Active Control in Vehicles and in the Inner Ear: a Review

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The low frequency sound inside a number of aircraft and cars is now attenuated using commercial active sound–control systems. These operate either using loudspeakers to directly drive the sound field, or with shakers acting on the structure to modify its vibration and, hence, reduce excitation of the sound field.

As the structure becomes larger, the number of actuators and sensors required for effective control rises significantly. Conventional, fully coupled control systems then become costly in terms of weight and sensitivity to individual failures. An alternative strategy of distributing the control over multiple local controllers will be disucssed, which has been shown to be effective in a number of cases.

The workings of the inner ear also provide a remarkable natural example of decentralised active vibration control, who's aim is to enhance the motion within the cochlea. A simple model for this cochlear amplifier will be described, in which each of the outer hair cells act as local control loops, and its use illustrated in predicting the otoacoustic emissions generated by the ear as a result of this mechanism. These emissions are used clinically to screen the hearing of young children, so it is important to understand how they are generated within the cochlea.

1. INTRODUCTION

In this paper, active mechanisms will be considered in two very different situations. In the first, active control is used as an engineering tool to *attenuate* vibration, and hence sound, inside vehicles. In the second, feedback control within the inner ear is considered as an active mechanism for the *enhancement* of its vibration, giving rise to the cochlear amplifier. Idealised modeling of the dynamics and feedback control are used to understand the mechanisms in the two situations. Of particular interest in both cases is the use of large numbers of local feedback controllers working together to influence the global dynamics of the system. Not only is the stability of the overall system important in the two cases, but they both share a need to have an additional mechanism: tuning the gain of each of the multiple feedback loops for optimal operation under changing conditions.

In the next section, we briefly review the current state of the art of active control of sound inside aircraft and cars. The desire to control larger structures at higher frequencies is then shown to lead to a decentralized feedback control strategy by using a large number of self–contained modules, each having a sensor, actuator, local controller, and tuning mechanism. One possible tuning mechanism based on local power absorption is discussed.

The mechanism of wave propagation within the inner ear is then briefly reviewed, including the action of the local feedback loops driven by the 12,000 outer hair cells, which enhance the vibration within the cochlea by more than 40 dB. The sensitivity of this high-gain system to small perturbations is then demonstrated using a novel state-space description of the cochlear dynamics, and it is shown how this can give rise to spontaneous otoacoustic emissions. The mystery of how the gain is regulated in each of these outer hair cells to maintain the ear at its optimal operating point is then discussed.

2. ACTIVE CONTROL INSIDE VEHICLES

Active sound control works through destructive interference between the original, primary, sound field inside the vehicles and that generated by a number of controllable, secondary sources. A successful system requires that the sound field generated by the secondary sources matches the primary field both over space and over time. The spatial matching requirement can be achieved by the selection and positioning of the secondary sources, but it is subject to clear physical limits that restrict the bandwidth over which active control is useful. The temporal matching requirements must be met by an electronic control system that adjusts the signals driving the secondary sources to ensure that the two sound fields are coherent but out of phase.

Active sound control has been successfully applied in both road vehicles and aircraft. In the early versions of systems for both applications, the secondary sources were loudspeakers, directly generating the interfering sound field. Loudspeaker systems are still most common in the automotive application, but they have been slow to develop after their initial demonstration in the 1980s.[1]

Several recent trends have seen a resurgence of interest in automotive active sound control, however.[2] One of these trends is the desire to control not just the overall sound level but also the sound quality, which involves actively driving the sound field toward a command or target signal rather than just minimising it. Such systems can provide a smoothly changing sound profile with engine speed, for example, or emphasise a sporty sound during acceleration.[3] Another positive trend, which is significantly reducing the cost of automotive active control, is the integration of automotive systems, in particular, the integration of the audio system with the engine management system. This allows a fraction of the considerable signal-processing power now available in such audio systems to be used for active control.

Finally, there is an obvious trend in the automotive industry