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Active sound control in 3D bounded regions

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HIGHLIGHTS

- Active sound control in the 3D bounded domain is considered, including wanted sound.
- The noise source or transmission path data is not needed to obtain the solution.
- The controls, located at the boundary, cancel the noise but preserve the wanted sound.
- If wanted sound is present, it is doubled outside the shielded region.
- The noise reduces by 2.5 dB if the number of controls doubles in each direction.

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ABSTRACT

We consider active sound control with the preservation of wanted sound in 3D bounded regions via numerical experiments. In contrast to some previous papers which are based on the difference potential method, our approach in the present work is based on surface potentials. In active sound control, some bounded domain is shielded from noise generated outside by situating additional sources at the perimeter of the domain to be protected. The method does not require knowledge of the source of noise (nature, location, and intensity). The approach allows the presence of wanted sound in the shielded domain, which is preserved, while the noise is canceled. To implement the method, the only required knowledge is the total acoustic field at the perimeter of the shielded domain. A number of test cases in different 3D bounded domain configurations are considered in the frequency domain. Furthermore, for the first time the effect of the number of secondary sources on the noise cancelation is studied. A significant level of volume noise cancelation is achieved at most parts of the shielded domain.

1. Introduction

Although active sound control (ASC) is a relatively new research area, it is extensively being developed. In ASC problems, it is supposed that some bounded domain (internal or external) has to be shielded from noise by implementing additional (secondary) sources also known as controls. In contrast to the passive sound control, ASC does not require any mechanical insulation to achieve noise reduction. The problem becomes much more complicated if there is a wanted sound in the shielded domain, which has to be preserved. Nowadays, it is important to satisfy strict noise regulations in industrial applications. Therefore, there are growing research activities into various noise control means, both active and passive. Passive sound control, which uses mechanical insulation to reduce noise, is well suited for high frequency noise but becomes inefficient for low frequency noise. In turn, ASC appears to be efficient for low frequency noise. In practice, the two approaches are often combined so that a broad part of the audible sound spectrum can be covered.

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Due to a large number of publications in the area of ASC, it is not possible to provide a full review in one research publication. Thus, the reader is referred to [1,2] for more details.

Paul Lueg published a pioneering work on ASC in 1930s. He used a noise source in a duct with a microphone connected to a controller and a loudspeaker as the control to demonstrate noise cancelation. However, practical implementation of his patent was not possible at that time. Theoretical and experimental works have been done by M. Jessel, G. Mangiante and G. Canevet, who together developed the JMC method. The JMC approach is based on the Huygens principle in wave propagation. Their methodology uses monopoles, dipoles and quadrupoles situated at the perimeter of the shielded domain to cancel noise generated outside [3–6]. However, it is important to note that their approach does not allow wanted sound to be present in the shielded region.

More recently, ASC has been implemented with limited success in ducts and industrial exhaust towers [2,7], aircraft pilot headsets and car and aircraft cabins [7,8]. Other studies consider the effect of the location of controls [9], the number of controls [10], types of controls [11], dimension of a shielded domain [12], shielding algorithm and nature of noise [13,14] on ASC. In these papers, bounded regions were considered. Wright, Vuksanovic and Atmoko published a paper [15] in which they consider ASC in unbounded regions. They generate a controlled acoustic shadow via the wall of controls and use it to shield targeted regions from noise. The authors demonstrate via computer modeling that the approach has a considerable potential to shield a target region from noise.

In another aspect of the ASC problem, it is required to protect a region from noise but filter a wanted sound. In this case, all sound sources are situated outside the region. For example in [16,17], different configurations of ASC and noise reduction systems are considered. They are required to operate together to achieve a desired effect in a hearing aid. The objective is to cancel the noise leakage entering the ear from the medium via ASC.

With the exception of the JMC theory, the considered ASC methods require detailed knowledge of the noise source(s) and/or transmission path in order to construct control sources. In practice, this knowledge is often difficult to obtain.

There is a separate class of potential-based methods which do not require detailed knowledge of the noise source(s) or transmission path in order to obtain controls. The only knowledge required is the total acoustic field at the perimeter of the shielded domain, which can practically be obtained by measurement. The total acoustic field includes both the noise and wanted sound. Using the formalism of the difference potential method (DPM) [18,19], it is possible to obtain the general solution to the ASC problem in a discrete formulation. In order to obtain the solution, the boundary value problem must be linear and correct. The solution can be applied for quite arbitrary domains and medium properties. The optimization problems for monochromatic waves are considered in [20–23]. In [24], the DPM is applied to the system of hyperbolic equations to obtain local one-layer and two-layer control sources. In [25], the general solution of the ASC problem is obtained in a differential form and the correspondence between the analytical and finite-difference solutions is shown. The mechanism of the ASC solution based on the DPM is analyzed via a study of monochromatic waves in a 1D duct with termination in [26]. In [27], the DPM technique is applied to the system of acoustic equations. The analogy between the finite-difference and continuous solutions based on Green's function is studied for the case of a uniform medium. The ASC problem for composite regions is formulated and the solution is obtained in [28]. The solution, which is obtained in the continuous formulation, allows a selective shielding of one sub-domain from the influence of the other and vice-versa. The general solution to a discretized composite ASC problem is obtained in [29]. It is shown that the problem can be reduced to solving a set of auxiliary problems for composite domains. An experimental implementation of the ASC methodology based on the DPM for 1D domains is presented in [30]. The solution of the ASC problem in a general non-stationary formulation is obtained for the wave equation in the time domain in [31].

In this paper, we present numerical experiments of ASC in 3D bounded regions, which contain a sub-region to be shielded from external noise. The shielded regions containing wanted sound are also considered. In contrast to the previous papers, which are based on the DPM and achieve total noise cancelation at selected discrete points, the used approach is based on the formalism of surface potentials. The technique based on surface potentials achieves adequate noise cancelation in most parts of the shielded domain. The calculations are carried out for three different regions in the frequency domain. In addition, the effect of the number of controls on the noise cancelation is analyzed. The paper is organized as follows: the formulation of the ASC problem is given in the next section. The implementation of the algorithm is considered in Section 3. Finally, in Section 4 numerical test cases are described and the results of the experiments are discussed.

2. Formulation of the active sound control problem

Let D_0 be the entire computational domain such that $D_0 \subset \mathbb{R}^3$, $D^+ \subset D_0$ be the domain to be shielded and $D^- := D_0 \backslash \overline{D^+}$ be the region containing the noise source (Fig. 1). The boundary of D^+ is surface Γ. The boundaries of D^+ and D_0 are assumed to be smooth enough.

Suppose the sound field is described by the following boundary value problem (BVP):

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

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

where the operator L is an appropriate linear partial differential operator, and U_{D_0} is a linear space of functions such that inclusion (2) guarantees the existence and uniqueness of the solution. Here, the operator L corresponds to the Helmholtz equation operator. A and B are the reference points that are described in Section 4.

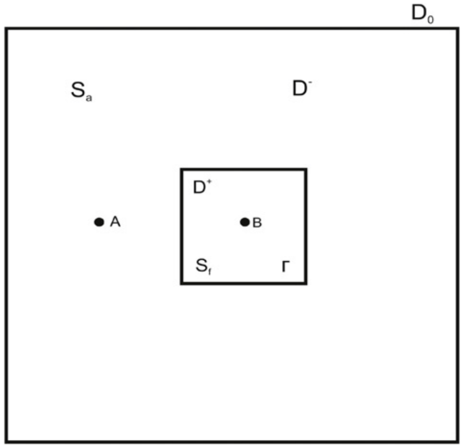

Fig. 1. Domain sketch.

The acoustic sources S on the right hand side consist of adverse and wanted sources:

$$S = S_a + S_f. \tag{3}$$

The adverse sources S_a are located in D^- and wanted sources S_f, in D^+:

$$\text{supp}\, S_f \subset D^+, \qquad \text{supp}\, S_a \subset D^-.$$

Furthermore, one can consider the opposite case with the adverse field generated in D^+, while the wanted sources are situated in D^-. Then, the region D^- is supposed to be protected.

Assume that the field of U nearby the boundary Γ of the protected region is known. Then, the ASC problem is reduced to obtaining additional sources G such that the solution to the following BVP:

$$LV = S + G, \tag{4}$$

$$\text{supp}\, G \subset D_0 \backslash D^+,$$

$$V \in U_{D_0} \tag{5}$$

coincides with the solution of BVP (1) and (2) in the domain D^+ if $S = S_f$.

It is worth noting here that an obvious solution $G = -S_a$ cannot be applied because the distribution of S_a is supposed to be unknown. In addition, such a solution would not be realistic for practical applications.

3. Numerical implementation of the algorithm in the frequency domain

We assume that the wave propagation is modeled via the Helmholtz equation. A monopole source is used as the adverse source. The wanted sound in the domain to be protected is also generated by a monopole. Thus, BVP (1) and (2) is reduced to the following formulation:

$$\Delta p + k^2 p = f, \tag{6}$$

$$p_{|\partial D_0} = 0$$

where p is the sound pressure, f represents the sound and noise sources altogether and k is the wavenumber. The sound and noise sources are delta-sources given by $\delta(X - X_f)p_f$ and $\delta(X - X_a)p_a$, respectively.

In turn, BVP (4) and (5) is reduced to

$$\Delta p + k^2 p = f + g \tag{7}$$

$$p_{|\partial D_0} = 0.$$

Here, g represents the controls, which are combinations of monopole and dipole sources [20,25]:

$$g = \delta(\Gamma)\frac{\partial p}{\partial \boldsymbol{n}} + \frac{\partial \delta(\Gamma) p}{\partial \boldsymbol{n}}, \tag{8}$$

where $\boldsymbol{n}$ is the outward unit normal to the boundary Γ of the domain D^+. The first term corresponds to the monopole while the second term represents the dipole.

Table 1
Noise and wanted sound source coordinates and intensities.

Test Case	Noise source coordinates	Noise source intensity	Wanted sound source coordinates	Wanted sound source intensity
1	(0.21, 0.46, 0.50)	10^5	–	–
2	(0.21, 0.21, 0.46)	10^4	–	–
3	(0.50, 0.50, 0.46)	6×10^5	–	–
4	(0.21, 0.46, 0.50)	10^5	(0.75, 0.75, 0.46)	10^5
5	(0.21, 0.21, 0.46)	10^4	(0.50, 0.50, 0.46)	10^3
6	(0.50, 0.50, 0.46)	6×10^5	(0.10, 0.10, 0.46)	6×10^5

The boundary Γ of the protected domain is divided into small enough areas. The size of the areas depends on the number of controls to be implemented. The controls are situated at the boundary in such a way that one pair of controls is located at the center of each area. Their discrete distribution is based on the approximation of the surface delta-function as follows:

$$\delta(\Gamma) \approx \sum \Delta s_i \delta(X - X_i), \tag{9}$$

where Δs_i is the area of the grid around the ith control source, which corresponds to the ith area. The point delta-source at an ith cell is approximated as follows:

$$p(X_i)\delta(X - X_i) \approx \frac{p_i}{V_i} \tag{10}$$

where V_i is the volume of the ith cell. The wanted sources that are situated in the region to be protected are approximated in the same way. As the result, we arrive at the following prototype of Eq. (7):

$$\Delta p + k^2 p = \delta(X - X_f)p_f + \delta(X - X_a)p_a + \sum_i \Delta s_i \left[\frac{\partial p}{\partial n}\delta(X - X_i) + \frac{\delta}{\delta n}(p\delta(X - X_i)) \right]. \tag{11}$$

The Helmholtz equation is approximated using the fourth order of approximation [32]. The operation of the controls is based on the total field from the primary sources at the points that coincide with the controls situated at the boundary Γ. The dipoles in Eq. (11) are approximated by two monopoles with the opposite signs placed at a small distance apart along the outward unit normal n.

4. Numerical results

The field (sound pressure) and sound pressure level (SPL) were calculated with and without ASC for six test cases: in the first three cases, wanted sound is not generated in the protected region while in the second three cases, it is allowed to be present. The SPL is calculated as follows:

$$\text{SPL} = 20 \log(p/p_{ref})\text{dB}$$

where $p_{ref} = 2 \times 10^{-5}$ is the reference sound pressure.

The computational domain is a unit cube in the x, y and z directions of the Cartesian coordinate system. In Test Cases 1 and 4, the shielded region is the right half of the computational domain. In Test Cases 2 and 5, it is a cube with the length of 0.2 situated at the center of the computational domain which lies between points 0.4–0.6 with respect to each coordinate. Test Cases 3 and 5 are opposite to Test Cases 2 and 5, respectively, i.e. the noise source is situated in the cube while the region outside the cube is to be shielded. The noise and wanted sound source coordinates and intensities can be found in Table 1. For the purpose of discussion, the two reference points mentioned in Section 2 (Fig. 1) are used. Point A is outside the shielded region whereas point B is inside. The coordinates of the reference points differ from one test case to another because of the different domain configurations in the test cases. Point A has coordinates (0.25, 0.5, 0.5) in Test Cases 1 and 4, (0.25, 0.5, 0.5) in Test Cases 2 and 5 and (0.5, 0.5, 0.5) in Test Cases 3 and 6. For Test Cases 1 and 4, point B is situated at (0.75, 0.5, 0.5), (0.5, 0.5, 0.5) in Test Cases 2 and 5 and (0.25, 0.5, 0.5) in Test Cases 3 and 6. In addition, interval AB which joins points A and B and passes through the unprotected and protected domains is chosen to compare the fields with and without ASC. All calculations are carried out at wave number $k = 36$. However, the results are similar for other wavenumbers. Furthermore, the effect of the number of controls on the noise cancelation achieved is also assessed for a domain configuration from Test Case 1.

4.1. ASC without wanted sound

In these calculations, the domains in Test Cases 1–3 are considered without wanted sound generated in the protected region. Fig. 2 shows the sound pressure in Test Case 1 with ASC.

The controls, as many as 65,538, are situated at the boundary of the shielded domain and uniformly distributed along the boundary. In this test case, a large number of controls are exploited to achieve almost complete noise attenuation in the protected region. The reduction of the number of controls leads to a drop of the level of noise attenuation mostly nearby the

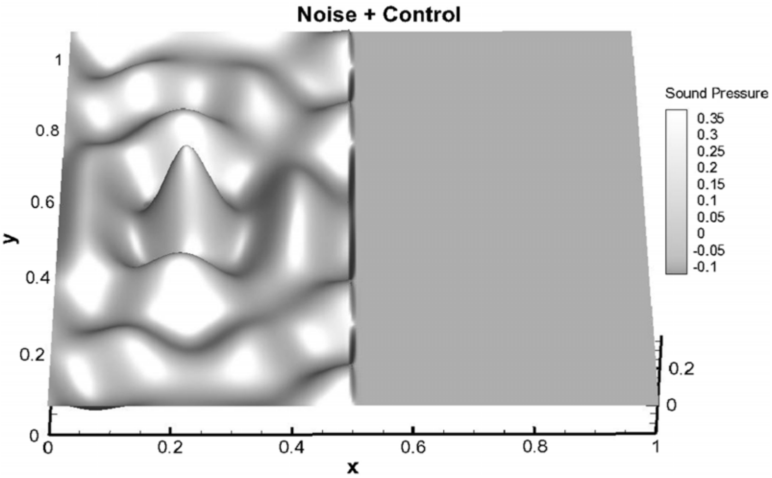

Fig. 2. Sound pressure with ASC in Test Case 1.

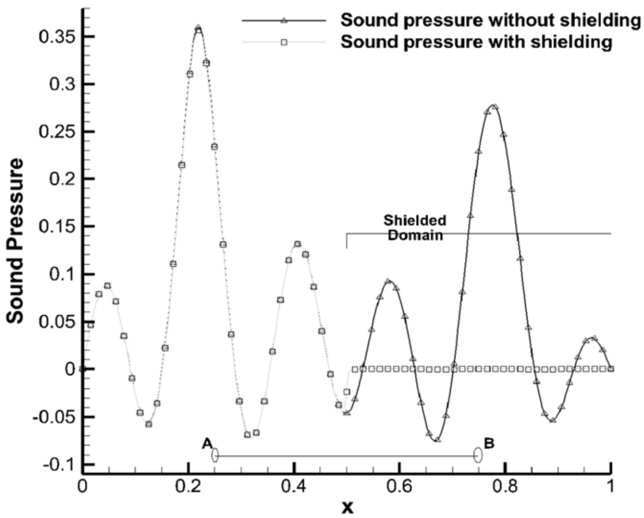

Fig. 3. Sound pressure without ASC and with ASC at line *AB* in Test Case 1.

boundary. As shown in Fig. 2, the noise in the shielded domain is almost completely canceled. In addition, the noise outside the shielded domain is unaffected by the controls.

At point *A*, the field is equal to 2.358×10^{-4} without ASC and 2.338×10^{-4} with ASC. In the same way, a field of 2.28×10^{-1} is obtained at point *B* in the shielded domain without ASC and 2.8×10^{-4}, with ASC. Overall, for most of the shielded domain there is over 30 dB of noise cancelation. However, there are areas with less than 20 dB of noise cancelation. Fig. 3 shows the sound pressure with and without ASC along line *AB*. It is clear that the noise is canceled by over 30 dB and that the cancelation is not total.

In Test Case 2, we put the controls at the perimeter of the protected domain, in accordance with the approach. There are 51 controls along each axis, 2601 controls on each side of the boundary and 15,606 controls in total at the perimeter. The cubic region is to be shielded from noise generated outside the domain. With ASC, the noise outside the protected domain remains nearly the same as without ASC. However, in the protected region it is almost completely canceled (Fig. 4). At point *B*, without ASC the field is equal to 3.68×10^{-3}.

With ASC at the same point, the field is equal to -7×10^{-5}, with the difference in SPL of 34.71 dB. For the most part of the shielded domain, noise cancelation of over 30 dB is achieved. However, there are areas in the shielded domain where the noise cancelation is less than 20 dB. The lowest cancelation is obtained close to the boundary of the shielded domain. It is worth noting that at all points within the shielded domain some level of noise cancelation is achieved. The field obtained without ASC at point *A* is equal to -5.94×10^{-3}, and -5.13×10^{-3} with ASC.

In Fig. 5, the sound pressure with and without ASC in interval *AB* is shown. After ASC, the sound pressure drops significantly in the shielded region but changes only slightly outside it. A small sound pressure can be seen in the shielded domain. The loudest noise has SPL over 45 dB without ASC, while noise not louder than 15 dB occurs in the shielded region.

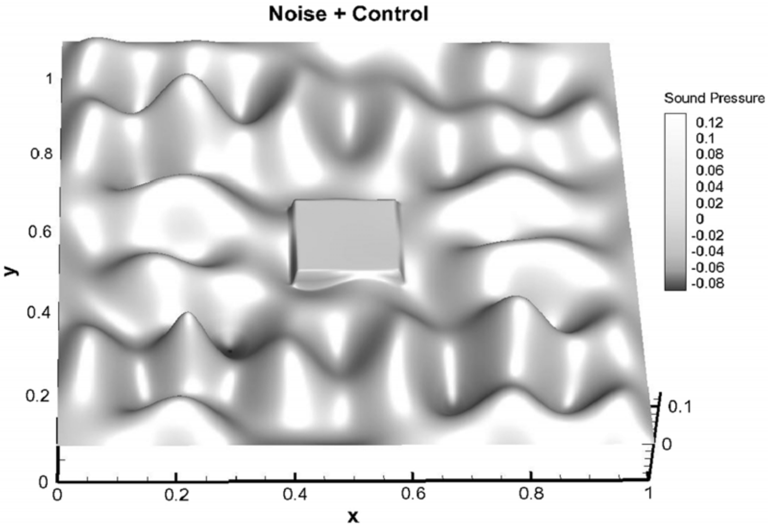

Fig. 4. Sound pressure with ASC in Test Case 2.

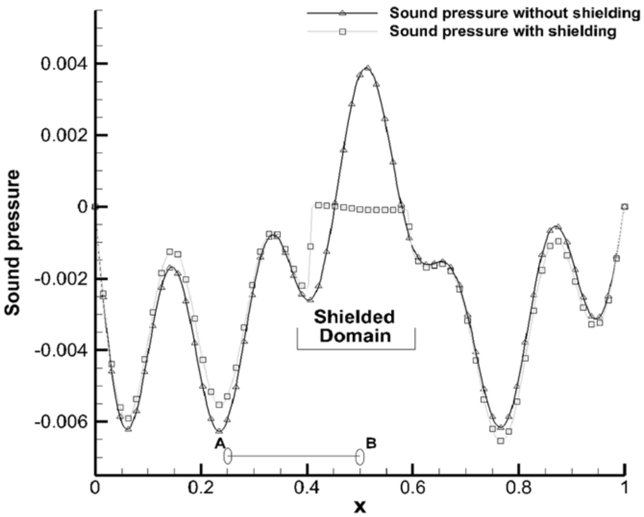

Fig. 5. Sound pressure with and without ASC in Test Case 2.

Test Case 3 is opposite to Test Case 2, i.e. the noise source is located at the center of the cubic region while the surrounding area is to be protected from the noise. Similar to the previous test cases, the controls are situated at the boundary of the cubic region on all sides. The number of controls coincides with that in Test Case 2. With ASC implemented, the noise in the enclosed protected region is almost unchanged. However, the noise generated outside is canceled to a large extent (see Fig. 6). At point *A*, the field without ASC is 3.85×10^{-1}. With ASC it equals 3.84×10^{-1}. Outside the shielded region, at point *B* the field without ASC is equal to -3.87×10^{-2} and 2×10^{-4} with ASC, with the difference in SPL of 44.6 dB. The maximum and minimum noise cancelation equal to 75.8 and 2 dB are reached, respectively.

Fig. 7 shows the cancelation of the noise in Test Case 3.

Thus, the first three test cases show that the approach can produce global noise cancelation in the protected region without affecting the noise outside. Detailed information about the boundary conditions and noise was not required to implement the algorithm. The results from the first set of experiments are summarized in Table 2.

4.2. ASC with wanted sound

In the next calculations, wanted sound is present in the shielded domain. Three test cases of protected domains are considered, which are geometrically identical to domains in the previous test cases. However, in addition to canceling the noise the wanted sound in the shielded domain has to be preserved with ASC. The coordinates and intensities of the wanted

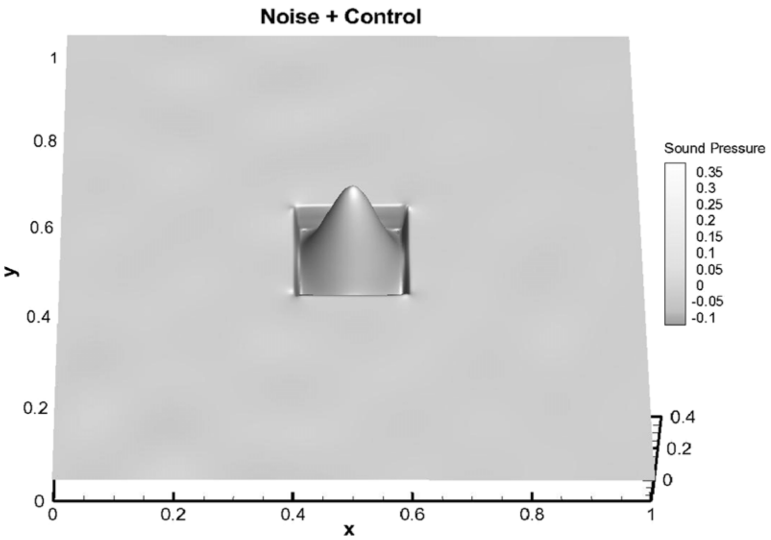

Fig. 6. Sound pressure with ASC in Test Case 3.

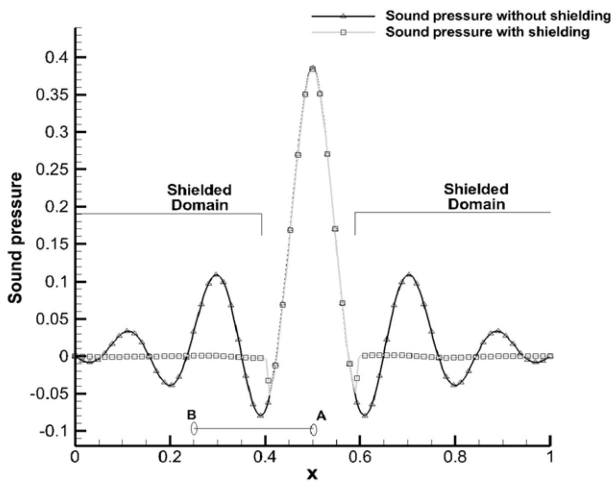

Fig. 7. Sound pressure without and with ASC in Test Case 3.

Table 2
Summary of the SPL (dB) inside and outside the shielded domains.

Test Case	Unshielded region			Shielded region		
	SPL without ASC, dB	SPL with ASC, dB	Difference, dB	SPL without ASC, dB	SPL with ASC, dB	Difference, dB
Test Case 1	81.42	81.36	0.05	81.16	22.99	58.16
Test Case 2	49.2	48.19	1.008	45.3	10.85	34.45
Test Case 3	85.7	85.67	0.03	65.73	21.13	44.6

sound source are given in Table 1. For ease of understanding, the noise and wanted sound fields without ASC are presented separately while the combined field with ASC is given.

Fig. 8 shows the fields in the entire computational domain with ASC in Test Case 4. The number of controls coincides with that in Test Case 1. With ASC, the noise in the shielded domain is attenuated, leaving mostly the wanted sound. However, outside the shielded region, the field from both noise and wanted sound is amplified as shown in Fig. 8. The noise and wanted sound components of the total field at point A outside the shielded domain are equal to 2.36×10^{-1} and 0.041×10^{-1}, respectively, without ASC. With ASC the field is equal to 3.3×10^{-1}.

In turn, at point B the fields are equal to 2.29×10^{-1} and 1.3×10^{-2}, respectively, without ASC and 8×10^{-3} with ASC. The sound pressure in the domain at interval AB is shown in Fig. 9. With ASC, what remains in the shielded domain is mostly the wanted sound. The noise is effectively canceled. Meanwhile, outside the shielded domain the wanted sound is doubled.

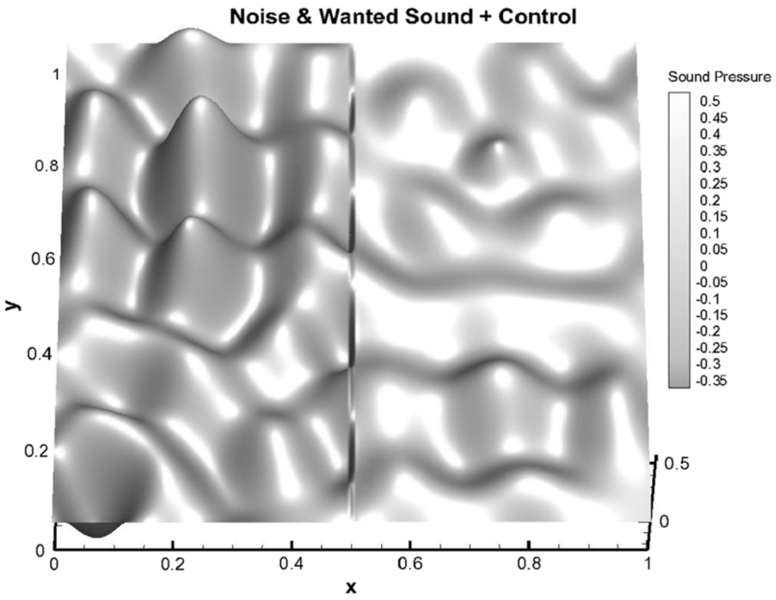

Fig. 8. Sound pressure with ASC from noise and wanted sound in Test Case 4.

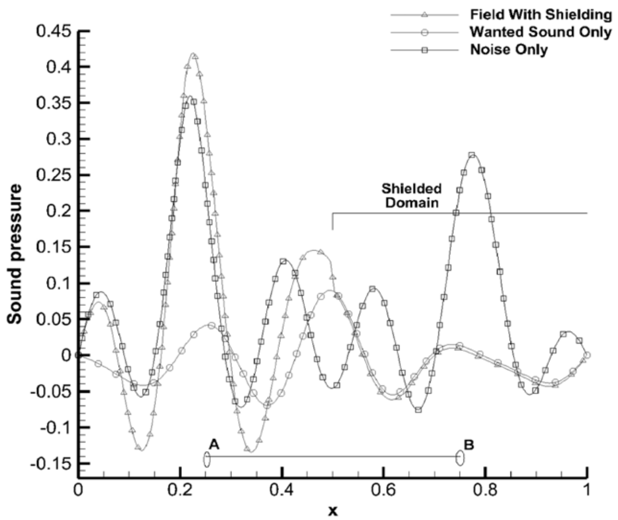

Fig. 9. Noise and wanted sound without and with ASC in Test Case 4.

The field from the noise and wanted sound sources in the entire computational domain with ASC for Test Case 5 are shown in Fig. 10. The protected domain and number of controls coincide with those of Test Case 2. The wanted sound outside the protected region is doubled, as expected from the theory [33]. In turn, in the protected domain the noise is attenuated, leaving mostly the wanted sound. The field at points *A* and *B* is considered in Fig. 11. At point *A*, the noise and wanted sound components of the sound pressure are equal to -5.9×10^{-3} and 5×10^{-4}, respectively, without ASC. At point *B* the fields equal 3.7×10^{-3} and 6.4×10^{-3}, respectively, without ASC. With shielding, the total sound pressures are equal to 6.3×10^{-3} and -4.2×10^{-3} at points *B* and *A*, respectively.

The shielded domain and the location of the noise and wanted sound sources in Test Case 6 coincide with those of Test Case 3. Similarly, the number of controls corresponds to Test Case 3. The result in Fig. 12 shows that with ASC implemented, the wanted sound in the protected domain remains almost unaffected while the noise is being canceled.

Although this is not clear from Fig. 13, the field from the noise and wanted sound outside the shielded domain change. At the reference point *A*, the noise and wanted sound components of the total field equal 3.85×10^{-1} and 1.21×10^{-2}, respectively, without ASC and 3.6×10^{-1} with ASC. In the shielded domain, the fields at point *B* are 3.27×10^{-2} and -5.2×10^{-3}, respectively, without ASC and 5.1×10^{-3} with ASC.

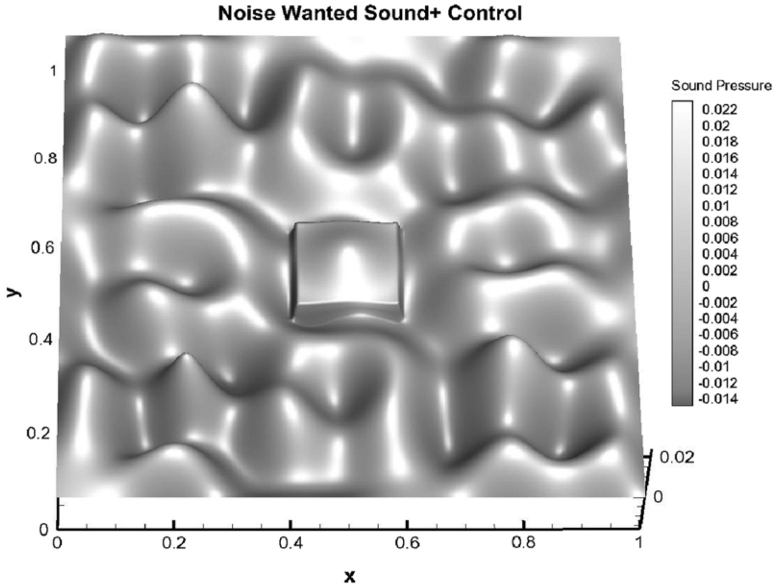

Fig. 10. Fields with ASC with wanted sound in Test Case 5.

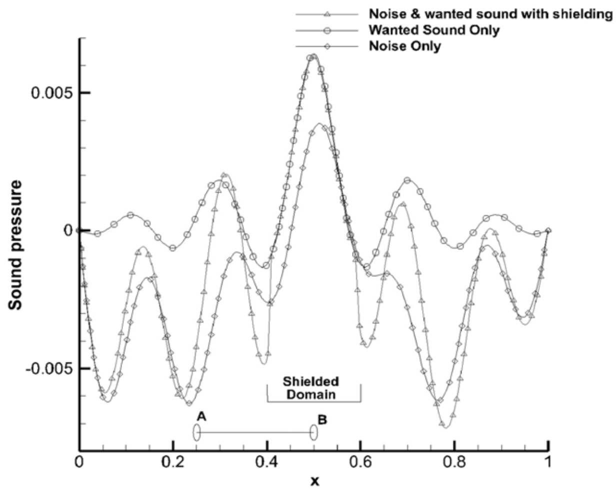

Fig. 11. Fields without and with ASC in the domain in the Test Case 5.

In general, the results demonstrate the capability of ASC of canceling the external noise while simultaneously preserving the wanted sound in a given region. In this case also, the only required information is the total acoustic field at the boundary of the shielded region. Summary of the results of the ASC calculations with wanted sound in the shielded region is given in Table 3.

4.3. Effect of the number of controls

In the Test Cases 1–6, the controls are implemented continuously. However, in practice this is not realistic. Therefore, it is important to consider the effect of the number of controls on the noise attenuation achieved. For this purpose, a domain configuration from Test Case 2 is chosen and the step size between the controls is successively increased. With every increase in the step size, the number of controls is decreased accordingly. The parameters of the noise source and the domain configuration are kept constant to analyze only the effect of the number of controls.

The sound pressure and SPL values at point B for a different number of controls are compared in Table 4. The results show that the sound pressure in the shielded domain increases with decreasing number of controls, i.e. there is more noise if the number of controls is reduced. Outside the shielded domain, the noise remains practically unchanged as the number of controls changes.

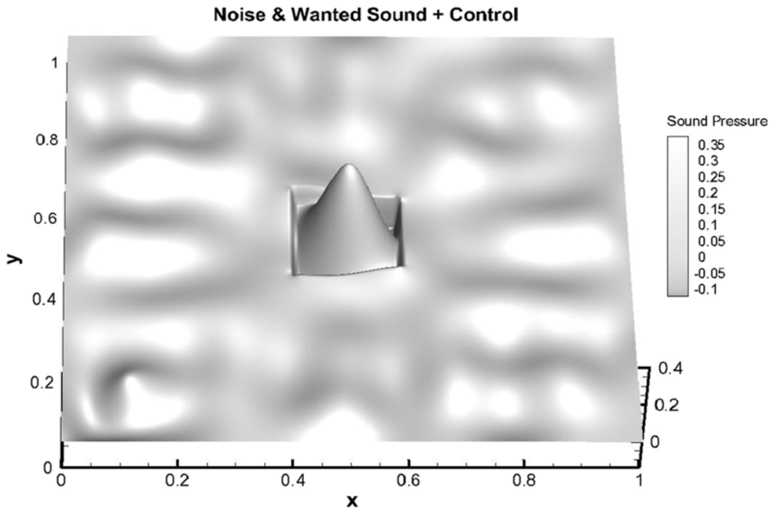

Fig. 12. Sound pressure with ASC with wanted sound in Test Case 6.

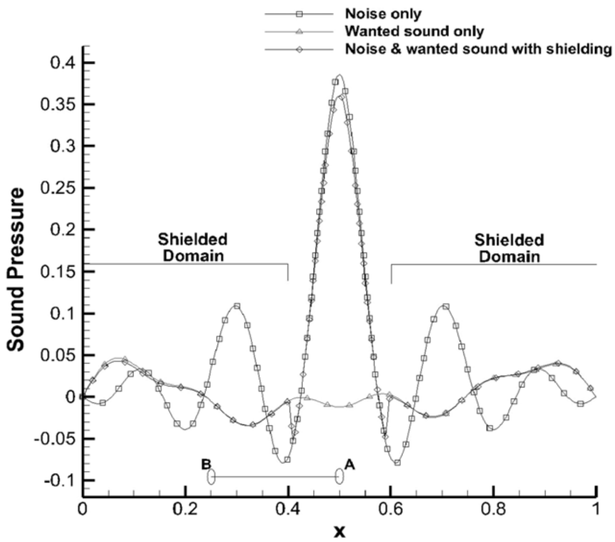

Fig. 13. Sound pressure without and with ASC in Test Case 6.

Table 3
Summary of the SPL (dB) inside and outside the shielded regions.

Test Case	Unshielded region			Shielded region		
	Noise SPL without ASC, dB	Wanted sound SPL without ASC, dB	Combined SPL with ASC, dB	Noise SPL without ASC, dB	Wanted sound SPL without ASC, dB	Combined SPL with ASC, dB
Test Case 4	81.43	66.25	84.34	81.16	56.51	52.18
Test Case 5	49.46	28.70	46.49	50.13	45.30	49.96
Test Case 6	85.67	61.44	85.12	33.25	49.63	48.20

Table 4
Effect of the number of controls on ASC at point *B*.

No.	Number of controls	Sound pressure without ASC	Sound pressure with ASC	SPL without ASC, dB	SPL with ASC, dB	SPL difference, dB	E_2
1	4704	0.208	0.01	80.341	54.218	26.123	0.1168
2	1176	0.208	0.02	80.341	60.083	20.258	0.1464
3	384	0.208	0.035	80.341	64.754	15.587	0.2290
4	216	0.208	0.044	80.341	66.865	13.476	0.3541
5	96	0.208	0.06	80.341	69.586	10.755	0.9075

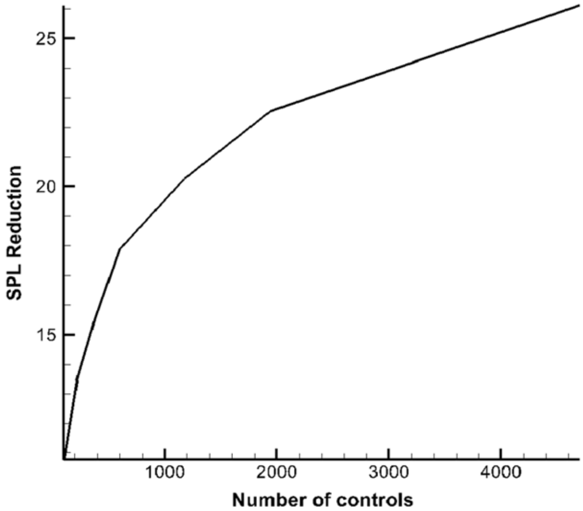

Fig. 14. Effect of the number of controls on noise shielding.

The last column in Table 4 shows the level of noise attenuation in the sense of L_2 where

$$E_2 = \sqrt{\frac{\sum_{i:X_i \in D^+} {p_i}^2}{N}}.$$

Here, N is the number of nodes within the shielded domain.

The size of the interference zone, i.e. the area around the boundary of the shielded domain in which there is low noise cancelation, grows as the number of controls is reduced. In addition, local peaks start forming around the controls. Thus, the controls become more individually distinguishable. The effect of the number of controls on the noise attenuation achieved is shown graphically in Fig. 14.

It should be noted here that in all test cases, the noise cancelation in the shielded region is not total. However, the magnitude of the remaining noise is small when compared to the original level of noise. At most parts there is over 20 dB noise cancelation. In the presence of a wanted sound in the region to be shielded, the wanted sound remains almost unaffected while the external noise is effectively canceled.

5. Conclusion

The capabilities of ASC in 3D bounded domains based on surface potentials have been demonstrated via numerical experiments in the frequency domain. In the calculations, the only required knowledge is the total acoustic field at the boundary of the shielded domain from the noise and wanted sound sources. The knowledge of the characteristics or nature of the noise sources or the propagation medium is not required to obtain the controls. In all test cases, significant volumetric noise cancelation is achieved, i.e. for most of the shielded domain, the noise cancelation greater than 20 dB. It has also been shown that the methodology can cancel noise in the shielded domain while preserving the wanted sound component. Furthermore, in another application the region surrounding a closed domain is shielded from noise that is generated inside the closed domain. In this case, any wanted sound that is generated is preserved. The dependence of the number of controls on their shielding effect has been demonstrated. The level of noise cancelation achieved decreases if the number of controls is reduced.

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