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CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 513104

TITLE

Controller Technologies for Active Control of Low Frequency Noise and Vibration in Ship Structures

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to:

2nd CanSmart Workshop 1999

SMART MATERIALS AND STRUCTURES

Canadian Space Agency, St-Hubert, Quebec, Canada

CONTROLLER TECHNOLOGIES FOR ACTIVE CONTROL OF LOW FREQUENCY NOISE AND VIBRATION IN SHIP STRUCTURES

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ABSTRACT

This study has been motivated by the need to control low frequency engine noise in ship structures. A wide range of controller technologies, methodologies and algorithms (including feedforward control, feedback control, adaptive control, control of tonal noise, control of broadband noise, decentralised control, neural network control, active noise cancellation, active vibration control and active structural acoustic control) have been reviewed. Furthermore, the steps involved in the design of an active control system have also been reviewed. The most likely significant noise and vibration transmission paths associated with engine problems namely, the engine mount, the piping and cooling systems, the drive shaft, the mechanical couplings and the airborne radiated noise have been considered in the survey. Based on factors such as robustness of controller technology, the characteristic of the disturbance, the operating environment and experience in other applications, recommendations on controller technologies for the various vibroacoustic paths have been provided. It is concluded from the study that the adaptive feedforward controller technology that uses 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.

FUNDAMENTALS CONCEPTS ON SHIP NOISE CONTROL

There are many sources of noise produced by a ship. These include the propulsion systems, exhaust stacks, and various types of on board equipment. For typical operational environments however, the engine systems are generally the predominant source of noise on board. A typical ship engine along with its mounting system is schematically depicted in Fig. 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, fuel intake, and 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 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 ship, which may induce an acoustic load on the ship hull. This resulting excitation is radiated to the surrounding water as acoustic noise.

The objective of ship noise control is the minimisation of the acoustic radiation from the ducting system and the ship hull to the surrounding medium. 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 here.

In passive noise control, 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 effective at medium and high frequencies [Harris, 1991; Beranek and Ver, 1992].

Attempts to overcome the limitation of passive control at low frequencies led to the development of active noise control. This type of 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 following physical characteristics of the overall acoustical system: 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. 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 matches that of the unwanted noise, but whose phase is shifted by 180° [Leitch, 1987]. The source of the unwanted noise is referred to as primary source. The source of the cancelling noise is referred to as the secondary source and is usually driven by a controller.

The objective of the study is to review and recommend active controller technologies for practical applications in the marine environment. Particular emphasis is placed on active control methodologies that have been found to be effective in the control of noise and vibration produced by marine diesel engines.

REVIEW OF ACTIVE CONTROL STRATEGIES

Controller Technologies

Active noise control methodologies can be classified into two main categories [Hansen and Snyder, 1997]:

- Feedforward control;
- Feedback control.

The controllers that have been used in active noise control methodologies have evolved over the years from analogue to digital designs. This evolution has allowed for the use of adaptive control strategies, which are briefly presented in the following. In adaptive filters, the error signal is used to allow the controller to adapt to changes in the physical system being controlled. Such changes can arise from temperature, flow velocity and other system parameters that make the system transfer functions time-varying.

The basic features of a feedforward control system are shown in Fig.2. The undesired noise, which is measured by the input sensor labelled as *x* in the figure, is referred to as the reference signal. The reference signal is passed through the adaptive filter (controller), *M*, to generate the output, *y*. The output is used to drive the actuator to cancel the unwanted noise. The objective of feedforward control is the minimisation of the residual noise signal measured by an error sensor, *e*. The performance of a feedforward controller is quantified by the magnitude of the residual noise. The smaller the residual noise, the better the performance. In general, the performance of a feedforward controller depends on the coherence between the reference signal, *x*, and the output from the plant *d*. Higher coherence between the two signals results in better performance. The reference signal can be obtained with an acoustic or a non-acoustic sensor. When the noise source is tonal (as in the marine engine noise problem under consideration) then a non-acoustic sensor should be used. The use of a non-acoustic sensor for the reference signal has several advantages: the elimination of acoustic feedback, stability robustness, removal of causality requirements and the elimination of ageing and nonlinearity problems associated with acoustic sensors. Hansen and Snyder, 1997, have noted that the best methodology for controlling engine related tonal noise problems is a feedforward approach that employs non-acoustic sensors to synthesise the reference noise either by waveform or sinewave technique.

The basic features of a feedback control system are shown in Fig. 3. The signal, *e*, is the residual noise obtained from the error sensor. It is due to a combination of the primary disturbance from the acoustic source and the secondary disturbance controlled by the feedback loop. This error signal is passed through the controller, *M*. 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 called the plant. The Table 1 presents a comparison between feedforward and feedback control.

Multichannel Control

For very large systems, with numerous secondary actuators and numerous error sensors, the fully coupled controller may require considerable processing power and memory allocation [Snyder and Hansen, 1992]. 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. In fact, with N secondary actuators and N error sensors, the processing power and the memory allocation are proportional to N^2. 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 [Date and Chow, 1994]. This is called the decentralised control approach. For such decentralised control systems, stability and performance issues are of particular concern [Gong, 1997].

Control Strategies

Three distinct strategies can be used to control the vibration and the noise radiated by a structure. The *Active Noise Control* (ANC) strategy employs sensors and actuators located in the acoustic field [Elliott and Nelson, 1993]. The second strategy is called *Active Vibration Control* (AVC) and is used to minimize the vibration of a structure [Fuller, Elliot and Nelson, 1997]. The third strategy, *Active Structural Acoustic Control* (ASAC) [Baumann, Fu-Sheng and Robertshaw, 1992; Jacques, Spangler, Russo, and Palombo, 1997], uses sensors and actuators located on the structure with the objective to minimize the noise radiation from the structure. ASAC essentially transforms the control of radiated sound to the control of structural modes that have high radiation efficiencies. 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 and von Flotow, 1995] and the possibility of building very compact and lightweight active control systems.

CONTROL DESIGN AND IMPLEMENTATION TECHNIQUES

Main Steps

In general, the design and implementation of a control system, is a process involving three steps:

- 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 studied in order to obtain a complete model of the closed-loop system. In addition, an appropriate control algorithm must also be developed.
- Using the complete model developed in the first step, 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 any of the above steps if any problems are encountered. These steps are briefly adressed in this section.

System Analysis

System analysis can provide an in-depth knowledge of the complex dynamics of a system. System identification and physical system modeling are used to generate a mathematical representation of the complete system behavior based on both acquired data and known physical principles. The physical system to be controlled, as well as the sensor and actuators, must be modelled in order to advance to the simulation stage of the control implementation.

Simulation

Simulation can be defined as the discipline of designing a model of an actual or theoretical physical system, running the model on a computer and analysing the output. The traditional approach to system design typically involves 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 enables analysts 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 analysts to design a real time simulator of the physical system which will be used to simplify the laboratory testing and prototyping phases. For computer simulation, classical languages are slowly being replaced by graphical languages such as: Simulink™, LabVIEW™, 20-Sim™, ACSL™, Dymola™, Extend™ and VisSim™. With the emergence of Digital Signal Processor (DSP) boards and embedded systems, simulation tools like Simulink™ and LabVIEW™ have been enriched by real time extensions which enable analysts to easily transpose simulations to embedded systems such as dSPACE™ and Opal-RT™.

Implementation

There are a number of products available which allow for the rapid implementation of control systems within specific conditions. These products are usually efficient for specific problems but do not allow for great flexibility. In this respect, ANC and AVC turnkey products appeared several years ago. The first and most popular are active headsets (NCT, Technofirst, Sennheiser, SoftdB). In vibration isolation, products such as active engine mounts (Hutchinson-Paulstra) are now available. Active devices such as ACTA (Aldes-Technofirst) are available for reducing noise in ventilation ducts. Commercial controllers are also available from a number of companies (EZ-ANC™ (Causal Systems), NOVACS™ (Technofirst), Digisonix, NCT, SoftdB).

When considering applications involving more complex and general problems, where the control configuration involves the coupling between different sources, complex sensor and actuator configuration or when non-linearities are to be dealt with, customised control implementation is the only alternative. For this case, the control implementation must be 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. Evaluation boards and prototyping environments such as dSPACE™ and OPAL-RT™ are useful in this regard. The first step allows for the definition of specifications that dictate the choice of the hardware for final implementation in the second step. The second step aims at optimising the control hardware and software for the specific application. The following criteria should be considered when attempting to select appropriate hardware:

- The type and quantity of data to store;
- The quantity of data to transfer (between I/O boards and DSP board, between PC and DSP board, between two DSP's,...) during one cycle of the algorithm;
- The computation performed during one cycle of the algorithm;
- The quality of signal conditioning (filters specifications, delays, S/N ratio);
- The sampling frequency;
- The working rate of the algorithm.

APPLICATION TO NOISE AND VIBRATION CONTROL IN SHIP STRUCTURES

There are four vibroacoustic paths that must be controlled for the ship engine noise problem:

- Path 1: Duct and piping system (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 from the engine

These paths are shown in Fig. 1. A general rule of active control is that feedforward control should be used whenever it is possible to obtain a suitable reference signal. This is due to the fact that the performance of a feedforward control 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 feedforward controller technology with non-acoustic sensors should be used. The controller configurations that are recommended for the various vibroacoustic paths are summarised below.

Path 1: Active control of noise in ducts and pipes

ASAC and ANC configurations that are based on adaptive feedforward controller technologies are recommended 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. Accelerometers and piezoelectric sensors and actuators can be used to create active pipe sections in an ASAC configuration, while microphones and loudspeakers can be used for an ANC configuration. Useful error signals could be distinguished from random turbulence noise originating from substantial fluid flow by time averaging.

Path 2: Active Control of Beam-type Structures

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, an adaptive feedforward controller is preferred. ASAC configuration is recommended for the control of the noise resulting from the vibration of the driving shaft. Piezoelectric sensors and electromagnetic actuators can be used.

Path 3: Active Vibration Isolation

The diesel engine considered in this study had multiple mounts. Therefore, multiple output control is required. 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 a passive control system, in order to reduce cost and provide fail-safe design. Decentralized controllers could be used here, with one controller per mount. An adaptive feedforward controller operating in the AVC configuration is recommended for this path.

Path 4: Active Control of Airborne Radiation of the Noise

Airborne noise from machinery inside the ship can excite the hull in such a way that it becomes responsible for noise radiation into the sea via ship hull acoustically induced vibrations. 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 significant after the active control of the structural paths has been effectively realized. In such a situation, the airborne noise could be reduced using active control. An active envelope surrounding the engine could be used in combination with some sound absorbing materials inserted between the engine and the active envelope. This could be achieved using ANC or ASAC with an array of microphones and loudspeakers located around the engine [L'Espérance *et al.*, 1998]. An adaptive feedforward controller with external reference signal is recommended for this path.

Global Control

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 any residual radiated noise. Global control of residual externally radiated noise into the sea should be addressed by ASAC based on an adaptive feedforward controller with distributed sensors and actuators.

CONCLUSIONS

The objective of this study was to review and recommend controller technologies for active control of marine engine noise. It was motivated by the need to control underwater noise from naval vessels. Both the range of controller technologies and methodologies that could be used for active noise and vibration control in ships, and the steps involved in designing such a system, were briefly reviewed.

Since the diesel engine noise problem was the focus of the study, consideration was given to the control of low frequency noise at multiples of the engine RPM. Given this scenerio, the most likely significant noise and vibration paths were considered and based on factors such as characteristic of the disturbance, robustness of the controller technology and experience in other applications, recommendations on controller technologies for the various vibroacoustic paths have been presented (Akpan et al., 1999).

In particular, since the primary source of noise is accessible and can be measured with non-acoustic reference sensors, adaptive feedforward controller technology should be used for all the vibroacoustic paths. It has been shown that this method has superior performance over feedback control under these conditions. The adaptive feedforward controller should be operated in ANC mode for the piping and cooling system and the engine radiated airborne noise; ASAC mode for the drive shafts and the mechanical couplings; and AVC mode for the engine mounts.

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OPAL-RT, http://www.opal-rt.ca

MATLAB Simulink, http://www.mathworks.com/dsp/index.shtml

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 1: Differences between feedforward and feedback control

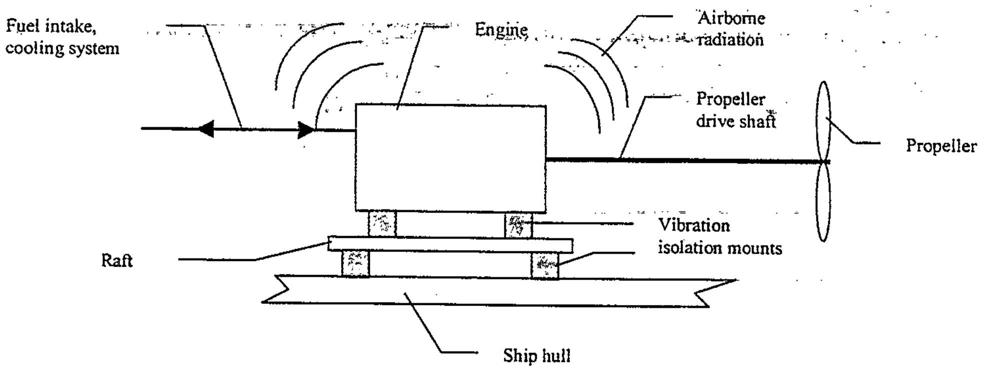

Figure 1: Schematic of a ship propulsion system

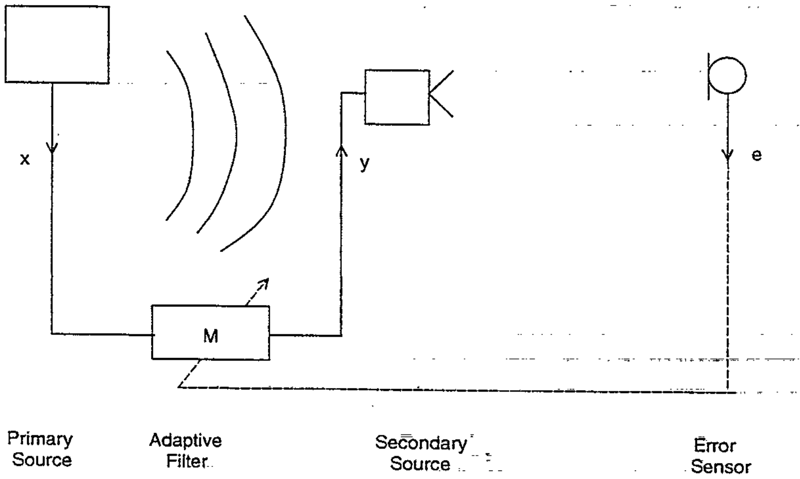

Figure 2: Active feedforward control system

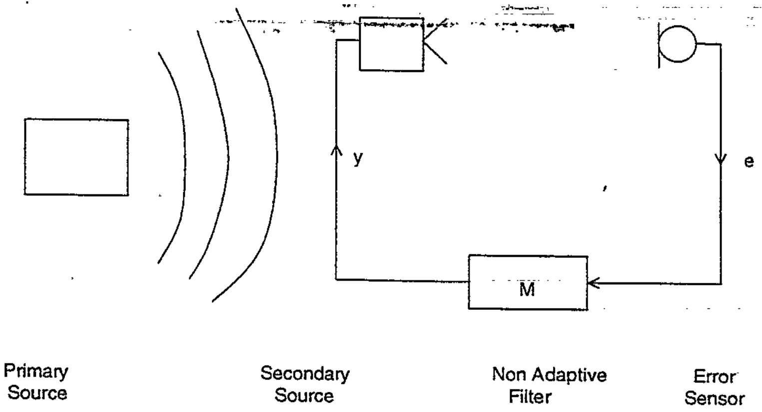

Figure 3: Active feedback control system

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