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Active sound control in composite regions

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ABSTRACT

In active sound control, noise shielding of a target region is achieved via additional sources (called controls) situated at the perimeter of the region. The sources protect the target region by adjusting the acoustic field near the boundary of the region. In the present paper a numerical model of active sound control based on surface potentials in 3D bounded composite regions is numerically studied. In the composite region setup, it is required that the regions be shielded from noise while allowing admissible sound that is generated in the shielded regions to be preserved. The admissible sound is usually required to propagate freely inside the protected regions or in a (selective) predetermined pattern. The adjusting approach used here does not require any knowledge of the sound sources or the properties of the propagation medium in order to obtain the controls. Moreover, the approach differs sharply from some other approaches where the detailed knowledge of the sound sources and the propagation medium is required. For the first time, numerical test cases involving both free communication and predetermined communication pattern between the regions in three dimensions are considered. In all test cases, these regions are effectively shielded from the noise while any present admissible sound is preserved. In addition, selective propagation of the admissible sound between the regions is enforced. The effect of the number of controls on their operation is also studied. Whether admissible sound is present or not, the level of noise cancellation decreases linearly as fewer controls are used. In addition to the increase in size of the interference zone, the controls become individually distinguishable.

1. Introduction

Nowadays, active sound control (ASC) has become a research area which draws high interest. This is partly due to the ever more stringent noise control regulations in industry. In the ASC problem, some region is supposed to be protected from noise generated outside through sound field manipulation via additional sources known as controls. The controls, situated at the boundary of the shielded region, adjust the acoustic field at the boundary to cancel the noise. In comparison to passive noise control, this form of noise control does not use mechanical insulation to reduce the noise. The passive noise cancellation is suitable for high frequency noise while ASC is better suited to low frequency noise. In practice, the two may be combined.

This review focuses on ASC with selective sound cancellation in composite regions. A detailed review can be found in references [1,3,5,6,18]. In modern hearing aids, it is required to cancel noise leaking into the ear through the fitting in

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order to preserve gains in the output signal to noise ratio. Hence, ample means are employed to distinguish the admissible sound from the noise. ASC techniques are then employed to cancel the noise [2,16,17]. A number of patents have been filed in which sound fields entering acoustic headsets are classified as noise or admissible sound via electronic control circuits using various algorithms. The field considered to be noise is then suppressed or eliminated, while the desired admissible sound can be amplified or treated as desired [2]. In these two cases, both noise and admissible sound sources are situated outside the protected region. There are problems in which the admissible sound sources are situated inside the region to be shielded. For example, in [4], the admissible sound interferes with the operation of the ASC system. Specifically, an error microphone picks up the admissible sound in addition to the field from the noise and control sources. In the used algorithm, the admissible sound adversely affects the performance of the ASC system. In other words, it is canceled together with the noise. It is worth noting that in the mentioned techniques, the detailed knowledge of the noise and/or admissible sound sources as well as the characteristics of the propagation medium are required in order to generate the controls.

The potential-based approaches do not require the detailed knowledge of either the noise and admissible sound source characteristics or the propagation medium. As an additional advantage, they allow admissible sound to be present in the shielded regions. The mathematical framework of ASC for time-harmonic acoustic sources in single regions is considered in [6]. In the paper, the authors present the possibility of canceling the noise component of the total field in the protected region with very little information. Specifically, only the sound pressure and the normal derivative of the particle velocity at the boundary of the protected region are required. The methodology of [6] was extended for the first time to composite regions in [11] by Petersen and Tsynkov and in [13,15] by Ryaben'kii, Tsynkov and Utyuzhnikov. It was shown that the same information, i.e. the sound pressure and the normal component of the particle velocity, can be used to provide cancellation of noise and enforce a predetermined communication pattern between the regions in a composite region setup. In [13], the ASC problem is considered as an inverse source problem. It is then reduced to solving a number of auxiliary problems for simply-connected regions. The solution does not require any extra information besides those of the original methodology to provide noise cancellation while allowing admissible sound in composite regions. However, additional steps are required to enforce a predetermined communication pattern between the regions. Experimental validation of ASC in one-dimensional bounded composite regions is given in [5]. The used technique is based on surface potentials, and is applied to broadband noise.

The optimization of the general solution of the ASC problem using certain criteria is studied in [7–9]. Optimization in the sense of L_2 (i.e. least squares) is considered in [9]. Though the chosen optimization criteria lack a clear physical interpretation, it is easy to be used numerically. On the other hand, the optimization in the sense of L_1 which has clear physical interpretation (the minimization of the total acoustic source strength) is considered in [7]. Although it does have a clear physical interpretation, it is difficult to solve numerically. However, the authors demonstrate that the optimization problem can be solved without actually solving the numerical problem. In [8], the optimization of the power required to operate the controls in the ASC system is considered. The main finding is that even though it may appear to be counter-intuitive, optimization of power in an ASC which uses a combination of monopoles and dipoles as controls could lead to significant net power production.

The approach based on surface potentials has been successfully applied numerically to 3D single regions in our previous paper [10]. In the current paper, we extend the technique to 3D bounded composite regions via numerical experiments in the frequency domain. Particularly, the used approach is applied to 3D bounded composite regions with two objectives: (1) to allow the admissible sound freely propagate from one region to the other and (2) enforce a predetermined communication pattern of the admissible sound among the regions. While achieving the two objectives, the noise must be canceled in the protected regions. In contrast to other methods, our approach achieves volume noise cancellation in most parts of the regions while canceling or allowing the admissible sound as desired. In addition, we study the effect of the number of controls on the level of noise cancellation achieved. In doing this, test cases with and without admissible sound are considered.

In the next section, the formulation of the ASC problem for 3D composite regions is given. In Section 3 the numerical implementation of the algorithm in the frequency domain, along with all the peculiarities and additional steps, is described in detail. The numerical results are discussed in Section 4.

2. Formulation of the active sound control problem

The region sketch is given in Fig. 1. D_0 is the entire computational region such that $D_0 \subset \mathbb{R}^3$, the regions ${D_1}^+ \subset D_0$, ${D_2}^+ \subset D_0$, ${D_1}^+ \cap {D_2}^+ = \{\emptyset\}$ are the regions to be shielded and $D^- := D_0 \backslash (\overline{D_1}^+ \cup \overline{D_2}^+)$. The boundaries of ${D_1}^+$ and ${D_2}^+$ are the surfaces Γ_1 and Γ_2, respectively. It is assumed that the boundaries of ${D_1}^+, {D_2}^+$ and D_0 are smooth enough. The reference points A, B, E, F and intervals CE and FG are described later.

The boundary value problem (BVP) is formulated as follows:

$$LU = S, \tag{1}$$

$$U \in U_{D_0}, \tag{2}$$

where L is the Helmholtz equation operator, U_{D_0} is a linear space of functions such that inclusion (2) guarantees the well-posedness of the BVP according to Hadamard. The acoustic sources consist of both adverse noise sources S^- and admissible sound sources ${S_n}^+$ which are situated in D^- and ${D_0}^+ := {D_1}^+ \cup {D_2}^+$, respectively.