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Technical Note

Active noise control of a diesel generator in a luxury yacht

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ABSTRACT

Active noise control has been applied to a variety of systems in order to improve performance without the increases in size and weight that would otherwise be required by traditional passive noise control treatments. This paper investigates the application of an active noise control system to the control of generator noise in the master cabin of a luxury yacht. A multichannel, multi-tonal active noise control system employing loudspeakers and microphones in the master cabin of the yacht is investigated. It is shown that, due to the high number of engine orders produced by the generator, in order to achieve significantly perceptible levels of noise attenuation it is necessary to control at least 7 individual orders. A controller is investigated which targets 19 engine orders and it is shown to achieve in excess of 5 dB broadband attenuation, whilst achieving up to 23 dB attenuation in individual orders. This corresponds to a 23% reduction in the Zwicker loudness.

1. Introduction

Passive noise control treatments are an effective means of reducing the levels of noise and vibration experienced by humans in a variety of applications [1]. However, due to both weight and size restrictions their performance in practice is generally limited to the control of higher frequency noise and vibration. To overcome this limitation and achieve significant levels of low frequency noise attenuation, active control methods have been widely investigated [2–5]. Active control systems reduce the unwanted primary disturbance by the introduction of secondary sources, which produce either additional noise or vibration to control the original source.

Active control has been successfully demonstrated in a variety of engineering applications where the perception of the acoustic environment is particularly important. For example, in the aircraft environment the low frequency tonal noise induced by the propellers has been successfully controlled using a feedforward active noise control system, and a broadband attenuation in the sound pressure level of 7 dBA has been reported [6]. In the automotive environment a variety of active control systems have been proposed for both engine [7,8] and road noise control [9,10]. More broadly, active control technology has been applied to fan noise [11], active earmuffs [12], noise transmission through windows [13] and sound radiation from a helicopter transmission [14].

This paper investigates the application of active noise control to the attenuation of the noise produced by the generator in a luxury yacht, with the specific aim of creating a quiet region in the master cabin around the sleeping area. The application of active control technologies to the maritime environment has previously been investigated for vibration isolation [15,16] and the control of radiating structural resonances [15]. More specifically, active noise control around the sleeping area in the cabin of a luxury yacht has been considered by Peretti et al. [17]. In this previous work an adaptive feedback control system has been used to control the noise in the master cabin under a variety of operating conditions, including whilst stationary with the generator running and cruising at a variety of speeds. The control system used 4 error microphones, located at the headboard of the master cabin bed, and two sub-woofer loudspeakers, located under the bed. When the primary disturbance was produced by the generator alone, the sound field was dominated by a single tone at 25 Hz and the control system achieved 15 dB attenuation in this tone at a single error sensor. When the system was tested under cruising conditions, the primary disturbance generally contained a second tonal component related to the engine speed, and the adaptive feedback controller was able to achieve a similar level of narrowband attenuation in this case.

For tonal noise control problems, such as those due to engine and generator noise, a reference signal can often be obtained directly from a tachometer. Therefore, a feedforward control architecture can readily be employed. This paper investigates the use of a feedforward system to control the sound produced in the master cabin of a luxury yacht by the generator. In Section 2 the noise

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control problem is outlined. In Section 3 the feedforward active noise control system is described and in Section 4 the performance of this system is presented in terms of both the attenuation and the reduction in perceived loudness. Finally, conclusions are drawn in Section 5.

2. Diesel generator noise control problem

The acoustic environment in high quality luxury yachts has become an important consideration for yacht manufacturers and may be seen as a potentially distinguishing feature between two different high quality products. High levels of noise and vibration can result in an uncomfortable environment and, therefore, there is a desire to achieve low levels of noise and vibration throughout the living quarters of luxury yachts. At mid to high frequencies passive noise and vibration control treatments can be employed to achieve a quiet living space on-board. At low frequencies, however, the size and weight of passive treatments becomes too large and is often either impractical or significantly increases the weight of the yacht, which in turn limits its speed and efficiency. Although occupants may accept the levels of noise and vibration produced by the yacht's engines whilst underway, they may be more sensitive to the noise produced by the electrical generator whilst moored. This is due to the low levels of background noise in this scenario and this is a particular problem when the occupants are trying to sleep. Therefore, focus has been made on controlling the noise produced by the generator in the master cabin.

Fig. 1 shows the layout of the real yacht considered in this work. The yacht is a 60 ft vessel and the location of the generator in the engine room, which is adjacent to the master cabin, is shown in Fig. 1. In order to characterise the noise produced by the generator, the sound pressure level has been measured at the head of the bed in the master cabin using the microphones shown in Fig. 1 when the diesel generator is running. Fig. 2 shows the spectrum of the A-weighted sound pressure level measured at microphone number 2. The pressure has been plotted in decibels relative to an arbitrary constant due to commercial sensitivity, however, it should be highlighted that the sound pressure level is relatively low, but is disturbing when the background environmental noise level is low. From the results shown in Fig. 2 it can be seen that the noise spectrum is characterised by a large number of tonal components, which comprise a full series of both integer and non-integer harmonics of the fundamental engine order at the mains frequency of 50 Hz. This tonal disturbance has been reported to be subjectively disturbing and, therefore, in the following sections the feasibility of using active control to reduce the overall sound pressure level will be explored.

3. Feedforward active noise control system

The active control of tonal noise has been investigated for a number of different applications [6,7], as discussed in the introduction. An active tonal noise control system can be efficiently implemented using a feedforward controller and the most commonly employed algorithm is the filtered reference, or filtered-x, Least Mean Squares (LMS) algorithm [5]. The multichannel formulation of this algorithm was originally presented in the late 1980s [18] and has since been used in a variety of applications. The block diagram in Fig. 3 shows the general outline of the multichannel feedforward control system. In this block diagram $\mathbf{e}$ is the vector of error signals, which the controller attempts to minimise, $\mathbf{d}$ is the vector of disturbance signals, $\mathbf{u}$ is the vector of control signals, x is the reference signal, $\mathbf{R}$ is the matrix of filtered reference signals, $\mathbf{G}$ represents the physical responses between the control sources and the error sensors, $\widehat{\mathbf{G}}$ is a model of this plant response used in the control update algorithm, $\mathbf{W}$ represents the control filters and α is the convergence gain which determines the speed of adaptation for the controller.

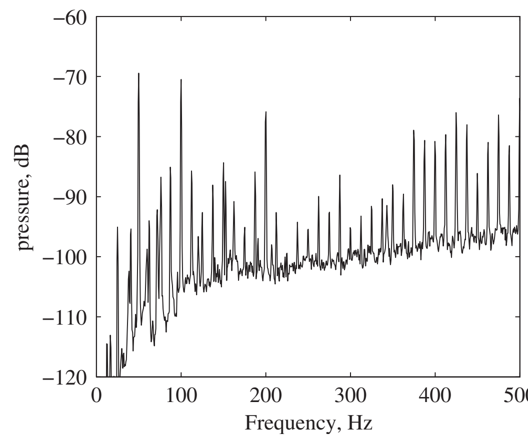

Fig. 2. The A-weighted sound pressure level measured in the master cabin at the headboard of the bed when the diesel generator is running plotted in decibels relative to an arbitrary reference.

For a multichannel control system with L error sensors, M secondary sources and control filters with I coefficients, the control filter coefficients can be adapted to minimise the sum of the squared error signals according to the leaky filtered-x LMS algorithm, which is

$$\mathbf{w}(n+1) = \beta\mathbf{w}(n) - \alpha\mathbf{R}^T(n)\mathbf{e}(n), \tag{1}$$

where $\mathbf{w}$ is the vector of MI control filter coefficients and β is the leakage coefficient. The inclusion of the leakage coefficient, β, improves the robustness of the algorithm and, therefore, is necessary in practice to ensure long term performance. A full description and analysis of this algorithm is widely available in the literature [5,19] and, therefore, will not be reproduced here. However, it is important to highlight that the single frequency, tonal controller can be efficiently implemented using two-coefficient control filters

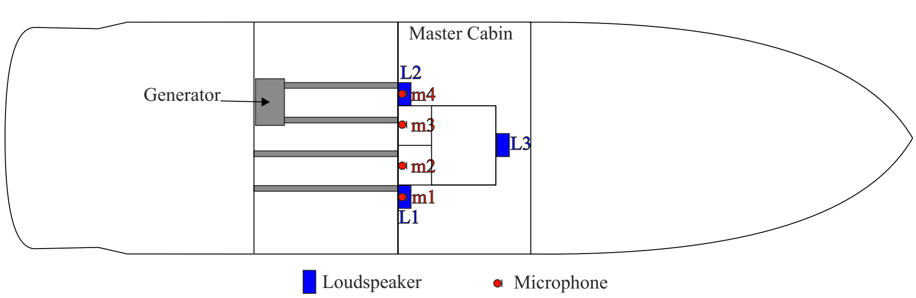

Fig. 1. The layout of the standby diesel generator and the control system components on the yacht.