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ACTIVE CONTROL OF MACHINERY NOISE IN A MARINE ENVIRONMENT - LESSONS LEARNED[§]

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ABSTRACT

A research programme to investigate the feasibility of using active control systems to control the radiated noise of a naval platform due to the on-board machinery was first set up in the late 1970s at the Defence Evaluation and Research Agency. The programme covers the development of control algorithms, development of the hardware for the controller, a trial on a naval platform, analysis of the trial results and the development of several actuators for different transmission paths. This paper presents the experience and lessons learned from the programme. The programme demonstrated that active control of tonals associated with a machine on board a naval platform is feasible. The key to success is a clear understanding of the interactions between all the possible transmission paths from the noise source. This applies to both passive and active controls. The major obstacles to wider application of active control techniques are a lack of suitable off-the-shelf actuators and their costs.

INTRODUCTION

Quietness is one of the essential requirements for successful operations of a naval platform. Nowadays, there are a number of drivers pushing for a lower radiated noise signature. The advances in the passive sonar performance over the last decade allow acoustic noise detection at lower levels and frequency. To increase the detection range of any hostility requires on board sensors not to be blinded by the ship's own noise. There are always inevitable noise and

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vibration generated by the prime mover and auxiliary machinery on board a ship. The conventional treatment is by means of isolation using compliant elements between the machines and their supporting or neighbouring structures. The progress in the passive isolation techniques in the past decades means that they are approaching their practical limits. Particularly at low frequency where the treatments become bulky or the compliant elements can not be softened further without compromising the stability of the machines in all operating conditions. This is where active control technique becomes a practical solution to compliment passive treatments.

DERA foresaw the limitation of passive controls and initiated a research programme in active control back in the late 1970s. The research programme went through a number of phases. It included the development of control algorithms; laboratory validation; full scale trials and actuators development. Valuable experience and lessons were gained from numerous experiments carried out on a floating test platform and from a trial conducted on a small diesel engine on board a naval platform.

This paper reflects the experience and lessons learned by the author from his involvement in the active noise control research programme at the Defence and Evaluation Research Agency.

BACKGROUND

Work on the active control was started at a low level in the late 1970s at DERA. The objective is to reduce the radiated noise associated with a machine on board. The work was concentrated on the attenuation of vibration transmission across an engine mount through the use of inertia shakers attached to the mount using analogue feedback control. The work demonstrated very effective attenuation on rigs in the laboratory (up to 30-40dB) across mounts and moderate attenuation (~10dB) on in-water noise levels for a small diesel engine in a floating test platform.

In the early 1980s efforts were switched to adaptive synchronous feedforward control to concentrate on the control of the tonals generated by machines running at constant speed. Machines on board a naval vessel are generally designed to run at nominal speeds and their harmonics are the noise sources. Synchronous control is therefore adequate for the problems and furthermore it does not suffer from the control instability. The research culminated in the mid 1980s with a trial on a naval vessel. The trial gave mixed results; very good consistent attenuation (~20-30dB) across the mounts for the controlled harmonics but poor attenuation (2-4dB) of the noise levels in the water. After the trial, efforts were then concentrated on understanding the poor performance by replicating the experiment on a floating test platform. Systematic modifications to the trials fit showed the causes of the problems and the culmination of this phase of work was the demonstration of 10-20dB attenuation of the in-water noise levels of the controlled harmonics.

In the early 1990s, the synchronous controller was updated using up-to-date commercial off-the-shelf personal computer and plug-in data acquisition and digital-to-analogue conversion boards. The control algorithm was also improved. During this period, DERA identified that different types of noise path require different types of actuator for control and no suitable units are available off-the-shelf. The emphasis on the programme was focused on the development of practical actuators.

REQUIREMENTS

Successful applications of active control depends on the four important technical requirements: namely, the understanding of the transmission paths of the system; appropriate control algorithm; availability of suitable sensors and actuators.

TRANSMISSION PATHS

The operation of an active system is to minimise the noise or vibration at certain locations by injecting an appropriate controlled input to each actuator at some other locations. In the military context, an example is the control of the radiated noise into the water associated with a machine on board, such as a diesel-generator. The noise and vibration generated by the diesel engine transmits via a number of transmission paths to the hull, and at which the vibrational energy radiated into the surrounding water. The mounts, cooling water pipes, air intake and exhaust and airborne path inside the machine room may all be significant transmission paths at some or all relevant frequencies. Their contributions to the noise in the water at a point in the far field are represented as vectors in an amplitude-phase plots (Fig. 1). The relative phases between the transmission paths are the required information and therefore the phases can be measured relative to a common arbitrary reference, such as the position of the crankshaft.

The vector representation demonstrates the importance of the clear understanding of the transmission paths. The contributions from the cooling water inlet and outlet as represented in Fig 1 are of similar amplitude, but almost 180° out of phase. Assuming that the inlet path could be perfectly controlled without altering the dynamics of the whole system, the noise level at the observation point would be increased (Fig 2). In practice, if one simply attack the most obvious path, say the mounts, only a few dBs reduction will be achieved at the observation point. This is because the vector sum of all the contributions will certainly be less than the sum of the amplitudes because of the relative phases.

CONTROL ALGORITHMS

Active controls can be grouped into two categories, namely active cancellation and active isolation.

Active cancellation relies on the injection of a controlled secondary noise or vibration which interferes with the primary noise or vibration. This concept of control is not new. Leug filed a patent in 1936 for a system which cancels the noise propagation in a duct [1]. The noise inside the duct is sensed using a microphone. The signal from the microphone is fed to a loudspeaker through an electronic controller. The controller is adjusted so that the loudspeaker produces a secondary sound wave which is 180° out of phase to the primary sound wave in the duct. The superposition of the two waves results in destructive interference and a total cancellation of any propagating wave downstream of the loudspeaker is theoretically possible.

Active isolation modifies the physical characteristics of a transmission path to create a significant impedance mismatch between the primary source and the receiving structure. Active control of vibration across an engine mount is an example. The physical stiffness of the mount is limited by the requirement of supporting the static weight of the engine. This constrains the isolation performance of the mount itself. An active engine mount will have the physical stiffness to support the static weight, but will have infinite compliance at the controlled frequencies. The primary vibrational energy will be reflected back at the active mount.

Active control systems are subdivided into two classes, namely feedback and feedforward.

A generic representation of a feedback control system is shown in Fig 3. The response of a system is sensed and fed to a controller and actuator. The controller is designed such that the output from the actuator will interfere with the primary source. The nature of the feedback means that the systems operate over a wide frequency band, i.e. asynchronous control. Control stability is a major problem with feedback systems. DERA's experience suggests that stable feedback system can be designed provided that the dynamics of the controlled system are fixed and time invariant. Good attenuation was achieved in the laboratory but inconsistent performance on a floating test platform. Nevertheless, feedback systems have been successfully applied on a number of systems, such as an active ear muff. Wider applications may be possible in future with digital filtering and model referencing techniques.

Nowadays, the control systems in service are digital systems based on adaptive feedforward control (Fig 4). The most successful ones have their operations synchronised to the operating speed of the controlled machine, such as the shaft rate of a diesel engine. They rely on the repetitive nature of the disturbance and are capable of controlling only the harmonics of the machine. This type of synchronous controllers is generally adequate for a naval platform since all its machinery run at nominal speeds, such as diesel generators and cooling water pumps. DERA has developed and tested two types of synchronous controllers: frequency and time domain. Experiments and trials have demonstrated that they are capable of achieving attenuation up to 30dB. The limiting factors are the sensitivity of the sensors and the performance of the actuators. The technique of adaptive feedforward control has been extended with some success to asynchronous control. Synchronous control offers better attenuation performance as compared with asynchronous control, but it is limited to the control of tonals.

SENSORS

Every active control system requires sensors to measure the response of the controlled parameter, such as acceleration, force or pressure, to monitor its performance. Appropriate sensors are generally available, for example accelerometers, force transducers, microphones and hydrophones. However, the sensors do not need to be calibrated. Linearity is the only requirement. A slab of piezoelectric ceramic will be adequate for sensing force or pressure. Sensors are therefore not a major issue in the implementation of active control.

The choice of monitored parameter is more important. In the control of vibration transmission across an engine mount, one can choose either the acceleration or force underneath the mount. Theoretically, both will give identical performance. However, experience suggested that active control of the force underneath the mount is preferred to the acceleration. Vibration reaches the supporting structure via different transmission paths and by different sources in real systems. Minimising the force has the effect of removing the excitation on the supporting structure. Control of acceleration results in fixing the connection point between the mount and the supporting structure in space, creating a discontinuity.

ACTUATORS

Lack of suitable actuators is a major obstacle preventing wider application of active control. Nearly all the active control systems in service use actuators specifically designed for the application. DERA initiated a programme to develop generic designs of actuators for different applications: engine mounts, exhaust gas noise and cooling water pipework [2,3,4]. They were identified as possible dominant transmission paths associated with up-to-date diesel generators installation on board a naval platform.

The choice of actuation in designing an actuator depends on the application. There are a number of possible mode of actuation, such as hydraulic, electrodynamics, piezoelectric, magnetostrictive and electrostrictive. Each has its own strong points and weaknesses. The parameters that need to be considered in choosing the appropriate actuation are output force, output displacement, frequency band and size. Table 1 lists the ranking of the different modes of actuation: 1 is the lowest or smallest.

Actuation	Frequency	Force	Displacement	Size
Hydraulic	1	4	5	4
Electrodynamics	2	1	4	3
Piezoelectric	3	3	1	1
Magnetostrictive	3	2	2	2
Electrostrictive	3	2	3	2

Table 1 Ranking of different mode of actuation

Active control is not a panacea for noise and vibration control. It is best for frequency below 1kHz at which the time delay due to the processing by the electronics will be acceptable for good noise and vibration cancellation. The higher frequency will therefore be controlled by passive means. Any actuators for active control will compliment with a passive element. The arrangement of the active and passive elements can either be in parallel or in series, appropriate to a particular application and choice of actuation.

APPLICATIONS

It has been emphasised in previous sections that all dominant transmission paths must be controlled in order to achieve the overall objective of quietness at the desired locations. However, this does not necessary mean that a centralised control system is required. Distributed control systems will be adequate for those transmission paths which have weak interactions. For example, single-input-single-output systems will be appropriate for the control of the vibration across engine mounts or noise inside the exhaust. On the other hand, multi-input-multi-output systems are essential for fluid-filled pipes, since the structural-borne vibration on the pipewall is strongly coupled with the fluid-borne noise. The application of active control systems should therefore be appropriate to the complexity of a particular problem.

CONCLUSIONS

Active control systems is not designed to replace good passive treatments. They compliment each other in the control of noise and vibration.

Successful applications of active (and even passive) control of noise and vibration depends on a good understanding of the dynamics of the target machine and its environment. The interactions between all possible transmission paths

Lack of suitable actuators is a major obstacle for wider applications of active control. A few generic designs developed by DERA and by the industries will enhance the prospects for the future.

Applications of active control systems should match the complexity of the problem. A mix of distributed single-input-single-output and multi-input-multi-output, synchronous and asynchronous systems is the most cost effective usage of active system, thus reducing the cost and weight of cabling as opposed to a single centralised system.

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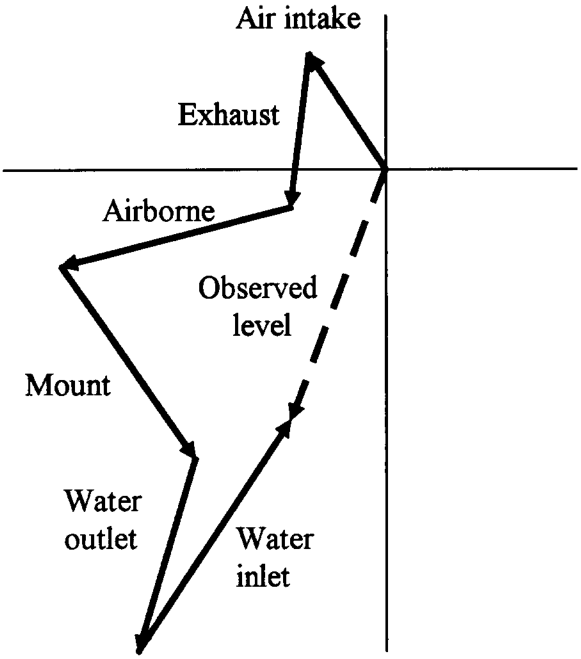

Fig 1 Hypothetical phasor plot of contributions to the radiated noise of a diesel engine

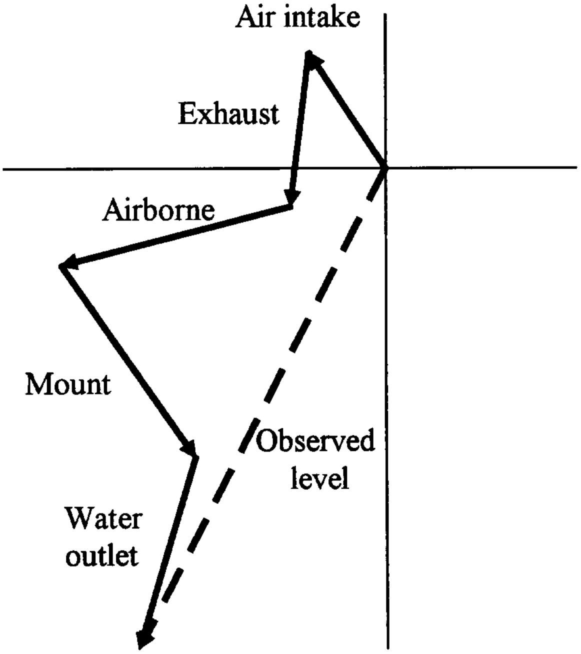

Fig 2 Effect on the observed signature of controlling water inlet noise

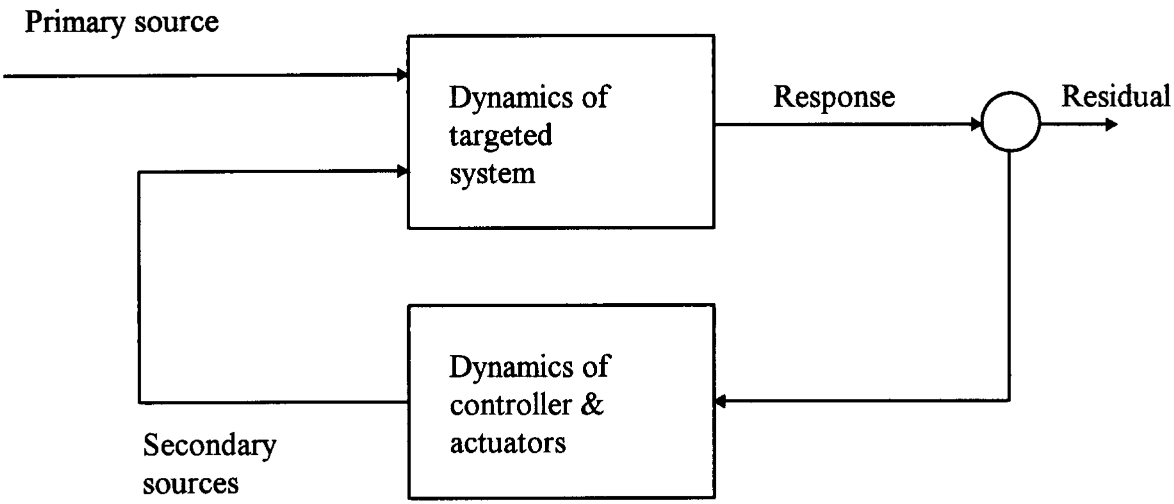

Fig 3 Block diagram of generic feedback control

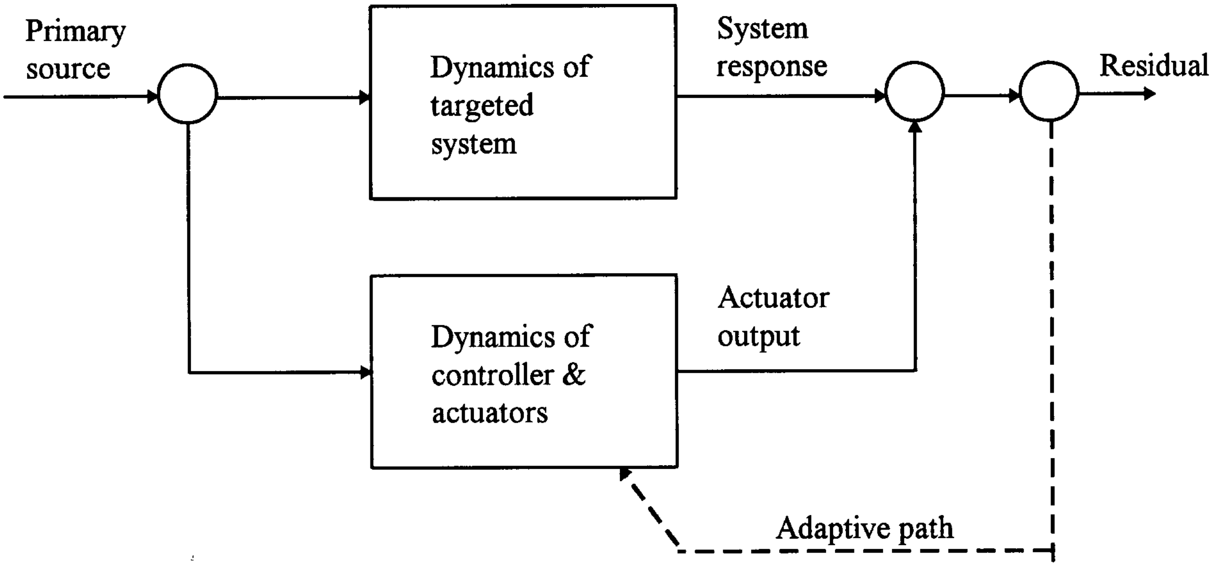

Fig 4 Block diagram of generic adaptive feedforward control