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On the synthesis of acoustic sources with controllable near fields

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HIGHLIGHTS

- We present an optimization strategy for the synthesis of controllable fields.
- 3D control can be done exterior to the convex hull of the secondary sources.
- It's possible to have an incoming near field pattern with far field constraints.

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ABSTRACT

In this paper we present a strategy for the synthesis of acoustic sources with controllable near fields in free space and constant depth homogeneous ocean environments. We first present the theoretical results at the basis of our discussion and then, to illustrate our findings we focus on the following three particular examples:

1. acoustic source approximating a prescribed field pattern in a given bounded sub-region of its near field.
2. acoustic source approximating different prescribed field patterns in given disjoint bounded near field sub-regions.
3. acoustic source approximating a prescribed *back-propagating* field in a given bounded near field sub-region while maintaining a very low far field signature.

For each of these three examples, we discuss the optimization scheme used to approximate their solutions and support our claims through relevant numerical simulations.

1. Introduction and main results

The problem of active control of acoustic fields is well studied in the literature with a multitude of ideas and techniques presented (see monographs [1,2]). The main strategies for active sound control are based on the use of boundary controls or secondary sources.

Applications of sound field control ideas are very important and they include: active noise control [3] (see also the pioneer works [4,5]), acoustic field reproduction [6–10] and active control of scattered sound fields [11–19]. A rigorous comparative analysis of the theoretical similarities and respective challenges for these three areas of applications is done in [20].

In a recent development in [21] (see also [22] for the low frequency approximation), a general analytical approach based on the theory of boundary layer potentials was proposed for the active acoustic control problem in homogeneous

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environments.Then, in [23], building up on [21], the authors presented a thorough two dimensional sensitivity analysis for the synthesis of time-harmonic weak radiators with controllable patterns in some exterior region and, as indicated by their numerical results, postulated that such acoustic sources will be feasible only if the region of control is in the reactive near-field of the source.

The work presented in this paper uses ideas from, and is relevant to, a wide array of important research areas: acoustic wave field synthesis, inverse source problems, optimization, personal audio techniques, acoustic near field control. We are making use of the theoretical results developed in [21] and, through a Tikhonov regularization procedure (with Morozov discrepancy principle for the choice of the regularization parameter), we synthesize acoustic sources in one of the following scenarios:

1. Sources approximating a given pattern in a prescribed exterior near field sub-region.
2. Sources approximating a given pattern in a prescribed sub-region of their near field while having a null in a different given sub-region of their near field.
3. Sources which have a very weak field in a given (sufficiently far) exterior annuli while approximating a given pattern in a prescribed sub-region of their near field.

The first type of sources are relevant for the problem of acoustic rendering [24,6]. The second type of sources above present an interest for the problem of personal audio studied in [8–11] where we assume that by superposition our strategy will imply the possibility to approximate, with such sources, different given sound patterns in disjoint regions of space. For the third type of sources above, although our theoretical results apply to the general question of synthesis of weak acoustic radiators approximating any given pattern in the near field control region, we focused on the problem of characterizing the necessary inputs (normal velocity or pressure) on the boundary of the source so that it approximates a backward propagating plane wave in the region of control while maintaining a very weak field in the given exterior annuli. This problem is relevant for the question of acoustic shielding or cloaking since by using a similar strategy we believe we can synthesize a planar array with similar properties: having a very weak field in an exterior annuli (where enemy detection measurements are taken) while approximating a given backward propagating plane wave in a near field region in front of it. Thus, by superposition, such an array could, when paired with a time control loop for the detection of interrogating signals, annihilate through destructive interference any incoming signal in its near field region without a large signature in its far field (i.e., shielding an object located behind the array). Then, a compact volume surrounded by a similar conformal array would lead to an active cloaking device for any object located inside.

The results presented in the literature regarding pattern synthesis use arrays of secondary sources (usually approximated by point sources) to control the field in interior regions (i.e., located in the interior of the geometric convex hull of the point sources), or focus on planar rendering (i.e. control in a horizontal plane) or assume that the field to be approximated propagate away from the source to be synthesized.

In the present paper we propose a theoretical optimization strategy for the synthesis of acoustic sources which approximate different prescribed field patterns in given disjoint *exterior* regions in free space and constant depth homogeneous ocean environments. To simplify the exposition, in the numerical support section, Section 3, we consider only the case of sources in free space and focus on the three particular cases listed above.

The paper is organized as follows: In Section 2 we present the theoretical results in two parts: first, in Section 2.1 we briefly recall the theoretical results of [21] for acoustic control in free space and then, in Section 2.2 we discuss their extension to the problem of underwater acoustic control in the context of a constant depth homogeneous ocean environments. In Section 3, we build up on our previous results in [23] and discuss the L^2 - Tikhonov regularization with Morozov discrepancy numerical approximation for the acoustic control problem in 3D and (assuming the superposition principle) without losing the generality present numerical simulations in the three important situations listed above: first, in Section 3.1 we present the synthesis of an acoustic source approximating a prescribed plane wave in a given near field sub-region; then in Section 3.2 we present the synthesis of an acoustic source with a null in a given sub-region of its near field and approximating an outgoing plane wave in a disjoint near field sub-region; and finally, in Section 3.3 we synthesize a very weak acoustic radiator (almost non-radiating source (ANR)) approximating, in a sub-region of its near field, a given backward propagating (propagating towards the source) plane wave. Finally, in Section 4 we present the conclusions of the paper with particular highlights for several possible applications of this work together with important future challenges.

2. Theoretical results

In this section we present the theoretical results behind our optimization scheme described below. In Section 2.1 we will recall the results of [21] developed for the free space environments (i.e., homogeneous media with no boundaries and radiating condition at infinity) and then in Section 2.2 we will present their extension to the case of constant depth homogeneous ocean environments as introduced in [25,26] (i.e., infinite rectangular waveguide with constant depth along z direction, $z \in [h, 0]$ for some $h < 0$, and pressure release boundary at the water–air interface $z = 0$, total reflecting boundary at the ocean bottom interface $z = h$ together with radiation condition at infinity).

We consider the source support represented by D_a, a compact region of space with Lipschitz continuous boundary, and as in [21] we assume that $D_1 \Subset \mathbb{R}^3$ and $D_2 \Subset \mathbb{R}^3$, with $D_1 \cap D_2 = \emptyset$ and $\{D_1 \cup D_2\} \cap D_a = \emptyset$. We also assume that u_1 is a