification in regions outside the specified frequency range. They have, therefore, advocated for the use of a hybrid control approach.

Other methods for control of narrow band noise that rely on the feedback architecture have been proposed. They include the Linear Quadratic Regulator (LQR) model with frequency shaping constant function and the LQR model with disturbance modelling, Sievers and von Flotow, 1992.

4.5 Control of Broadband Noise

When additional noise control is required beyond the suppression of discrete engine tones, then the control problem is broadband. A broadband noise is one that tends to distribute energy evenly across some frequency band.

Successful applications of ANC for broadband duct noise control have been reported. Nowicki et al. 1994 and Pelton et al, 1994. Pelton et al, 1994, employed the filtered –U algorithm that was described in Chapter 3 in the feedforward mode to control duct noise in a large 50,000ft building. 85 single units of the controller were used for the purpose. Nowicki et al, 1994, used the filtered-X LMS feedforward algorithm to attenuate blower/motor noise. The 800 Hz tone was reduced by 17.8 db while the overall A-weighted broadband noise was reduced by 10.9dBA.

Hull et al., 1993, controlled the broadband noise in a duct by using an observer (sensor) with the pole placement algorithm in the feedforward mode. They demonstrated that this approach could reduce the noise level at all points in the duct by 58%.

4.6 Controllers and Nonlinearities

4.6.1 Definition of a Nonlinear System.

A system (path or controller) is said to be linear if the following rule is satisfied. If the input $X1$ generates the output $Y1$ and if the input $X2$ generates the output $Y2$, then the input $a*X1 + b*X2$ must generate the output $a*Y1+b*Y2$. If this rule is not satisfied, then the system is said to be nonlinear. A quick test for estimating the nonlinearity level of a system is to use a pure tone as an input signal and to observe the output signal. If the system is nonlinear, harmonics (and sometimes sub-harmonics) are present. The amount of nonlinearity can be estimated by comparing the energy levels of the harmonics/sub-harmonics with the fundamental frequency.

4.6.2 Possible Locations of Nonlinearity

Figure 4.8 shows the possible locations of nonlinearity in active control systems (the notation used in Figure 3.3 has also been adopted in Figure 4.8).

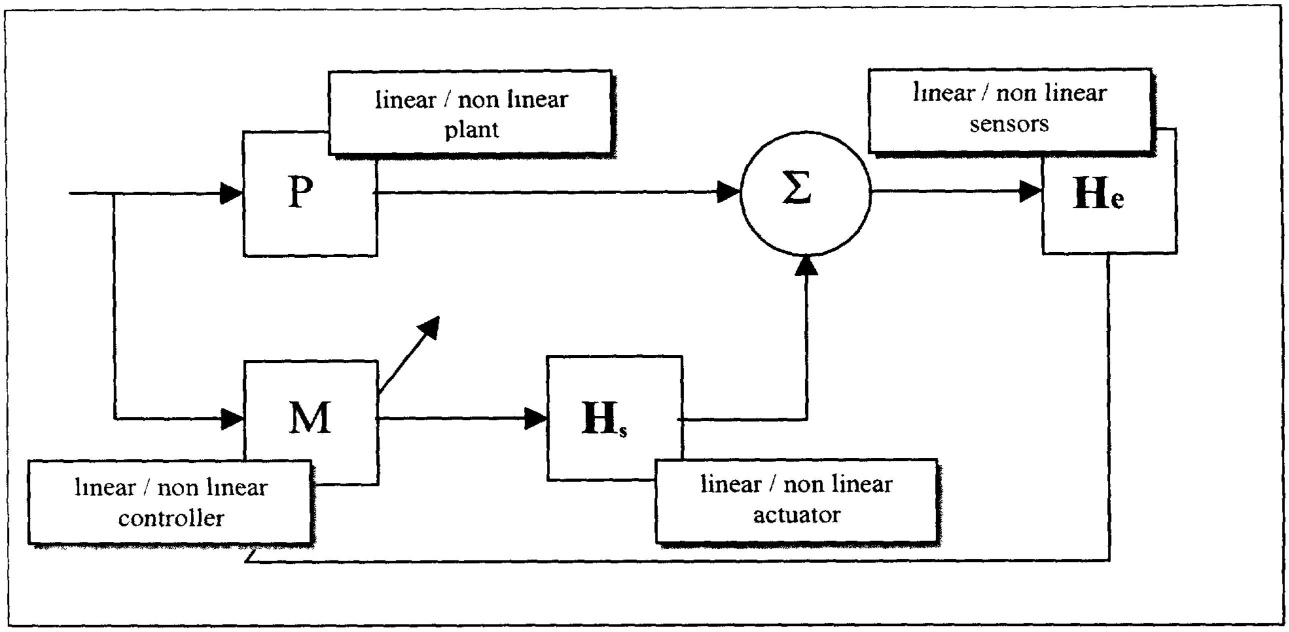


Figure 4.8. Possible Locations of Nonlinearity in Active Control Systems

Two different types of nonlinearity locations can be distinguished: (i) in the plant and error sensor and (ii) in the actuator. Depending on the location of nonlinearity (i.e. into H_S or H_e) the use of a linear or nonlinear controller is discussed in the following lines.

First case: nonlinearity in the plant or error sensor. In such a case, the transfer function H_s is still linear so that classical identification techniques can be used. The model of H_s obtained during the identification process will be valid for any actuating level during the control process.

Second case: nonlinearity in the actuator. In such a case, the identification of the actuator transfer function is difficult since theoretically, the identification will be valid only for the particular combination of frequencies, phase and amplitudes that are used during the identification process, the principle of superposition or linearity does not work in this case. There is no guarantee that the performance of the controller will be adequate during the control process since the model of the transfer function of the actuator built during the identification process is no longer valid during the control process.

4.6.3 Use of a Linear Versus Nonlinear Controller

In the two cases previously presented, both types of controllers can be considered: linear or nonlinear. In the first case, a linear controller will not provide a proper model of the plant and sensor transfer function. In the second case, a linear controller will not be able to compensate for the nonlinearity of the actuator when generating the control signal. In summary, linear controllers will provide poor performances in controlling nonlinear systems. The only way to improve the control performances on nonlinear systems is to use nonlinear controllers. Such controllers are mainly based on fuzzy logic genetic algorithms, and Neural networks. A dedicated section about neural networks is presented in this document, since it is the most promising way to realize effective nonlinear controllers. If the structure of the controller is sufficiently sophisticated (i.e. with a sufficient number of degrees-of-freedom) good performance can be expected from nonlinear controllers but they require high performance processors and complex algorithms that cannot be expected from commercialised classic controller technologies (turnkey systems)

4.6.4 Practical Considerations

In practice, the main source of nonlinearity is the actuator when high levels of actuation are required. Unfortunately, this is the worst case to control with classical linear controllers. There are two ways of improving active control of heavy structures: (i) improving the linearity of the actuators and using linear controllers or (ii) using classical actuators and compensating for their nonlinearity by using advanced nonlinear controllers. Both ways require further research and development before reaching satisfying solutions.

4.7 Active Engine Mount

The objective of an active engine mount is the reduction in the transmissibility of vibration force from the engine to the receiving structure (ship hull). Since the source of vibration is the rotating machine, then the primary disturbance is a deterministic, periodic and narrowband signal.

Conventionally, the reduction in transmissibility between the engine and the structure is achieved with passive mounts. Passive isolation systems are required to be very soft and this requirement is at variance with the need for the mounting system to provide stable support for the engine. Furthermore, for a ship hull structure, the performance of a passive isolation system can be degraded at the resonance frequencies of the structure. Chapman, 1980, has shown that in order to overcome these difficulties it is expedient to supplement the passive mount with an active mount.

In a practical marine engine, for example, the engine is mounted on the flexible ship hull through a multiplicity of mounting points. A typical mount has potentially six degrees-of-freedom – three translational and three rotational. At any given mounting point, the machine is capable of applying primary excitation to the receiving structure by all the six forms of input.

Chapman and Smith, 1983, and Smith and Chapman, 1983, 1986, presented several studies on the potential of applying active vibration control to multiple mount machinery installations. They suggested two methods by which the secondary active forces can be applied:

(i) The parallel cancellation system with the actuator between the machine and the support structure; and
(ii) The receiver cancellation system in which the receiver is attached to the structure directly.

Both cancellation systems are illustrated in the campanion document on actuator and sensor technology (Koko, et al., 1999). In the parallel cancellation system, the actuator aims to eliminate the transmissibility of the machine vibration by acting between the receiver and the machine while in the receiver cancellation system, the reaction of the actuator against an inertial mass is used to provide the cancelling force. Smith and Chapman, 1983, 1986, employed a feedforward approach in active engine mount design. In particular, a reference signal that was synchronised with the rotations of the machine was used to derive the output to the secondary actuators. The algorithm used in the adaptive filter designed by Smith and Chapman, 1986, was based on a trial and error approach.

White and Cooper, 1984, undertook a similar study using feedforward control. In order to adapt the coefficients of the adaptive filter, an iterative matrix inversion scheme was employed. The problem that they investigated was the active isolation of a ship hull from a low frequency rotating machine vibration.

Jenkins, 1990 and Jenkins, et al., 1991, have studied the active isolation problem. They used a feedforward control approach that employed multiple error LMS algorithm for the adaptation of the filter coefficients. The multiple error LMS algorithm develop by Elliot, 1987, is a generalisation of the filtered X-algorithm LMS algorithm. Jenkins et al., 1991, investigated the effectiveness of the active engine mount in reducing the transmissibility of vibration. The result of their study showed that employing a secondary force in parallel with an existing mount offers the advantage that the mount may be made much stiffer. Furthermore, the combination of a passive and active element can reduce the physical instability of a conventionally passive mounted machine. They also demonstrated that a passive isolation system is relatively ineffective at low frequencies and that the passive/active isolation system is more robust than the purely passive system at low frequencies.

MacDonald et al., 1991, have used a procedure similar to Jenkins' to design active engine mounts for automotive vehicles. The algorithm employed was a multiple-error *LMS* algorithm. Ushijima and Kumashawa, 1993, employed a similar approach to automotive engine mount vibration control, but the mount that they used included a piezoelectric actuator embedded in a conventional passive isolator. Sumali and Cudney, 1994, have developed an active engine mount with a layered stack of piezoelectric actuators.

Sievers and von Flotow, 1988 and von Flotow, 1988, developed two feedback control algorithms that employ the linear quadratic regulation (LQR) disturbance rejection model and the linear quadratic Gaussian (LQG) model with a frequency shape function for the design active engine mounts. The use of a disturbance model was based on the fact that although the engine noise is tonal, it is subject to contamination that may result in a broadband spectrum for the signal.

Watler et al., 1988, and Berkman and Bender, 1997, combined the feedforward architecture that uses an adaptive LMS algorithm with the feedback model, employing either disturbance rejection or LQG with frequency weighting to design active engine mount for marine vessels. The rationale for using combined control methodologies as noted by Walter et al., 1988, was that the noise that originates from the engine is basically broadband with high tonal densities at certain frequencies. Electromagnetic actuators were used to implement the active engine mount.

It can be seen that the feedforward, the feedback and hybrid techniques have been employed in active engine mounts.

4.8 Active Structural Acoustic Control (ASAC)

Active noise control can be achieved either by active cancellation which involves the superposition of waveforms or by using active elements (for example, piezoelectric smart structures) to modify the dynamic properties of the system, such that the physical characteristics of the overall acoustical system are changed. The second approach is particularly relevant for large structural systems that act as radiators of noise. In particular, an area of research that has gained momentum for naval and aerospace applications in recent years is active structural acoustic control, Fuller et al. 1997. The Office of Naval Research, DARPA, has funded a great deal of research work in this area, Clark and Fuller, 1992, etc. Therefore, we believe this area of research will be of great interest to DREA especially in the minimisation of noise radiated from the structure into the sea. As noted by Fuller et al., 1996, active structural acoustic control is of great importance in situations that involve the radiation or the transmission of sound through some form of structure, for example, the hull of a submarine or the fuselage of an aircraft. Active structural acoustic control (ASAC) has gained momentum in recent years because of the limitations of active noise cancellation (ANC) techniques for global noise reduction. The limitations of ANC for control of radiated noise include, Fuller, 1992:

- The impracticability of having errors sensors located away from the structure (for example, in order to control the noise radiated by the ship hull into the ocean, microphones will have to be located in the ocean water to get some form of error feedback); and

- The number of acoustic actuators that are required for control of the global sound radiation is enormous.

Active structural acoustic control has been developed to circumvent these limitations. Structural acoustics is concerned with the coupling between the motion of elastic structures (for example, a ship hull) and the surrounding sound fields. In structural acoustic analysis the response of the acoustic and structural systems must be studied simultaneously.

There are two ways by which radiated sound from a structure, for example, a ship hull, can be reduced. The first approach is to completely reduce the overall structural response with active vibration control. This method requires a large number of actuators and sensors and is therefore not practical for a large structure.

The second approach is to minimise the sound radiation, of the various modes of vibration, of the structure. Different modes of structural vibration have different sound radiation efficiencies and some are better coupled to the radiation field than others. Therefore, to reduce the sound radiated by a structure, only selected modes need to be controlled. That is, active control should be applied to the structure to control only the modes that are strong radiators of sound. Table 4.5 summarises the main differences between active structural acoustic control (ASAC), active noise cancellation (ANC) and active vibration control (AVC).

Table 4.5 Differences Between AVC, ANC and ASAC

	Active Vibration Control (AVC)	**Active Noise Cancellation (ANC)**	**Active Structural Acoustic Control(ASAC)**
Objective	Minimization of Mechanical Vibration. Control structural modes that contribute most to vibration.	Minimization of Radiated Noise	Minimization of Radiated Noise. Controls structural modes with high radiation efficiencies
By	A Mechanical Actuator Such as Piezoelectric Materials.	Acoustic Actuator Such as Loudspeakers.	Mechanical Actuator Such as Piezoelectric Materials.

The advantages of active structural acoustic control over conventional active noise cancellation especially for global control of radiated noise, include a reduction in the number of control channels, Fuller et al, 1997, Jacques, 1997 and Fuller and von Flotow, 1995. Furthermore, when implemented using smart structures or other strain inducing actuators a very compact and lightweight configuration is obtained.

ASAC essentially transforms the control of radiated sound to the control of structural modes that have high radiation efficiencies. Distributed sensors and actuators such as piezoelectric materials or shape memory alloys that are surface bonded or embedded have been developed and used in ASAC. These transducers are integrated directly into the structure with an adaptive controller. The new integrated structure/controller/actuator/sensor system is commonly referred to as a smart or intelligent structure, Fuller et al. 1992.

An important issue that arises in active structural acoustic control is optimal placement of the distributed actuators and sensors. Wang et al., 1991, and Clark and Fuller, 1992, have demonstrated that in order to obtain high performance with a reduced number of transducers, the locations and shapes of the distributed transducers must be optimised. The objective function for the optimisation is the radiated sound. The optimization can be executed experimentally by building prototypes of the integrated smart structure and comparing the values of the radiated sound for different locations and shapes of the transducers. This approach is expensive, tedious and time consuming. An alternative strategy is to use a computational tool for numerical testing. The computational tool must have capabilities for integrated modelling of structural acoustic control with distributed sensors and actuators. Furthermore, it must have a capability for optimisation with radiated noise as the cost function. To the best of our knowledge, such a computational tool does not exist. However, Martec has developed two computational tools that have all the required components. These tools are AVAST and SMARTCOM. AVAST has the ability to model structural acoustic interactions. SMARTCOM has the capabilities for optimising integrated structural control with piezoelectric distributed transducers. Enhancement and seamless integration of SMARTCOM capabilities into AVAST will provide a tool that can be used for ASAC. It is worth noting that, to the best of our knowledge, the SMARTCOM program that has been developed by Martec is the only commercial software that integrates optimisation of actively controlled smart structures with finite element modelling capabilities.

Various controller technologies have been implemented in ASAC. Fuller et al., 1996, have noted that the most important consideration in the choice of a control strategy is the nature of the noise source: whether it is steady state sinusoid (tonal), including multiple frequencies, or broadband (random). Both the feedforward and feedback control strategies have been employed in ASAC. This includes multi-channel feedforward control methodologies that employ the filtered-X algorithms, Clark and Fuller, 1992, Fuller et al., 1992, Wang and Fuller, 1992, Burdisso and Fuller, 1992, 1994, and Fuller et al., 1997, and feedback control methodologies that use the LQG algorithm for the control design, Baumann, et al., 1992 and Jacques, 1997.

5 CONTROLLER DESIGN AND IMPLEMENTATION TECHNIQUES

In general, the design and implementation of a control system is a process involving a number of steps. The steps are illustrated in Figure 5.1.

- First, the physical system to be controlled must be identified, either analytically or experimentally, including the disturbance sources.
- The physics and mechanical coupling of the sensors and actuators must be taken into account in the next step.
- An appropriate control algorithm is developed in the following step.
- Using the complete model developed in the first two steps, computer and real-time simulations are then used to evaluate alternative control system designs, explore the performance of different control strategies, and expose unanticipated problems.
- The last step is the practical implementation of the control system, including laboratory testing and the embedded system design.

It may be necessary to revisit previous steps if any problems are encountered. It is also possible to bypass some steps if knowledge of the physical system is known. In this chapter, the general control design and implementation strategy is discussed.

5.1 System Analysis

System analysis can provide an in-depth knowledge of the complex dynamics of a system. System identification and physical system modelling are used to generate a mathematical representation of the complete system behaviour based on acquired data and known physical principles, respectively. The physical system to be controlled as well as the sensor and actuators have to be modelled to allow simulation in the next step of the control implementation.

The purpose of establishing a model of a dynamic system is twofold: for simulation and for prediction and control. Models make it possible to explore situations which would be hazardous, difficult, or expensive to set up in the actual system. Simulation models are valuable for "what if" analyses. Accuracy and completeness may be less crucial when qualitative outcomes are being explored rather than precise numerical consequences.

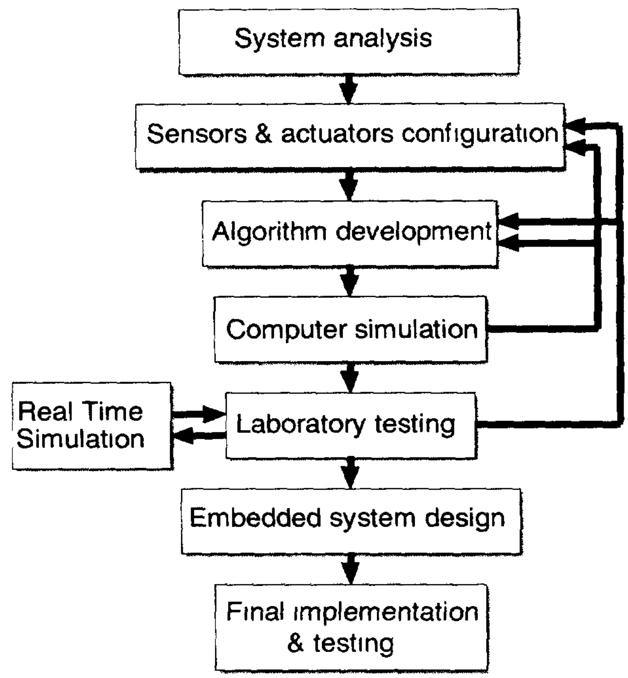


Figure 5.1. The Main Steps in the Design and Implementation of a Control System

Prediction by a dynamic model can also be important in control system design. Control schemes can be designed based on a predetermined model of a system. The development of a highly accurate model may not be achievable, however, due to the variability in the system to be controlled. Ideally, the model would indicate the extent of the variability. The controller could then be designed to have an adaptation scheme that can compensate for the expected variability. Most control schemes, however, employ a model for prediction only, revealing how the system will respond, to a standard input from the actuators.

The characteristics of the disturbance exciting the physical system are also to be identified in order to get a complete model of the system. Again, the disturbance can be identified using prior knowledge of the physical mechanisms involved and some measurement systems.

Identification is the process of constructing a mathematical model of a dynamic system from observations and prior knowledge. Basically, there are two ways of constructing mathematical models:

- *Physical modelling.* This is an analytical approach. Basic laws from physics (such as Newton's laws, balance equations and variational formulations) are used to describe the dynamic behaviour of a phenomenon or process.
- *System identification.* This is an experimental approach. Experiments are performed on the system. A model is then fitted to the recorded data by assigning suitable numerical values to its parameters (filter coefficients).

A comparison can be made of the two modelling approaches. In many cases, the processes are so complex that it is not possible to obtain reasonable models using only physical insight. In such cases, one is forced to use identification techniques. It often happens that a model based on physical insight contains a number of unknown parameters (eg. characteristics of the excitation source), even if the structure is derived from physical laws. Identification methods can be applied to identify the unknown parameters. Physical modelling and system identification are briefly presented here.

5.1.1 Numerical Modelling

Measurement systems and a prior knowledge of the physical system dynamics can be used to establish a numerical model of the system. Computers are now used extensively for simulation. For this reason, the analogy approach based on equivalent electrical circuits has been replaced by *block diagram* approaches (eg. Matlab Simulink). Block diagrams are much more powerful, flexible and intuitive than circuit models because they usually work in the Laplace domain and can describe a wide variety of physical systems with a limited number of simple block structures (see Figure 5.2) [Shetty, 1997]. Block diagrams allow for easy connection between electrical, mechanical, fluid and other systems and efficient simulation tools based on them are now available. One special family of dynamic models has identification methods far more fully developed than the rest: finite-order, linear, lumped and time-invariant models [Norton, 1986].

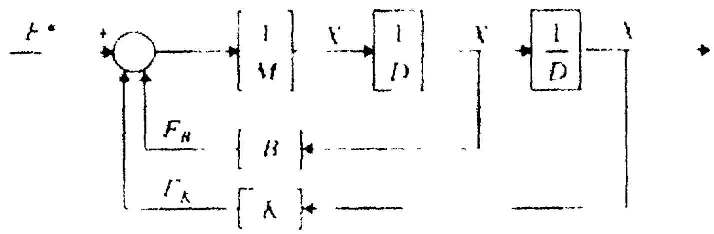


Figure 5.2. Example of a mass-spring damper block diagram [Shetty, 1997]

For a dynamic system, the output at any instant depends on its history, not just on the present input as in an instantaneous system; the input-output relation is thus a differential equation. The past of a system or model influences the future by way of a number of initial conditions or stored energies; the number is called the system or model order. Any model must describe how each of its energy storage modes contributes to the output, so the number of model parameters is at least equal to the model order. The model is complicated if there is significant pure delay in the system. Since changes propagate through the system at finite velocity some delay is always present, but it may be negligible.

Linear models are the simplest models to identify. Linearity allows the response to any input, however complicated, to be computed by breaking the input into simple components, and than add the responses to each component. In identification, this implies that only the response to a suitable standard input be identified.

When the variables describing a system are written as functions of time only, each of the variables implicitly describe a physical quantity located at one point in space, without a spatial significance: the system is *lumped*, not distributed. When a distributed variable is represented by one or more lumped variables, an approximation error is incurred in the dynamics in addition to loss of resolution.

A dynamic system is *time-invariant* if the sole effect of delaying its forcing and initial conditions is to delay its response by the same amount. In other words, the input-output relations do not vary with time and are relatively easy to analyze.

Within the family of linear, lumped, time-invariant and finite-order models, there are quite a few further distinctions to be made: input-output versus state-variable models; time domain versus transform models; deterministic versus stochastic models; single-input-single-output versus multi-input-multi-output models; continuous time versus discrete time models; parametric versus non-parametric models.

5.1.2 Experimental Identification

In general terms, an identification experiment is performed by exciting the system (using some sort of input signal such as a step, a sinusoid or a random signal) and observing its input and output over a time interval [Sagara, 1998]. These signals are normally recorded in a computer mass storage device for subsequent information processing. We then try to fit a parametric model of the process to the recorded input and output sequences. The first step is to determine an appropriate form of the model (analytic model or numerical, filter model). As a second step, some statistically based or minimisation method (least mean square [Wang, 1995], fuzzy logic [Lin, 1999], neural networks [Wang, 1998]) is used to estimate the unknown parameters (physical parameters or filter coefficients). In practice, the estimations of structure and parameters are often done iteratively. The model obtained is then tested to see whether it is an appropriate representation of the system.

The models obtained by system identification have the following properties, in contrast to models based solely on mathematical modelling (see Figure 5.3):

- They have limited validity, for a certain working point, and a certain type of input;
- They give little physical insight, since in most cases, the parameters of the model have no direct physical meaning; and
- They are relatively easy to construct and use.

Experimental identification of the model of a physical system needs to be done carefully. Identification can be very poor for certain experimental conditions [Söderström, 1989]. The specification of the experimental condition includes such things as the choice of pre-filtering, sampling interval and input generation. Many systems work under closed-loop control. The open-loop system may be unstable or so poorly damped that no identification experiment can be performed in open loop. It is very important to know if and how the open-loop system can be identified when it must operate under closed-loop control during the experiment [Quek, 1999]. Sometimes, there are certain practical restrictions on identification experiments that must be met. These can include bounds on the input and output variances.

System identification can be realised through the use of two distinct approaches: measurement systems and transfer functions identification [Norton, 1986]. The following figure illustrates the general flowchart involved in system identification. Data is collected from an experiment and a model of the physical system is proposed together with parameters, based on an *a priori* knowledge of the system. Iterations are then performed to adjust the model parameters, and possibly the model, so that the output from the model agrees with the experimental data.

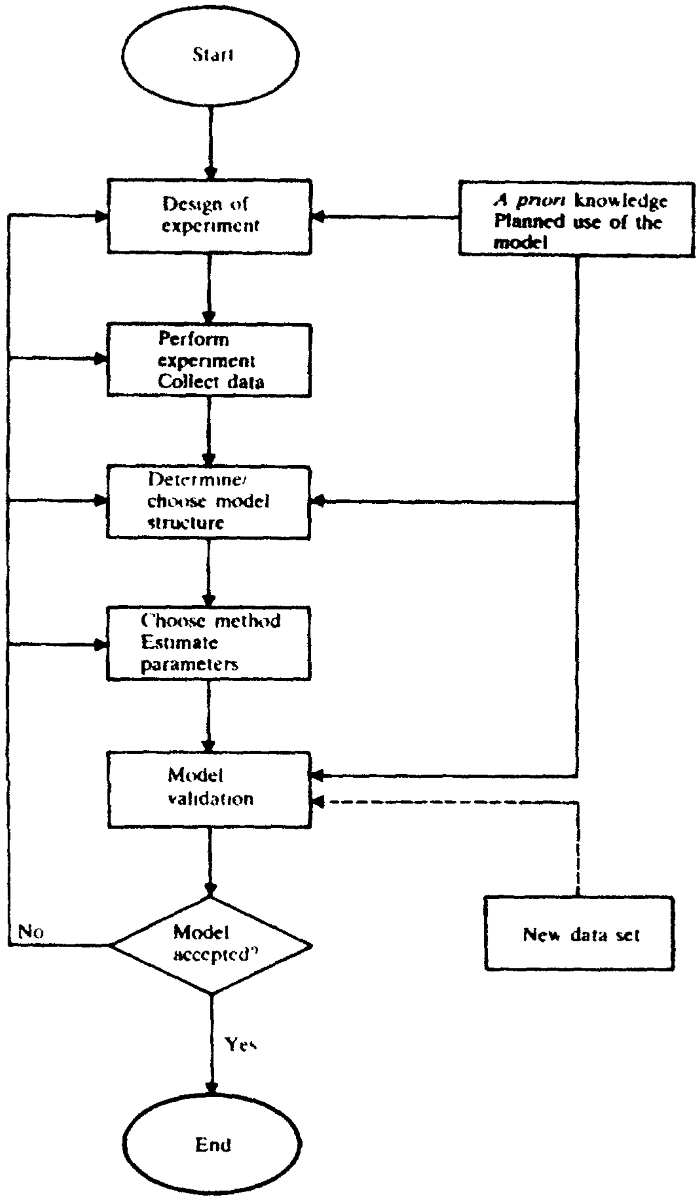


Figure 5.3. Schematic flowchart of system identification [Söderström, 1989]

The first type of identification (see Figure 5.4) uses *open-loop systems* such as spectrum analysers and data acquisition systems coupled to various sensors like accelerometers, laser vibrometers, microphones and others. This type of identification is used to measure the response of a system to the particular forced excitation acting on it; it does not provide any information on the internal properties of the system. However, this identification can supplement an *a priori* knowledge of the system to get some physical insight on the system behaviour.

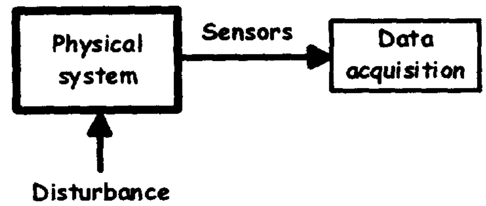


Figure 5.4. Measurement System (open-loop)

On the other hand, the identification of transfer functions requires (see Figure 5.5), in addition to sensors and data acquisition devices, the use of actuators to inject some energy into the system in order to estimate the transfer of energy from the actuators to the sensors.

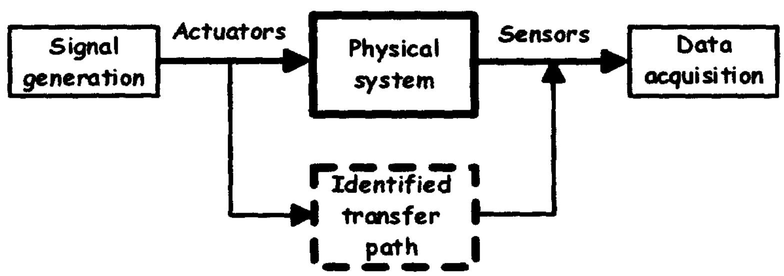


Figure 5.5. Transfer Function Identification

5.1.2.1 Data Acquisition

Today, personal computers are most often used for data acquisition (see Figure 5.6). In most cases, analog signals are measured as acquired by the sensors. The characteristics of the analog signals dictate the type of data acquisition (DAQ) equipment needed. Basic specifications, which are available on most DAQ products, give the number of channels, sampling rate, resolution and input range. The number of analog channel inputs is usually specified in terms of single-ended and differential inputs. Single-ended inputs are all referenced to a common ground point. These inputs are typically used when the input signals are high level (>1V), the leads from the signal source to the analog input hardware are short (<4 m) and all input signals can share a common ground reference. If the signals do not meet these criteria, differential inputs should be used. A differential, or non-referenced, measurement system has neither of its inputs tied to a fixed reference.

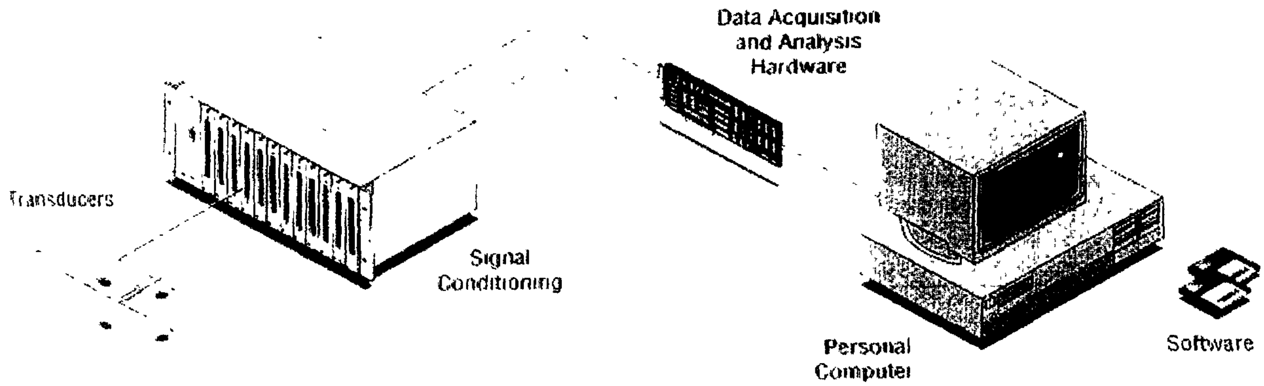


Figure 5.6. A Typical Data Acquisition System [National Instruments, 1999]

Sampling rate is another important parameter to consider when choosing a DAQ system. According to the Nyquist theorem, one must be sampled at least twice the rate of the maximum frequency component in the signal to prevent aliasing. Usually, when acquiring data from several input channels, an analog multiplexer connects each signal to the analog/digital converter (ADC) at a constant rate. This method, known as continuous scanning, is significantly less expensive than having a separate amplifier and ADC for each input channel. For those applications where the time relationship between the input channels is important, DAQ products capable of simultaneous sampling are available, using sample-and-hold circuitry for each input channel [National Instruments, 1999]. The use of an analog low-pass filter set to less than half the sampling frequency is required to avoid aliasing in the digitization process.

The number of bits that the ADC uses to represent the analog signal is the resolution. The higher the resolution, the higher the number of divisions the voltage range is broken into and therefore, the smaller the detectable voltage change. Range refers to the minimum and maximum voltage levels that the ADC can span.

Other parameters have to be considered in the choice of a DAQ system. The differential nonlinearity in the ADC, the relative accuracy of the board, the settling time of the ADC and the noise inherent to the board (electronic, mechanical) are all to be considered carefully.

A wide variety of data acquisition systems exist on the market. These systems range from simple acquisition boards to complete systems including the acquisition software. Among them, the major companies are:

- National Instruments
- Hewlett-Packard
- Bruel and Kjaer
- Stanford Research Systems
- Larson Davis, Inc.
- Spectral Dynamics, Inc.
- Data Physics Corporation
- Endevco
- Nicolet Technologies
- Daytronic Corporation
- Circuit Specialists, Inc.
- National Semiconductor
- ines GmbH
- VMIC
- ADAC Corporation
- Computer Boards

Supplier's addresses are given in the reference section.

5.1.2.2 Signal Generation

The sensors can provide a variety of electrical inputs to the controller and, in the same way, a variety of electrical outputs can be used to drive the actuators [Carstens, 1993]. Signals can be generated either by the sensors or by the controller to drive the actuators.

The most widely used type of signal is the *analog signal* which is a continuous data signal comprised of a flow of current or a voltage level whose amplitude, frequency or phase relationship with some reference signal contains data information. This information represents a proportional relationship or analog of the input measured quantity or the output signal. Among the analog signal methods of transmission, the variable current loop systems (4 to 20 mA) and the variable voltage output systems can be distinguished. The analog signals are the easiest to process but suffer from short transmission distances and electrical noise.

Another type of signal is the *digital signal* which is comprised of a series of interrupted flows or pulses of current or voltage levels. Each pulse or series of pulses contains the encoded information corresponding to the input data. A decoding process must then be used to decipher the desired information. Pulse amplitude modulation, pulse width modulation, pulse position modulation, pulse frequency modulation and pulse code modulation are the modulation or encoding schemes used for digital signals [Carstens, 1993]. The generation of digital signals by transducers is a fairly recent innovation in transducer design. Obviously, the fact that a transducer has a digital capacity makes that transducer a natural choice for interfacing with a microprocessor chip.

A third type of signal is the *carrier signal* which is an electromagnetic wave of constant amplitude that acts as an electromagnetic vehicle for transporting data. Data being transmitted by a carrier may be either analog or digital, depending on the methods used to modulate the carrier. Perhaps the technique most often used for transducer outputs is frequency modulation (FM).

The signal measured by a sensor is converted to an electrical signal by the physical principle governing the given sensor. In the same way, the electrical signal fed to an actuator is converted to a mechanical action according to the governing physical principle.

For experimental identification purposes, in order to drive the actuators, a variety of signal generation equipment is available on the market, ranging from harmonic to wideband signal generators. The main manufacturers of signal generators are:

- Hewlett-Packard
- Wavetek
- Bruel and Kjaer
- Larson Davis, Inc.
- Stanford Research Systems
- Spectral Dynamics, Inc.

Supplier's addresses are given in the reference section.

5.1.2.3 Signal Conditioning

In a broad sense, signal conditioning units, adapters or amplifiers are measuring system elements that start with an electric sensor output signal and then yield a signal suitable for display, recording or transmission. They normally consist of electronic circuits performing any of the following functions: amplification, filtering, impedance matching, modulation and demodulation. Signal conditioning can be seen as a series of functional modules [Shetty, 1997]:

- *Conversion module.* Converts one physical variable to another. It is also known as a transducing element. In certain cases, the transduction of the input signal may take place progressively in stages, such as primary, secondary and tertiary transduction;
- *Variable manipulation module.* Usually involves such elements as amplifiers, linkage mechanisms, gear boxes and magnifiers; and
- *Data transmission module.* Sends a signal from one point to another point. For example, the transmission element could be a simple device such as a shaft and bearing assembly, or it could be a complicated device such as a telemetry system for transmitting signals from the system to a remote control unit.

In the usual case, one of the stages of the measuring system is digital and the sensor output is analog. Then, an analog-to-digital converter (ADC) is used. ADC are available as integrated circuit modules and, consequently, very few additional discrete components are needed to construct the circuit needed to perform the conversion. The ADC devices have low input impedance and require that their amplitudes not exceed specified margins, usually less than ±10V. Therefore, sensor output signals, which may have an amplitude in the millivolt range must be signal conditioned before they can be applied to the ADC. A wide range of preamplifiers and amplifiers are available on the market for the sensor signals. Dedicated and flexible filters and especially anti-aliasing filters are also available from many manufacturers.

In the same way, the signal fed to the actuators must often be amplified from a signal not exceeding ±10V to voltages in the order of 100V for piezoelectric actuators. Some of the manufacturers of amplifiers for piezoelectric actuators are:

- PCB Piezotronics
- Sensor Technology Limited
- Piezomechanik GmbH
- EDO Corporation

Supplier's addresses are given in the reference section.

5.1.2.4 Sensor and Actuator Configuration

The complete analysis of the system must include the sensor and the actuator configuration (see Figure 5.7). The physical modelling of these transducers must be taken into account in the mathematical model of the whole system. The mechanical coupling between the transducers and the physical system as well as the signal conditioning required to measure or inject energy to the system must be properly modelled, either analytically or experimentally.

Figure 5.7. Complete System Including Sensors and Actuators

A transducer is a device that converts a signal from one physical form to a corresponding signal having a different physical form. Therefore, it is an energy converter. This means that the input or output signal has energy or power but, in measurement systems, one of the two components of the measured signal (eg. voltage or current), which is multiplied to yield power, is usually so small that it is negligible and thus the remaining component is measured.

The output signal from a sensor can be of any useful physical form. In practice, however, only devices offering an electric output are used in most measurement systems. Some features of electronic measurement systems include the following:

- Electrical transducers can be designed for any non-electric quantity, by selecting an appropriate material. Any variation in a non-electric parameter yields a variation in an electric parameter because of the electronic structure of matter;

- Energy is not drained from the process being measured because the transducer output signals can be amplified. With electronic amplifiers, it is easy to obtain power gains exceeding 10^{10} in a single stage;

- A large number of diverse integrated circuits are available for electric signal conditioning or modification. There are even transducers that incorporate these conditioners in a single package; and

- Many options exist for information display or transmission by electronic means.

5.2 Computer Simulation

Simulation can be defined as the discipline of designing a numerical model of an actual or theoretical physical system, running the model on a digital computer and analysing the execution output, Fishwick, 1995. The traditional approach to system design typically includes building a prototype followed by extensive testing and revision. This method can be time-consuming and expensive. As an effective and widely accepted alternative, simulation is now the preferred approach to engineering design. It allows the user to quickly build and test virtual prototypes so that it is possible to explore design concepts at any level of detail with minimal effort.

In control system design, simulation appears at two different stages of the process. First, classical computer simulation is used to test control approaches. Next, high level embedded system development tools enable the user to design a real time simulator of the physical system which will be used to simplify the laboratory testing and prototyping phases.

5.2.1 Off line Computer Simulation

Traditionally, simulation may be carried out, Pollatschek, 1996:

- By running a computer program written in some general language;
- By running a computer program written in some special language for simulation; or
- By running specially built time domain simulators with appropriate inputs.

In active noise and vibration control, the third method is not of practical interest. The first two alternatives will therefore be explored.

All general purpose languages can be potentially used to carry out simulations. However, only a few of them present the required characteristics required to facilitate computer simulation. FORTRAN, C or C++ are widely used for this purpose. As these languages are commonly used, they will not be included in this review. Simulation has always occupied an important place in computing applications. It is then normal that a lot of languages have been dedicated to simulation. Most of them are dedicated to simulation in a particular domain such as: discrete event systems, electrical circuits, power plants and aeronautic. There are no specific tools for active control exclusively, but mathematical languages (Matlab [The MathWorks, 1999], Matrix [Integrated Systems Inc, 1999) and, more recently, languages using graphical block diagrams are often used in active control simulation.

5.2.1.1 Simulation with a Mathematical Language

Although there are a lot of mathematical languages, Matlab is the most widely used. It is a high level interpreted language, allowing people not familiar with programming to easily design small programs. It combines numerical computation capabilities with advanced graphics and visualization tools. It is an ideal tool to quickly run small simulations.

The advantages of such a language are:

- Simpler for beginners than C or FORTRAN;
- Extensibility and portability: It is possible to include C or FORTRAN subroutines in Matlab programs. It is also possible to compile Matlab programs in C or FORTRAN; and
- Visualization is easy compared with classical language like C.

The drawbacks are:

- Because it is an interpreted language, programs do not run as fast as with compiled languages; and
- Because it is poorly structured, it is not adaptable to large simulations.

5.2.1.2 Simulation with Graphical Block Diagrams

With the proliferation of Windows environments on computers, classical languages are slowly being replaced by graphical languages. A lot of them enable the user to compute a simulation with graphical block diagrams: Simulink [The MathWorks, 1999], LabVIEW [National Instruments, 1999], 20-Sim [Controllab Products B.V., 1999], ACSL [MGA Software, 1999], Dymola [Dynasim, 1999], Extend [Imagine that, 1999], VisSim [Visual Solutions, 1999]. The two first, Simulink and LabVIEW are the most popular and are often used in control design.

Simulink

Simulink is a Matlab extension which enables simulations with graphical block diagrams. It is defined as an interactive tool to model, simulate and analyse dynamic systems. It is commonly used in control system design, DSP design, communication system design, and other simulations applications. *"Simulink is a powerful simulation software tool that enables you to quickly build and test virtual prototypes so that you can explore design concepts at any level of detail with minimal effort. By using Simulink to iterate and refine designs before building the first prototype, engineers can benefit from a faster, more efficient design process"* [The MathWorks, 1999].

Matlab and Simulink are powerful tools for dynamic systems identification. So, it is possible to quickly obtain a numerical model of the physical system with Matlab. Moreover, Simulink enables the user to easily and quickly transpose the control block diagram and the numerical model of the system into the simulation environment. Today, it is the most adapted tool for active control simulation.

The advantages of Simulink are:

- It is a graphical language using block diagrams (see Figure 5.8). It is therefore very easy and fast to test different control approaches; and
- Real Time Workshop is a Matlab/Simulink extension oriented towards DSP design. It enables to quickly transpose Simulink block diagrams to DSP.

The drawbacks are:

- Such an environment does not offer as much versatility as programming in the C language; and
- It does not allow testing of some real-time problems, such as particular problems related to fixed point computation.

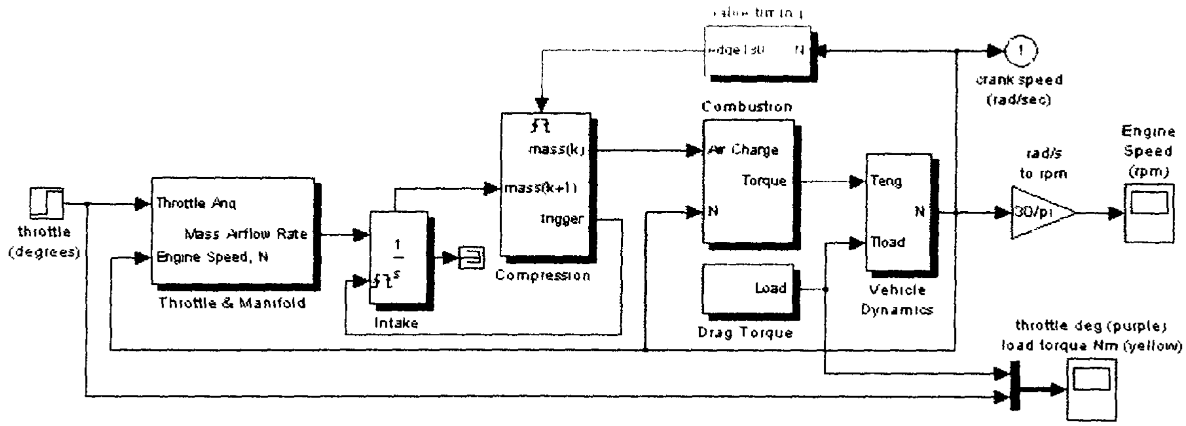


Figure 5.8. Example of Simulink graphical block diagram [The MathWorks, 1999]

LabVIEW

LabVIEW is not really a tool for simulation. LabVIEW is a graphical programming development environment oriented towards virtual instrumentation (see Figure 5.9). It is frequently used to interact with acquisition and signal processing boards. It is very powerful for building graphical user interface for DSP board applications. Many DSP systems designers are familiar with this software and prefer this tool for simulation and testing in system control design mainly because of the graphical interface tools available.

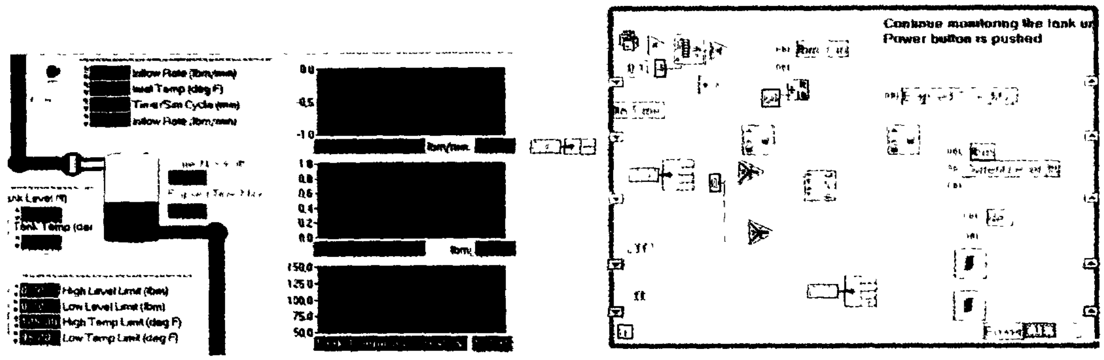


Figure 5.9. Example of Labview graphical user interface and block diagram [National Instruments, 1999]

The advantages of LabVIEW are :

- It is a graphical language therefore, programming is easy and fast.
- Like Simulink, it offers real time tools designed for embedded systems implementation.

The drawback is:

- It is not really a simulation language. It does not have all the Simulink functionalities.

5.2.2 Real-time Simulation

With the emergence of DSP boards and embedded systems, simulation tools like Simulink and LabVIEW, have been enriched by real time extensions which allow one to easily transpose simulations to embedded systems. These extensions are Real Time Workshop (RTW) for Simulink [The MathWorks, 1999] and LabVIEW RT for LabVIEW [National Instruments, 1999]. Based on RTW, some manufacturers propose products, including DSP boards, to develop embedded applications within the Matlab/Simulink environment: dSPACE [dSPACE Inc, 1999] and Opal-RT [OPAL-RT Technologies Inc, 1999] are the most popular.

Such tools may be used to design real time simulators as well as implement control algorithms in embedded systems. RTW, dSPACE and Opal-RT are quickly introduced here and will be studied more in the next part concerning implementation.

Real Time Workshop

RTW supports the execution of dynamic system models on a wide range of computer platforms, including real-time hardware, to allow rapid prototyping, hardware-in-the-loop testing, and real-time simulation of embedded systems. With RTW, it is possible to quickly convert block diagrams realised with Simulink and its different blocksets (DSP, signal processing, control, fuzzy logic) to real-time C code for PC [Intel, 1999], DSP [See DSP chips manufacturers], Dec Alpha [Digital Equipment Corporation, 1999] and PowerPC [Motorola, 1999].

dSPACE

dSPACE uses DSP, Alpha and PowerPC boards, I/O boards and the software environment to develop real-time embedded applications from Simulink block diagrams. It furnishes specific blocksets to combine different boards and easily includes each one in the Simulink diagram. It enables the user to easily control inputs, outputs and converters. It provides interfaces to easily compile and download the code into an embedded system as well as a graphical interface to run applications, exchange and visualise data and adapt parameters during the real-time execution (see Figure 5.10).

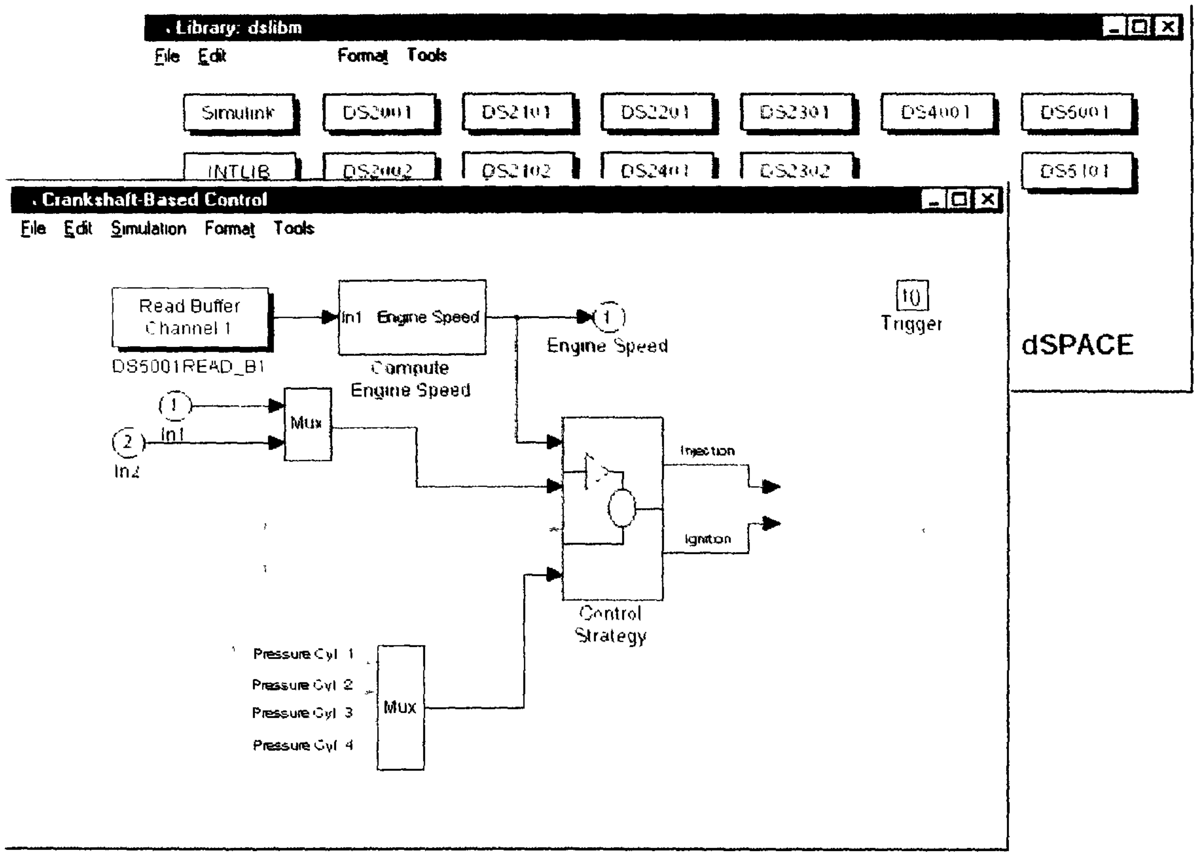


Figure 5.10. Example of Simulink diagram for dSPACE real time application [dSPACE Inc, 1999]

Opal-RT

Opal-RT offers the same environment as dSPACE. The difference between Opal-RT and dSPACE is that Opal-RT uses PCs as processing boards instead of DSPs or Alpha boards. This choice is due to the relatively low price of PCs compare to DSPs. It can represent a low-cost solution for large simulators.

5.3 Control System Implementation

The approaches and steps involved in practical implementation of the control system are outlined in this section

5.3.1 Dedicated Control Systems

There are a number of products available to implement rapid control systems within specific conditions. These products are usually efficient for given problems but do not allow great flexibility. This section presents a few of these products. The next section will present more flexible control implementation methods which can be more easily tailored to a large variety of problems.

5.3.1.1 Turnkey Systems

ANVC turnkey products appeared several years ago. The first and most popular are active headsets (NCT, Technofirst, Sennheiser, SoftdB). In vibration isolation, interesting products appeared like, for example, active engine mounts (Hutchinson-Paulstra). Active devices, reducing noise in ventilation ducts, are available. The following figure shows the example of ACTA, an active muffler for air-conditioning ducts, manufactured by Aldes and Technofirst.

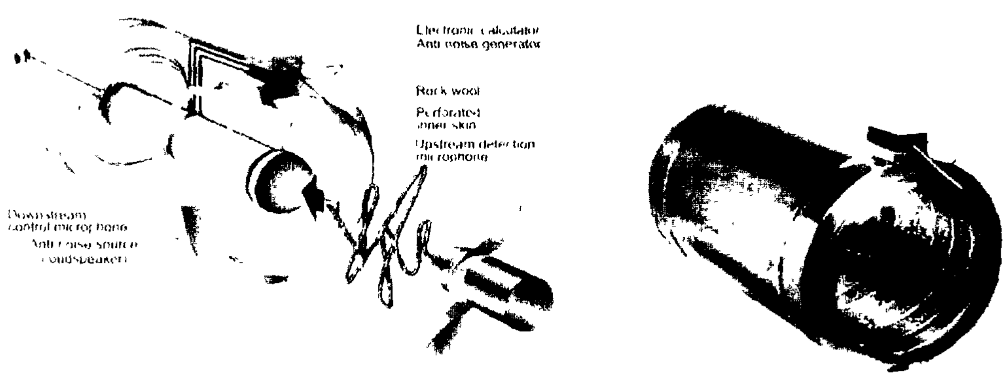


Figure 5.11. The ACTA device

ACTA is a device which can be inserted in a ventilation network by anyone, without engineering requirement. The system includes a section of duct, sensors, actuators and controllers (see Figure 5.11). The device just needs to be plugged in to a 120 V supply to work. Such a system is the most simple to implement, but it is actually limited to a few specific applications.

5.3.1.2 Functional Systems

There are, across the world, several companies which specialize in ANVC (SoftdB, Causal Systems, Technofirst, Digisonix, NCT). Most of these companies have developed their own controllers. Applications of active reduction of noise emitted by exhaust or intake, of industrial processes have been successfully implemented for several years. We present two examples of such applications here.

Multi-channel active control of noise in an industrial stack (Lauralco-Alumax / SoftdB)

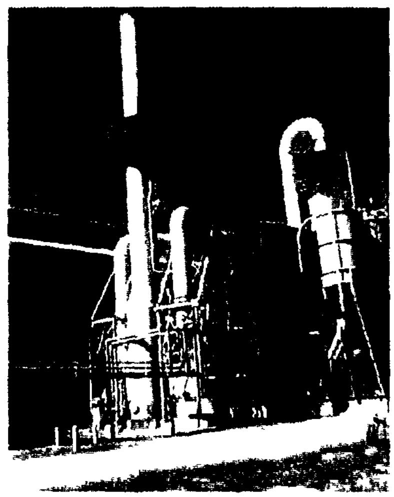


Figure 5.12. Industrial Stack

A strategy was developed to actively suppress the noise emitted by the impellers at the base of an industrial stack. The noise consists of a single harmonic at 320 Hz. A multi variable controller was necessary because of the multi-modal propagation at this frequency (12 input/output channels). This controller combined real and non-real time processing to allow multi-channel control on a single DSP. Specific and fully automatic control software was designed to load the control software on a DSP board, verify and calibrate the various sensors, perform the identification, perform the control, check the efficiency of the control system and send an alarm in case of failure. A special protective design was used to protect the loudspeakers and the microphones from hot corrosives gases.

Active noise control on the rotary positive displacement blower

Active noise control (ANC) systems have been successfully used on the positive displacement (PD) blowers by several different manufactures. The following figures present some typical results obtained using ANC. The PD blowers in this study were Roots-Whispair 1024 and URAI-47; MD-Pneumatics 9020-17T2; Duroflow 7012 V-B and 4512; and Aerzen 287-314 units. Work was conducted with several Fortune 500 companies within the United States. All had a desire to reduce harmful noise in operating areas or to reduce unwanted boundary noise migration (see Figure 5.13).

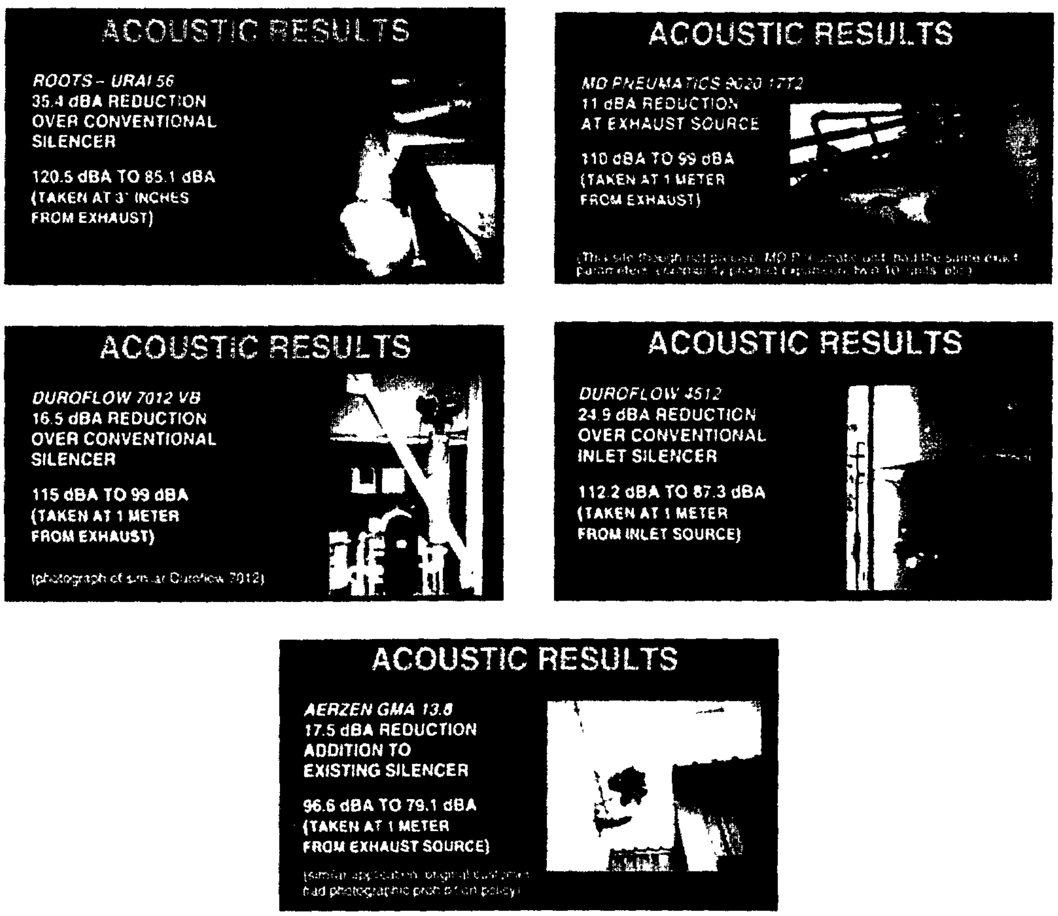


Figure 5.13. Active Noise Control Systems for Positive Displacement Blowers

Such applications proved that ANVC is being used more and more as a viable solution, even within difficult conditions as found in exhausts of industrial processes.

5.3.1.3 Modular Systems

Several ANVC companies also sell modular ANVC devices which can be used to implement active control with various applications. Two of them, the Causal Systems EZ-ANC and the Technofirst NOVACS, are presented here.

EZ-ANC

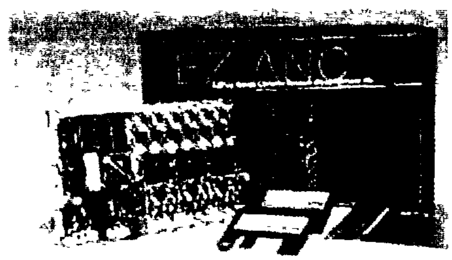


Figure 5.14. EZ-ANC Active Noise Control Package

The EZ-ANC system is a software kit, especially developed for the Analog Devices EZ-KIT (a DSP kit presented in another section) which permits easy implementation of LMS type algorithms for active control (see Figure 5.14).

In a complete design process of an ANVC system, such a device leads to reduction in development time of the choice of controller hardware and algorithm programming. It simplifies electrical engineering problems, but requires some minimum skills in this area. It requires engineers with experience in active control and knowledge of LMS to successfully adjust controller parameters.

NOVACS (Technofirst SA)

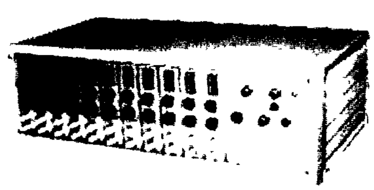


Figure 5.15. NOVACS Controller

The NOVACS is a good example of what can actually be an "universal" controller. It is presented as a box with inputs, outputs and control buttons. It is based on a Texas Instrument DSP with a LMS algorithm (see Figure 5.15). The user simply has to adjust gains, filter lengths and the convergence coefficient of the algorithm. It does not require electrical engineering knowledge, but as for the EZ-ANC system, knowledge of active control and the LMS algorithm is very useful to correctly adjust all the parameters.

These systems are interesting because, in all the cases, they save time, especially concerning electrical engineering. However, such systems are not very flexible and their application is often limited to simple applications, like control of plane waves propagating in ducts, and cannot be efficiently adapted to complex problems. In addition, even if algorithm programming is not needed, knowledge of active control algorithms, especially LMS is required.

5.3.2 Customised Control Implementation

The last section presented few systems designed to work on specific, linear problems. To get the flexibility needed on more complex and general problems, where the control configuration involves the coupling between different sources, complex sensor and actuator configurations or when non-linearities are to be dealt with, customised control implementation is the only alternative.

The control implementation is then divided in two distinct steps. The main objective of the first step is to test the algorithm in real-time conditions on the real physical system. This stage allows for definition of specifications which will dictate the choice of the hardware for the final implementation (second step).

5.3.2.1 Laboratory Testing

The laboratory testing step is complementary to the simulation step. Its aim is to perform all the tests that were not possible with simulation before prototyping. It is the last step where it is possible to come back to the algorithm development step.

It is often the only way to test many important points. It is useful for:

- Testing the control algorithm with a realistic system;
- Testing the effect of A/D and D/A converters and anti-aliasing filters on the control algorithm; and
- Evaluating the need for computer power and memory.

All these points are necessary before designing the embedded system.

5.3.2.2 Choosing Hardware

The choice of hardware for laboratory testing is not really important, because this choice is not definitive. The important point is to choose some hardware with which you are the most familiar. It is also important that the available memory and computational power are largely sufficient, because the needs are not yet precisely known. The language chosen for simulation may influence the choice of hardware. If it is possible to use the same language that was used for the simulation, this may represent an important gain in time since there is no need to validate algorithms again.

The choice of hardware is therefore related to the language used to design both the simulator and controller. The choices are about the same as presented in the preceding section : The choice is often between C [Kernighan, 1988] or Simulink [The Mathworks, 1999].

If the algorithm is developed with C, almost all DSP manufacturers provide a C compiler and debugger. Therefore, any DSP boards can be used [See DSP boards]. However, the most difficult task in DSP programming is rarely the control algorithm itself, but managing memory, interrupts, converters, and data exchange. This is why DSP manufacturers offer evaluation boards. Such kits integrate DSP, converters, filters, data communication interface on the same board and programming software including compiler, linker, debugger and libraries useful to drive each function of the board (converters, filters, data exchange).

The most popular integrated boards are:

- TI DSP Starter Kits (DSK) for processors C2x, C3x and C5x [Texas Instruments, 1999];
- TI Evaluation Modules (EVM) for C1x to C6x [Texas Instruments, 1999];
- EZ-KIT and EZ-KIT LITE for ADSP-2100 family [Analog Devices, 1999]; and
- DSP56xxxEVM [Motorola, 1999].

If the algorithm is developed within the Simulink environment, dSPACE [dSPACE Inc, 1999] products are certainly the most appropriate.

Examples of dSPACE boards integrating both processor and converters:

- DS1102: 4 analog inputs/4 analog outputs board with one TMS320C31 at 60 Mflops; and
- DS1103: 20 analog inputs/8 analog outputs, 32 digital I/O with one PowerPC at 333 MHz.

Since the RTW environment, on which dSPACE systems are based, enables the user to easily integrate several boards in the Simulink block diagrams (see Figure 5.16), it is possible to use more powerful systems composed of several I/O and processor boards. dSPACE offers I/O boards with up to 32 analog input or output channels and up to 96 digital I/O channels. These boards can be combined with processor boards like:

- DS1003 board, with one TMS320C40 at 60 Mflops; and
- DS1004 board, with one DEC Alpha at 500 MHz, featuring 1000 Mflops.

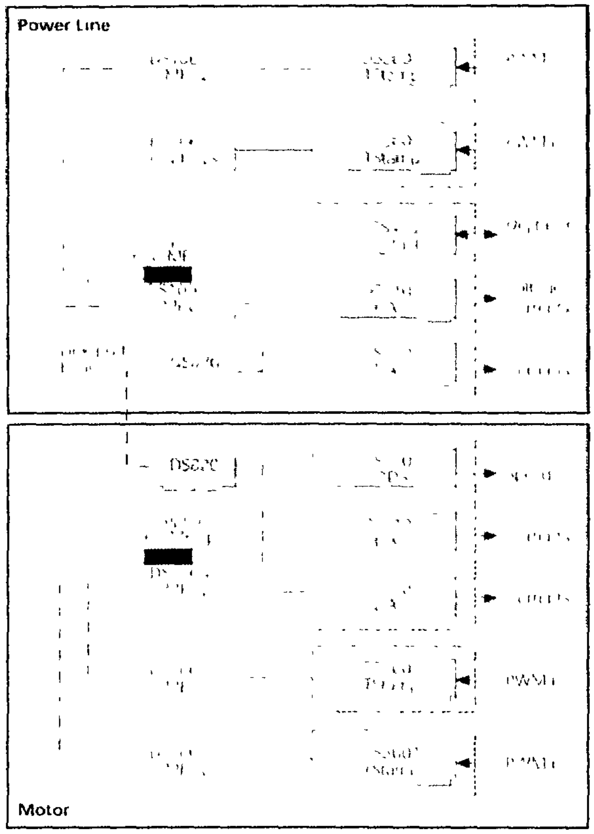


Figure 5.16. Combination of dSPACE Processor and I/O boards, for Hardware-in-a-Loop Simulation of an Electrical Locomotive [Keller, 1997]

5.3.2.3 Testing Within a C Environment

C manufacturers provide many tools, manuals, technical notes, tutorials and papers to help one implement algorithms with DSPs. Texas Instruments, in particular, offers several programming environments. The first, SPOX [Spectron Microsystems, 1999], is the combination of four principal components: - Spox kernel, which provides real-time multitasking, memory management, interrupt handling, inter-process communications, and I/O facilities, - Spox link, a host communication component which provides a seamless link between the host and target platform, Spox Math, a library of math and signal processing functions, - and Spox dbug, a debugger interface. Another proposed environment is Code Composer [Texas Instruments, 1999]. It is a fully Integrated Development Environment (IDE) offering advanced features specifically tuned for DSP code designers. It presents interfaces similar to Visual C++. It enables the user to edit, build, debug, profile and manage projects within a single unified application.

5.3.2.4 Testing Within Matlab/Simulink Environment

MathWorks developed many tools around Matlab and Simulink to improve real-time embedded applications design.

First, Matlab toolboxes provide functions for signal processing, system identification, wavelet analysis and system analysis which are very useful, in particular at the beginning of the design process. Other toolboxes, such as Control system, Robust control and Non-linear control design are particularly oriented at control design and are the most useful to simulate and test a large number of controls. Recently, toolboxes such as Fuzzy logic or Neural network have been proposed to quickly test new methods of control.

Next, Real Time Workshop is the tool which makes Simulink very attractive to program DSPs. It provides automatic C code generation directly from Simulink models. It considerably reduces the time for the entire design process, (Algorithm development/Design and simulation/Implementation/Test and verification) and enables the designer to easily come back to the previous step (see Figure 5.17).

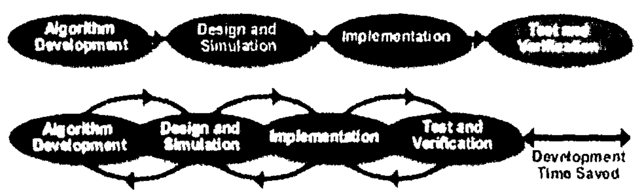


Figure 5.17. Time Saved Using Real Time Workshop for Real Time Systems Design [The Mathworks, 1999]

DSP blockset provides numerous Simulink blocks especially designed for DSP implementation. It includes matrix and vector calculus, linear algebra, statistics, signal operations, frequency transforms, buffers, switches, estimations, filter design and particularly adaptive filters. Using RTW to generate C code, it takes only a few minutes to implement a LMS adaptive filter (see Figure 5.18).

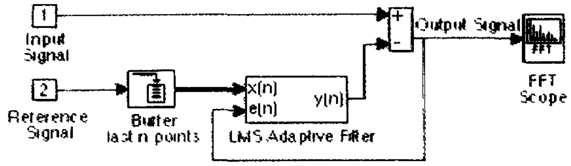


Figure 5.18. Simulink Block Diagram of a LMS Adaptive Filter Using DSP Blockset [The Mathworks, 1999]

Fixed-point blockset provides blocks to perform operations with fixed-point numbers. It is very useful if the final embedded system must use a fixed-point DSP, like the very popular TMS320C25 or C50. The Fixed-Point blockset bridges the gap between designing and simulating dynamic control systems or digital filters and implementing them on fixed-point digital hardware. Most of the features of the Fixed Point blockset are also useful in developing designs for implementation on custom hardware, such as ASICS or FPGAs.

In addition to these tools, dSPACE provides many extensions to the Matlab/Simulink environment:

- Real Time Interface (RTI): It provides Simulink blocks for each of the dSPACE boards, allowing the designer to easily manage inputs, outputs, converters, data exchange and synchronisation. For multi-processor applications, it enables dispatch of tasks between processors, defining one Simulink sub-system for each processor.

- Cockpit and Trace are Matlab Graphical User Interfaces (GUI). Cockpit is a virtual instrument panel which enables the designer to change parameters and monitor signals. Trace displays time histories of any variable being used in the application. They are both useful for experimentation and testing.

5.3.3 Embedded System Design

In the previous step, a controller was designed and tested. A system which is able to achieve active noise or vibration control with the desired performance level is now available. The next step therefore aims at optimising the control hardware and software for the specific application. Optimisation concerns mainly:

- Costs (especially if the controller will be reproduced in many copies); and
- Robustness (the controller must be adapted to the environment where it will be used).

The choice of hardware is made knowing the needs concerning:

- Type and quantity of data;
- Quantity of data to transfer (between I/O boards and DSP board, between PC and DSP board, between two DSP,) during one cycle of the algorithm;
- Computations to perform during one cycle of the algorithm;
- Quality of signal conditioning (filters specifications, delays, S/N ratio);
- Sampling frequency; and
- Working rate of the algorithm.

5.3.3.1 Memory

Depending of the type and the quantity of data to store, the choice of memory hardware can be made among:

- Read Only Memory (ROM): memory content is set during the chip manufacture;

- Programmable Read Only Memory (PROM): Memory can be programmed only one time. Useful to definitively set the control algorithm in an embedded application;

- Erasable Programmable Read Only Memory, by UV (UVPROM) or Electrically (EEPROM): Compared with PROM, it allows correction to be made to the algorithm; and

- Random Access Memory (RAM): to store data which evolve during time. There are different sort of memories using different technologies (On chip memory, fast and expensive, static memory, which is cheaper or dynamic memory, which is the cheapest and is very compact but must be constantly refreshed). The choice of memory is essentially a compromise between price and access speed.

5.3.3.2 Processors

Two factors determine the choice of a processor: the number of computation to perform during one cycle of the algorithm and the working rate of the algorithm required. An non-exhaustive list of processors which may be used for active control are presented here [see DSP chip and processor manufacturers]:

Floating-Point DSP

- Analog Devices (ADSP-21020, ADSP-2106x)
- Lucent Technologies (DSP32C, DSP32xx)
- Motorola DSP96002
- Texas Instruments (TMS320C3x, TMS320C4x)

Fixed-Point DSPs

- Analog Devices (ADSP-21cspxx, ADSP-21xx)
- IBM MDSP2780
- Lucent Technologies (DSP16xx, DSP16xxx)
- Motorola (DSP560xx, DSP561xx, DSP563xx, DSP566xx, DSP568xx)
- NEC uPD7701x
- Texas Instruments (TMS320C1x, TMS320C2x, TMS320C2xx, TMS320C5x, TMS320C54x, TMS320C62xx, TMS320C8x)
- Zilog (893xx, Z894xx, ZR38xxx)

Other processors

- DEC Alpha
- Intel Pentium
- Motorola PowerPC

Digital Signal Processors (DSP) are especially adapted for adaptive filtering. Most of them have a parallel Arithmetic Logic Unit (ALU) which can perform several operations during one processor cycle. It is very powerful to achieve fast convolutions. Some of them are also optimised to work within parallel a architecture which enables the designer to increase performance of the system (increasing price too).

Many recent processors like DEC Alpha or Motorola PowerPC are running up to 600 MHz (in comparison with most of DSPs which are running between 30 and 60 MHz), providing an alternative to parallel DSP architecture for many applications (MIMO control, for example). Processors like Intel Pentium (or equivalent Cyrix or AMD) are not well adapted for such applications. However, their very low cost allows them to be considered as interesting alternatives in some configurations.

5.3.3.3 Inputs/Outputs (I/O)

Inputs and outputs may be either digital or analog. In ANVC applications, most of I/O needed are analog.

The main differences between analog and digital I/O boards are:

- Maximum sample rate (determined by the converter technology); and
- Resolution (having influence on signal to noise ratio).

Because their cut-off frequency is related to the sample rate, anti-aliasing filters are often coupled with converters. The choice of these filters must be made carefully. First, spectral aliasing causes signal deterioration and may cause the divergence of the algorithm. Next, filters always have delays which generally have to be minimised to increase performances and stability of the control algorithm.

5.3.3.4 Communications

Communications between the different system components are very important, especially for multiprocessor applications:

- Data buses: used for high rate transfers. For example, a PHS bus enables I/O boards to exchange data with DSP at 20 Mb/s. ISA, PCI or PXI buses are often used to ensure communication between DSP and PC;

- Parallel connection: intermediate solution between data bus and serial connection;

- Serial connection: When a high transfer rate is not required, this is the method that is most often used. The RS232 protocol is simple and universally known. It also enables one to use a distant supervisor connected to the embedded system via a modem and a telephone line; and
- Ethernet link: It offers many possibilities for distant supervision.

5.3.3.5 Integration of the Different Hardware Components

The next question in the practical system implementation is: are there any boards that fulfil all the required hardware specifications? In spite of the large number of available boards [see DSP boards], it is often difficult to find the one which correctly fits. In such cases, it may be appropriate to design a board especially for the application. This is often the only way to obtain a prototype which perfectly matches the specifications. When a large number of copies of the controller must be produced, Application Specific Integrated Circuit (ASIC) design is more and more frequently considered. A summary of hardware configurations that are commercially available is given in Table 5.1.

Table 5.1: Hardware Controller Configurations of Commercially Available Systems

PRODUCTS	TURNKEY SYSTEMS	FUNCTIONAL SYSTEMS	MODULAR SYSTEMS	PROTOTYPING AND DEVELOPMENT TOOLS
Manufacturers (trademarks)	•Aldes/Technofirst (ACTA)	•SoftdB •Digisonix •Walker Electronic Silencing	•Technofirst (NOVACS) •Causal Systems/ Analog Devices (EZ-ANC)	•dSpace •Opal RT
Typical applications	Ventilation systems.	Noise from industrial stacks.	Noise in piping systems.	Suspension in automobiles, robotics.
Advantages	Easy installation, low cost.	Integrated solutions with the controller, the sensors and the actuators.	Accessible to an acoustic engineer, based on the LMS algorithm where gains and coefficients can be adjusted.	Full flexibility for algorithm development.
Disadvantages	No possible customizing.	Low flexibility.	No flexibility in the choice of the algorithm.	Requires an expertise in active control.

5.3.3.6 Software Integration

Software optimisation of the controller may require the use of machine code. Most of the time, this code is generated from C or Matlab sources or Simulink diagrams. These languages offer libraries (or toolboxes for Matlab and blocksets for Simulink) especially designed for adaptive filtering and control. The machine code generated with a function from these libraries is already optimised. It is always possible afterwards to modify the machine code generated from C or Matlab/Simulink sources slightly. In an ASIC design approach, the algorithm must be redefined in terms of logical functions, which can be derived from the machine code.

6 RECOMMENDATIONS OF CONTROLLER TECHNOLOGIES FOR ACTIVE NOISE AND VIBRATION CONTROL OF MARINE STRUCTURES

6.1 Introduction

The design of an active control system is a complex process that involves many steps. These steps, which have been discussed in Chapter 5, include:

- Identification of the physical system (acoustic and dynamic) to be controlled and the disturbance (noise/vibration) sources. This step involves the use of numerical and experimental identification procedures;
- Numerical implementation of various control strategies. This step helps in the understanding of the influence of the controllers on the system. It is a cost-effective approach and it generally results in the selection of appropriate control strategies;
- Prototype building and experimental testing of the selected control strategies; and
- Real time implementation of the active control system and the evaluation of the full-scale system.

The choice of appropriate controller technologies and algorithms for real-time implementation must be based on a thorough understanding of a number of factors, which include:

- The characteristics or nature of the primary noise/disturbance source;
- The ability to generate an appropriate sample of the noise source (reference signal) in advance of the implementation of the active control;
- The degree of contamination of the primary noise by other disturbance sources; and
- The degree of variability of the physical system.

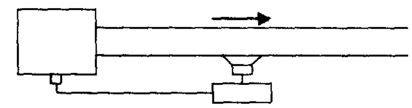
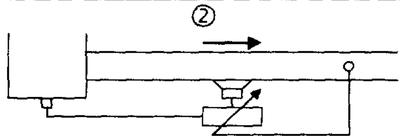
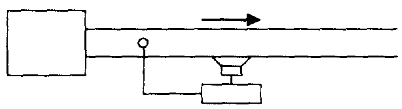
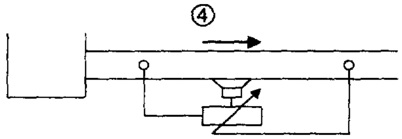
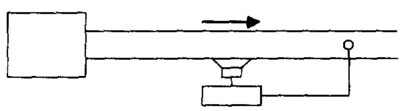
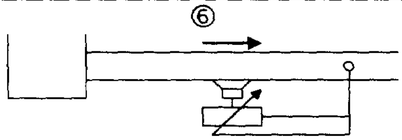
These factors, which are unique for every problem, determine the effectiveness of the active controller. For example, a controller that is designed for an application involving engine mounts, where the primary noise is purely tonal may not be as effective when the level of contamination of the primary noise is high. As a general rule, when the noise source is narrowband, tonal, periodic or stationary random and a suitable reference sample can be obtained well in advance of the region where noise attenuation is desired, and the level of contamination is low, then adaptive feedforward control methodology should be implemented. In particular, the filtered-X algorithm that was described in Chapter 3 has been found to be the most robust controller algorithm for such problems, Hansen and Snyder, 1997. When the noise source is non-stationary broadband, (time-varying) and the region of attenuation is very close to the source so that there is no time for sampling of the primary noise, feedback controller methodology is the only approach for tackling such problems.

In general, the particular engine noise problem under consideration in the present study has been characterized by most of the studies published in the open literature as tonal, periodic and narrowband, (Denenberg, 1992, Nelson and Elliot, 1992, Fuller et al., 1996, Hansen and Snyder, 1997). However, Walter, et al, 1988 and Berkman and Bender, 1997, have characterized the engine noise problem as non-stationary broadband with high tonal densities. Therefore, it is possible that the measured noise might be non-stationary and have temporal variabilities. The variabilities could be due to the time-varying nature of the system transfer function between the drive signal and the actuators. Furthermore, the foundation of the machinery (the ship hull), which is a large, complex, and lightly damped distributed mechanical structure, may have a number of resonant modes in the frequency range of interest. These issues introduce complexities into the control problem and must be addressed for every specific engine noise application. Therefore, the controller technologies that are recommended in this chapter should always be viewed with these issues in mind.

Table 6.1 summarizes different controller technologies and the characteristics of the disturbance and physical conditions in which they are effective. A detailed experimental and theoretical study of the various vibroacoustic problems as well as the general direction to be given to the project (a closed-form solution or an evolving solution to serve as a demonstration or test platform) will dictate the final choice of the system that will be used.

The following controller technologies are recommended for the various vibro-acoustic paths that need to be controlled.

Table 6.1: Summary of Effective Controller Technologies for Different Problems

CASE	PROBLEM DESCRIPTION	CONTROLLER TECHNOLOGY
① 	• Stationary Disturbance and • Stationary Physical Conditions	Fixed Feedforward with external reference
② 	• Variable Disturbance or • Variable Physical Conditions	Adaptive Feedforward with external reference
③ 	• Stationary Disturbance and • Stationary Physical Conditions	Fixed Feedforward
④ 	• Variable Disturbance Or • Variable Physical Conditions	Adaptive Feedforward
⑤ 	• Periodic Disturbance, • Stationary Disturbance and • Stationary Physical conditions	Fixed Feedback
⑥ 	• Periodic Disturbance, • Variable Disturbance and • Variable Conditions	Adaptive Feedback

6.2 Recommendations for Various Ship Noise Paths

There are four vibroacoustic paths that have to be controlled for the ship engine noise problem. These paths are shown in Figure 2.1 and are:

Path 1: Duct and Piping System (exhaust stacks, fuel intake and cooling system)
Path 2: Connections and beam type structures (drive shaft)
Path 3: Engine Isolation (mounting system, consisting of engine cradle, isolation mounts, raft and foundation)
Path 4: Airborne Radiation of Engine Noise

The recommended controller technologies for the various paths are presented in this section.

6.2.1 Path 1: Active Control of Noise in Ducts and Pipes

Cases 1, 3 and 5 of Table 6.1 are "academic cases" where stationarity of both the disturbance and the physical conditions must be satisfied. Since the realization of stationarity is not possible on a ship structure a fixed controller cannot be used.

A general rule of active control is that feedforward control should be used whenever it is possible to obtain a suitable reference signal, because the performance of a feedforward system is, in general, superior to a feedback control, Hansen and Snyder, 1997. This rule has direct relevance in the current application, since the main components of the disturbance are directly related to the engine RPM, and hence a reference signal can always be found. Therefore a feedforward control methodology should be used. An additional advantage of using an external reference signal is that it can be shared with other control branches. For example, the RPM of the engine can be a signal reference for other active noise control branches such as engine mounts. This may result in reduction in the number of required sensors. When the disturbance frequency components to be controlled are beyond the cut-on frequency of the duct/pipe a multi-input multi-output (MIMO) controller must be considered.

ASAC and ANC configurations can be used for the control of noise in ducts and pipes. ASAC will require the use of actuating pipe sections while ANC will require the use of loudspeakers.

In summary, the recommended controller technologies for ship duct noise problems in order of decreasing preference are:

Case 1: Adaptive Feedforward Control with External Reference;
Case 4: Adaptive Feedforward Control; and
Case 6: Adaptive Feedback Control.

6.2.2 Path 2: Active Control of Beam Type Structures

Stationarity of both the disturbance and the physical conditions is not to be expected in the control of the vibration of a rotating drive shaft (speed and load fluctuations), so that a fixed controller cannot be used for such an application.

As in the case of duct and pipe noise, a reference signal can always be found for shaft vibration control, since the main components of the disturbance are more or less directly related to the engine RPM. For this reason, the feedforward controller must be preferred. Vibration control requires the use of a reference signal taken outside of the controlled structure, as the structure is inherently very reverberant and would easily transmit the control signal to a reference sensor located on the structure. Case 4 in the Table 6.1 is therefore excluded. Since the structure is highly reverberant, a large number of coefficients in the filters modeling the system is to be expected.

An ASAC configuration is the only one that can be used for the control of drive shaft vibrations. Details on the sensors and actuators configuration are provided in the companion document (Koko et al., 1999).

In summary, the recommended controller technologies for ship's beam type structures in order of decreasing preference are:

Case 1: Adaptive Feedforward Control with External Reference; and
Case 6: Adaptive Feedback Control.

6.2.3 Path 3: Active Vibration Isolation

The diesel engine in this study has several mounts. Therefore, multiple output control is required. As noted in section 6.1, the engine noise problem can be characterized as either purely tonal or non-stationary broadband with high tonal densities. The first step in the choice of appropriate control methodology is the characterization of the engine noise. When the noise is characterized as tonal, narrowband with low levels of contamination, we recommend the multiple channel adaptive feedforward control technology that employs the filtered-X algorithm. A non-acoustic reference sensor should be used to synthesize the noise. This control methodology has been shown to be the most appropriate under these conditions. When the engine noise is characterized as non-stationary broadband with high tonal densities, and the frequency range of interest is affected by the resonant modes of the ship hull, we believe the multiple channel filtered-X feedforward control technology should still be used. However, it should be supplemented with a feedback control methodology. For increased efficiency, the control system must be designed to provide control forces in translational and rotational directions as engine vibrations could take place in all directions. Furthermore, the active control system should be used in conjunction with passive control system, to reduce cost and provide fail-safe design.

The recommended controller technologies for ship vibration isolation problem in order of decreasing preference are:

Case 1: Adaptive Feedforward Control with External Reference;
Case 4: Adaptive Feedforward Control; and
Case 6: Adaptive Feedback Control.

6.2.4 Path 4 : Active Control of Airborne Radiation of the Noise

The interior radiated noise can excite the ship walls in such a way that it becomes indirectly responsible for noise radiation into the sea via ship hull acoustically induced vibrations. It is our belief that this effect is most likely a second order effect in comparison with the structural paths which are the main cause of the hull vibration. However, this path could become non-negligible after the active control of the structural paths has been effectively realized. In such a situation, the control of the internal radiated noise could be minimized using active control.

An active envelope surrounding the engine could be used in combination with some absorbing materials inserted between the engine and the active envelope. This will allow for the optimization of the absorption of energy into the porous material and the minimization of the acoustic pressure on the envelope. This could be realized using MIMO ANC control. The controller technology that should be implemented in ANC will depend on the characteristics of the noise source as presented in Table 6.1.

An alternative to using ANC could be to use ASAC with sensors and actuators located on the noise sources, for example on the engine casing. This approach requires the use of actuators with sufficient authority. ASAC is particularly suited for the control of complex noise fields.

The recommended controller technologies for global control of enclosure noise in order of decreasing preference are:

Case 1: Adaptive Feedforward Control with External Reference;
Case 4: Adaptive Feedforward Control; and
Case 6: Adaptive Feedback Control.

6.3 Global Control of Externally Radiated Noise

In the previous section, controller technologies have been recommended for the control of noise through the various vibroacoustic paths. However, it is well known that controlling one path may actually increase the noise in other paths and that an efficient control of ship noise will require the control of all these paths simultaneously. This could prove to be difficult to implement in practice and therefore, there could be a need for the control of the externally radiated noise. Global control of externally radiated noise into the sea should be addressed by ASAC with distributed sensors and actuators (Smart Structures). ANC cannot be used for global control of externally radiated noise because it is not possible to have error sensors located away from the structure. For example, in order to control the noise radiated by the ship hull into the ocean, hydrophones would have to be located in the ocean water to get some form of error feedback. The controller technology that should be implemented in ASAC for global control will depend on the characteristics of the noise source.

The recommended controller technologies for global control of external radiated noise in order of decreasing preference are:

Case 1: Adaptive Feedforward Control with External Reference;
Case 4: Adaptive Feedforward Control; and
Case 6: Adaptive Feedback Control.

Table 6.2 gives a summary of the most preferred controller methodologies and technologies for the various vibroacoustic paths and the external global noise.

Table 6.2: Summary of Recommended Controller Technologies

VIBRO-ACOUSTIC PATH	CHARACTERISTIC OF ENGINE NOISE PROBLEM	RECOMMENDED CONTROLLER
Engine Mounts	Tonal, Narrowband, Periodic or Stationary Random.	AVC that uses Single Input Multiple Output Adaptive Feedforward Controller with External Reference Sensor.
	Non-stationary Broadband With High Tonal Densities	AVC control that uses Multiple Input Multiple Output Adaptive Feedforward Controller, Supplemented with Feedback Controller
Exhaust Stack and Piping System	Tonal, Narrowband, Periodic or Stationary Random	ASAC and ANC that use Multiple/Single Input Multiple Output Adaptive Feedforward Controller with External Reference Signal
	Non-stationary Broadband With High Tonal Densities	ASAC and ANC that use Adaptive Feedforward Controller, Supplemented with Feedback Controller.
Beam Type Structure	Tonal, Narrowband, Periodic or Stationary Random	ASAC that uses Multiple/Single Input Multiple Output Adaptive Feedforward Controller with External Reference Signal
	Non-stationary Broadband With High Tonal Densities	ASAC that uses Adaptive Feedforward Controller, Supplemented with Feedback Controller.
Airborne Radiation of Engine	Tonal, Narrowband, Periodic or Stationary Random	ASAC and ANC that use Multiple/Single Input Multiple Output Adaptive Feedforward Controller with External Reference Signal
	Non-stationary Broadband With High Tonal Densities	ASAC and ANC that use Adaptive Feedforward Controller, Supplemented with Feedback Controller.
External Global Radiated Noise	Tonal, Narrowband, Periodic or Stationary Random	ASAC that uses Multiple/Single Input Multiple Output Adaptive Feedforward Controller with External Reference Signal
	Non-stationary Broadband With High Tonal Densities	ASAC that uses Adaptive Feedforward Controller, Supplemented with Feedback Controller.

7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Summary and Conclusions

This study was motivated by the need to control noise in naval vessels in order to reduce their detectability and hence vulnerability to enemy attack. In this report, a detailed review of controller technologies, methodologies and algorithms that could be used for active noise, vibration and structural acoustic control in ship structures has been provided. The review focused on a wide range of controller technologies, methodologies and algorithms such as feedforward control; feedback control; adaptive control; control of tonal noise; control of broadband noise; decentralized control; neural network control; active engine mounts; active noise cancellation; active vibration control and active structural acoustic control. The steps involved in the design of an active control system have been exhaustively reviewed and documented.

The diesel engine noise problem was the focus of the study and consideration was given to the control of low frequency noise from the engine. All the noise and vibration transmission paths associated with the engine problem namely, the engine mounts, the exhaust stack and piping systems, the drive shaft, the mechanical couplings and the airborne radiated noise have been considered in the review.

Based on factors such as robustness of controller technology, the characteristic of the disturbance, the operating environment and experience in other applications, detailed recommendations on controller technologies for the various vibroacoustic paths have been provided. In general the following recommendations as summarized in Table 6.2 were made:

- Active Noise Control (ANC) that uses Adaptive Feedforward Control with External Reference for exhaust stack and piping system;
- Active Structural Acoustic Control (ASAC) that uses Adaptive Feedforward Control with External Reference for drive shafts and mechanical couplings;
- Active Noise Control that uses Adaptive Feedforward Control with External Reference for engine radiated airborne noise;
- Active Noise Control that uses Adaptive Feedforward Control with External Reference for engine mounts;

- Active Structural Acoustic Control that uses Adaptive Feedforward Control with External Reference for global control of external noise.

In order to increase robustness and for fail-safe design, it was advocated that the active strategy be combined with passive treatment whenever possible.

7.2 Recommendations For Future Work

In order to achieve the stated goal of noise control in ship structures, it is recommended that a combined experimental and numerical program be established by DREA to systematically implement the recommendations outlined in this study. Since the costs associated with this effort are expected to be high a pragmatic approach must be utilized. Such an approach should include the use of relevant on-going or prior DREA work; the use of data from friendly navies; and significant reliance on numerical modelling to reduce the costs associated with experimentation. However, it must be emphasized that experimental investigations must form part of any meaningful program.

Since the engine mount is by far the most important noise transmission path, attention must be focused on this path. A combined numerical and experimental study should be developed to implement the controller, actuator and sensor technologies (see Koko, et al., 1999) recommended. DREA has been investigating numerical modelling of elastometric mounts for vibration isolation. This study could be extended to include the effects of actuators and control in an integrated passive-active control methodology. The experimental component will address the implementation details and also serve to validate the numerical models.

The exhaust stack, fuel intake and cooling systems are also important noise transmission paths to be considered. In this regard, an investigation of the applicability of off-the-shelf pipe and duct noise control systems to the ship noise problem should be performed. Furthermore, numerical and experimental studies on the applicability of active structural acoustic control (ASAC) methods recommended for control of the drive shaft noise should be carried out, since ASAC methodologies are also suitable for global noise control.

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Phone: +46 46 182500 Fax: +46 46 182501

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T: 714-378-5805 F:714-378-5985

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T: 925-829-8700 F:925-829-9796

Pentek
http //www.pentek.com - netinfo@pentek.com
T: 201-818-5900 F:201-818-5904

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http://www perimos de - office@perimos.com
T: 011-49731968770 F:011-497319687710

Precision MicroDynamics Inc.
http://www pmdi.com - info@pmdi.com
T: 250-382-7249 F:250-382-1830

RadiSys Corp
http //www radisys com - info@radisys.com
T: 503-615-1391 8: 800-950-0044 F:503-615-1121

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http://www signal-data.suite dk - sigdat@inet.uni2.dk
T: 011-45 2162 1602 F:011-45 4542 3484

Signalogic, Inc.
http://www.signalogic.com - dspinfo@signalogic.com
T: 214-343-0069 8: 800-DSPower F:214-343-0163

Signatec, Inc.
http://www.signatec.com - sales@signatec.com
T: 909-734-3001 F:909-734-4356

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http://www.spectrumsignal.com - sales@spectrumsignal.com
T: 604-421-5422 8: 800-663-8986 F:604-421-1764

STN Atlas Electronik GmbH
http://www.atlas.de - marketing@stn-atlas.de
T: 011-494214570 F:011-494214572900

Sundance Multiprocessor Technology Ltd.
http://www.sundance.com - sales@sundance.com
T: 011-441494793167 F:011-441494793168

Transtech DSP Corp
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T: 011-441232664664 F:011-441232669664

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T: 011+441316679385 F:011+441316675176

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http://www.xemics.com - info@xemics.ch
T: 011+41327205170 F:011+41327205770

ZSP Corporation
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T: 972-578-1121 F:972-578-1086

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T: 510-657-7555 F:510-657-7576

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T: 818-597-1414 F:818-597-1427

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http://www.signalogic.com - dspinfo@signalogic.com
T: 214-343-0069 8: 800-DSPower F:214-343-0163

Spectron Microsystems (Texas Intruments Santa Barbara)
http://www.spectron.com - info@spectron.com
T: (805) 968-5100 F: (805) 968-9770

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T: 281-561-6952 F: 281-561-6037

Synopsys
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T: 650-962-5000 F:650-965-8637

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The MathWorks
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T: 978-392-0100 F:978-692-3102

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UNCLASSIFIED
SECURITY CLASSIFICATION OF FORM
(highest classification of Title, Abstract, Keywords)

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1 ORIGINATOR (the name and address of the organization preparing the document Organizations for whom the document was prepared, e g Establishment sponsoring a contractor's report, or tasking agency are entered in section 8)

Martec Ltd.
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2 SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable)

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3 TITLE (the complete document title as indicated on the title page Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title)

Active Noise and Vibration Control Literature Survey: Controller Technologies

4 AUTHORS (Last name, first name, middle initial If military, show rank, e g Doe, Maj John E)

Akpan, U.O., Brennan, D.P., Koko, Beslin, O., Masson, P., and Renault, S.

5 DATE OF PUBLICATION (month and year of publication of document)

November 1999

6a NO .OF PAGES (total containing information Include Annexes, Appendices, etc)

6b NO OF REFS (total cited in document)

7 DESCRIPTIVE NOTES (the category of the document, e g technical report, technical note or memorandum If appropriate, enter the type of report, e g interim, progress, summary, annual or final Give the inclusive dates when a specific reporting period is covered)

CONTRACTOR REPORT

8 SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development Include address)
Defence Research Establishment Atlantic
PO Box 1012
Dartmouth, NS, Canada B2Y 3Z7

9a PROJECT OR GRANT NO (if appropriate, the applicable research and development project or grant number under which the document was written Please specify whether project or grant)

Project 1ga20

9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

W7707-8-6156

10a ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity This number must be unique to this document)

10b OTHER DOCUMENT NOs. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

DREA CR 1999-177

11 DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)
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This study has been motivated by the need to control noise in naval vessels in order to reduce their detectability and hence vulnerability to enemy attack. In this report, a detailed review of controller technologies, methodologies and algorithms that could be used for active noise, vibration and structural acoustic control in ship structures has been provided. The review focused on a wide range of controller technologies, methodologies and algorithms such as feedforward control; feedback control; adaptive control; control of tonal noise; control of broadband noise; decentralized control; neural network control; active engine mounts; active noise cancellation; active vibration control and active structural acoustic control. The steps involved in the design of an active control system have been exhaustively reviewed and documented. The diesel engine noise problem was the focus of the study and consideration was given to the control of low frequency noise from the engine. All the noise and vibration transmission paths associated with the engine problems namely, the engine mount, the exhaust stacks and piping systems, the drive shaft, the mechanical couplings and the airborne radiated noise have been considered in the review. Based on factors such as robustness of controller technology, the characteristics of the disturbance, the operating environment and experience in other applications detailed recommendations on controller technologies for the various vibroacoustic paths have been provided. In particular for the engine mounting system, the active vibration control based on adaptive feedforward control technology was recommended. For the drive shafts and coupling, active structural acoustic control that uses the adaptive feedforward control technology has been recommended and an active noise cancellation technique which employs adaptive feedforward control was recommended for the exhausts stack and piping system. It was also recommended that the engine radiated noise be controlled with an active noise cancellation technique that uses the adaptive feedforward control technology. It is concluded from the review that the adaptive feedforward controller technology that uses an external reference signal is best the controller technology for all the vibroacoustic paths associated with the engine noise problem. Since it is well known that the control of one vibroacoustic path might lead to amplification of noise in other paths, it has also been suggested in this study that global control of external radiated noise based n ASAC technology be explored. For fail-safe design, it was advocated that the active strategy be combined with passive treatment whenever possible. A systematic and pragmatic program, based on combined experimental and numerical investigation, was suggested in order to implement the controller technologies recommendations made in the study.

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