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Multichannel control systems for the attenuation of interior road noise in vehicles

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ABSTRACT

This paper considers the active control of road noise in vehicles, using either multichannel feedback control, with both headrest and floor positioned microphones providing feedback error signals, or multichannel feedforward control, in which reference signals are provided by the microphones on the vehicle floor and error signals are provided by the microphones mounted on the headrests. The formulation of these control problems is shown to be similar if the constraints of robust stability, limited disturbance enhancement and open-loop stability are imposed. A novel formulation is presented for disturbance enhancement in multichannel systems, which limits the maximum enhancement of each individual error signal. The performance of these two systems is predicted using plant responses and disturbance signals measured in a small city car. The reduction in the sum of the squared pressure signals at the four error microphones for both systems is found to be up to 8 dB at low frequencies and 3 dB on average, where the sound level is particularly high from 80 to 180 Hz. The performance of both systems is found to be robust to measured variations in the plant responses. The enhancements in the disturbance at higher frequencies are smaller for the feedback controller than for the feedforward controller, although the performance of the feedback controller is more significantly reduced by the introduction of additional delay in the plant response.

1. Introduction

The application of active control methods to reduce the interior noise in road vehicles has been investigated within the automotive industry for around 20 years [1]. Feedforward control of engine noise was first demonstrated in the late 1980s [2] and has since been used in various configurations to control the increase in noise level due to lightweight vehicle design [1], to reduce the variation in the engine noise characteristic due to the use of economical engine designs such as variable displacement [3], and to improve the perceived sound quality of the engine noise [4]. A cost effective feedforward engine noise control system can be implemented using an engine speed reference sensor, low-cost microphone error sensors, the car audio loudspeakers and their amplifiers as control sources and the car audio digital signal processing (DSP) capabilities. Such active engine noise control systems have been implemented by a number of manufacturers.

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The design of lightweight vehicles also results in an increase in the low frequency broadband noise, in the car cabin, due to the interaction of the tyres and the road. Feedforward active noise control systems have previously been developed to reduce the noise levels in the car cabin using reference signals obtained by direct measurement of the vibration due to road excitation [5–7]. Although these feedforward road noise control systems could again be implemented using low-cost microphone error sensors, the car audio loudspeakers as control sources and the car audio DSP capabilities, it is also necessary to employ at least six accelerometers mounted to the vehicle's suspension and bodywork to obtain reference signals with sufficient coherence with the error signals in order to obtain reasonable levels of control [5,7]. Therefore, such control systems are relatively expensive to implement and have seen limited commercial implementation.

To reduce the cost of implementing a feedforward road noise control system, Mohammad et al. [8] have suggested that the necessary reference signals could be obtained using low-cost microphones positioned on the floor of the car cabin. This work showed that similar levels of control could be achievable using reference signals obtained from either accelerometers or microphones, although it was assumed that the acoustic feedback path between the control loudspeakers and the reference microphones is perfectly cancelled and the control filters were not causally constrained. The lack of causality constraint in this work means that the predicted levels of control do not consider the time advance provided by the microphone reference signals compared to the accelerometer reference signals. The effect of the inherent causality constraint on the achievable control must be investigated to determine the suitability of microphone reference signals for road noise cancellation. Additionally, in practice, perfect feedback path cancellation would not be possible, due to variations in the plant response, and it would be necessary to design the controller to be robustly stable to these variations.

An alternative method of reducing the cost of road noise control systems is to use a feedback control architecture. Feedback control of road noise using a single-input single-output controller has already been implemented in a mass-production estate car [9], although significant levels of attenuation are only achieved over a narrowband acoustic resonance, at about 40 Hz, in the front seats. This corresponds to a reduction in the first longitudinal enclosure mode. Other modal feedback control systems have also been proposed that may be suitable for similar road noise control problems [10–12]. To achieve control in vehicles where a single acoustic mode does not dominate the response, however, it has been shown to be necessary to employ a multi-input, multi-output (MIMO) controller [12]. A MIMO feedback controller has been investigated in [13] which uses four headrest mounted microphones as error sensors and the four car audio loudspeakers as control sources. This control system is predicted to achieve an average reduction in road noise at the headrest microphones between 80 and 185 Hz of around 3 dB, but also increases the average level of the road noise at all microphones by up to 5 dB between 185 and 240 Hz. The effect of additional delay in the plant response due to a digital implementation of this system has not been considered in this work, and it is expected that this will significantly limit the performance of this feedback control system, as discussed in [14].

This paper considers the design of a multichannel road noise control system employing loudspeakers as control sources, a number of microphones positioned near to the car cabin headrests as error sensors, as in [13], and an additional set of microphones, positioned close to the car cabin floor as reference sensors, to provide additional time advanced information to the controller. This control setup extends the field of active control of road noise in vehicles by fully investigating the limitations of control when microphones are used as the inputs to the controller without the additional feedforward reference signals usually provided by accelerometers mounted to the structure of the vehicle. It is also shown that such a control system can be formulated as either a feedforward, as in [8], or a feedback controller and this paper presents the first comparison of these two formulations in the context of a road noise control system using only microphone input signals.

Section 2 first shows that the proposed control system can be formulated using an equivalent feedback system. For a practical implementation it is necessary to enforce constraints on the robust stability, disturbance enhancement and open-loop controller stability and these design requirements are presented for this multichannel feedback system. A novel formulation of the disturbance enhancement constraint is presented, which limits the enhancement at each individual microphone, instead of the average level at all microphones. It is then shown in Section 2 that the same set of sources and microphones may alternatively be employed in a feedforward control configuration in which the microphones near to the headrests are used as error sensors and the microphones close to the floor are used as reference sensors. Due to the feedback from the control sources to the reference sensors, this feedforward configuration still requires similar constraints to the multichannel feedback controller and these design requirements are presented. Both the feedback and feedforward control strategies presented lead to quadratic cost functions with affine constraints and Section 3 describes a method by which such controllers may be optimised. In Section 4 the performance of the feedforward and feedback control systems are compared in a practical road noise control problem. Finally, Section 5 presents the conclusions of this work.

2. Multichannel active noise controllers

2.1. Feedback control employing internal model control architecture

The aim of a car cabin road noise control system is to reduce the sound pressure level at the occupants' head positions. Therefore, the proposed multichannel road noise control system uses a number of, L_e, error microphones positioned at the headrest locations, which may also be used in an active feedforward engine noise control system as described in [13]. However, to provide additional information to the feedback controller and improve the performance of the system, the proposed low-cost implementation will also use K microphones positioned on the floor of the car cabin, as previously