AIAA JOURNAL
Vol. 41, No. 10, October 2003

Computational Aeroacoustics Time-Domain Method Coupled with Adaptive Noise Control Optimizer

Shi Zheng* and Mei Zhuang†
Michigan State University, East Lansing, Michigan 48824

A design of an adaptive noise control system using a computational aeroacoustics (CAA) code combined with an optimizer to control adaptively liner impedance is proposed and tested for multidimensional acoustic problems. The adaptive noise control system consists of two primary components, an expert subsystem and a liner with controllable impedance properties. For a current acoustic field due to a noise source and a given mean flow condition, an optimization process is executed by the expert subsystem in search of a set of required impedance parameters that minimize the difference between the current and the desired acoustic fields. The liner properties then can be adjusted adaptively to the required impedance parameters. For a broadband noise source, the feasibility and potential of the design concept on the coupling of a CAA time-domain method with an optimizer are demonstrated by using the three-parameter impedance model of the Helmholtz type.

I. Introduction

REDUCING acoustic noise emission of jet engines is of great interest in civil applications. Because fan noise is an extremely important noise source in the current and the next generations of jet engines, the utilization of active noise control methodology is increasingly attractive. The traditional approach of fan noise suppression is to employ a passive duct liner in the walls of the engine nacelle. Because the performance of these conventional passive liners depends on both the source level and spectrum as well as the mean flow,[1] traditional passive liners with fixed impedance properties may not provide maximum noise suppression due to the inability of adjusting liner impedance properties to achieve the optimum impedance. To suppress the noise more effectively, the impedance properties may need to be adaptively adjusted to accommodate the continuously changing mean flow conditions and the spectra of the noise sources. This is the essential idea of truly active noise control. Naturally, the realization of such noise control requires 1) a liner whose impedance properties are adjustable and 2) an algorithm that determines the optimum impedance properties. The main objective of the current work is to establish a design for the coupling of a computational aeroacoustics (CAA) time-domain method with an optimizer for adaptive noise control. Although such noise control is still not a truly active noise control, it is a large step toward truly active noise control as compared with the traditional passive noise control.

A schematic of this adaptive noise control system is shown in Fig. 1. The system consists of two primary components, a liner with controllable impedance and an expert subsystem. For a given acoustic noise source and mean flow condition, the current acoustic field refers to the acoustic field resulting from the current values of the liner impedance. The desired acoustic field, which is assumed to be different from the current acoustic field, refers to the acoustic field that we would like to achieve. When the desired acoustic field is considered as an input, the expert subsystem calculates new values for the impedance parameters to which the liner is adjusted accordingly to achieve a resultant acoustic field that is the closest to the desired one. This is the basic idea of the adaptive noise control system. In the next section, the expert subsystem and liners with controllable impedance are discussed. The implementation of the adaptive noise control system are demonstrated in Sec. III. The conclusions are presented in Sec. IV.

Received 3 August 2002; revision received 14 March 2003; accepted for publication 20 May 2003.

*Graduate Research Assistant, Department of Mechanical Engineering.
†Associate Professor, Department of Mechanical Engineering. Senior Member AIAA.

II. Adaptive Noise Control System

A. Expert System

It is clear that different values of the impedance parameters will have different effects on the acoustic field, and thus, the resultant acoustic field will be different. To achieve an acoustic field that is the closest to the desired one, the expert subsystem is designed to determine the optimum values for those impedance parameters to which the impedance properties are to be adjusted accordingly. For this purpose, the expert subsystem can be treated as an optimization system, whose objective function is one that can indicate the difference between the current and the desired acoustic fields and whose design variables are the impedance parameters. Mathematically, the objective function is formulated as the relative averaged difference in the acoustic pressure of the current and the desired fields over a certain space V and a certain temporal range Δt as

$$D = \int_{\Delta t}\int_{V} |p_{\mathrm{cur}} - p_{\mathrm{des}}|\,\mathrm{d}V\,\mathrm{d}t \bigg/ \int_{\Delta t}\int_{V} |p_{\mathrm{des}}|\,\mathrm{d}V\,\mathrm{d}t \tag{1}$$

The acoustic pressure is treated in the time domain instead of the frequency domain, and thus, no amplitude, phase, and frequency are explicitly associated with it. Therefore, the definition in Eq. (1) indicates a complete comparison between the current and the desired acoustic pressure fields.

A real controllable-impedance substance may only allow its impedance parameters to be varied over specific ranges. This imposes the constraints for the optimization problem.

With the objective function, the design variables and the constraints well defined, the optimization or minimization process is realized with the aid of a MATLAB® function fmincon, which is provided in the MATLAB optimization toolbox. Details of the algorithms involved in this function can be found in Ref. 2 and the references cited in Ref. 2. Only the general ideas are outlined here. The problem under study is formulated as a constrained nonlinear programming problem. Such a problem is solved in MATLAB using the Newton–Lagrange method, with which the problem is first formulated in the form of the Kuhn–Tucker (K–T) equations, whose solution forms the basis of the original problem. The K–T equations are solved with a sequential quadratic programming (SQP) method, which uses a quasi-Newton method (the Broyden–Fletcher–Goldfarb–Shanno method) to update the Hessian of the Lagrangian function at each major iteration. At each major iteration, a quadratic programming subproblem for the updated Hessian

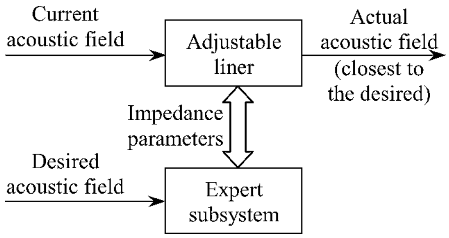

Fig. 1 Schematic of the adaptive noise control system.

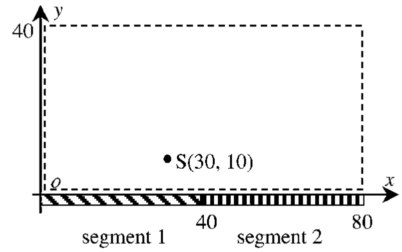

Fig. 2 Test problem schematic.

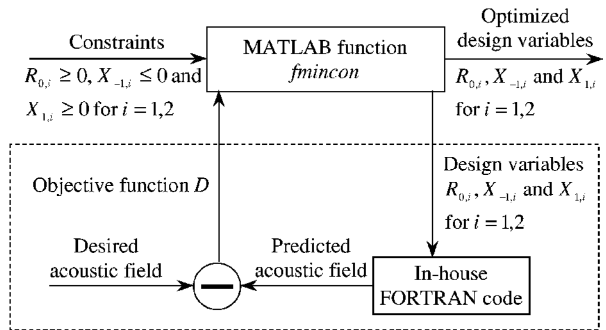

Fig. 3 Optimization process.

is first solved to provide a search direction for the current SQP iteration. Then along the search direction, a line search procedure is performed by means of cubic, quadratic, or mixed cubic/quadratic polynomial interpolation and extrapolation. The searching result is a new point of design variables that sufficiently decreases the value of a merit function that reflects both the minimization of the objective function and the violation of the constraints.

Note that the optimization process presented here is quite similar to the impedance eduction method of Watson et al.[3,4] In their works, the impedance eduction method is used to find the liner impedance in a duct by minimizing the difference between the measured acoustic pressure field and the predicted acoustic pressure field, which is numerically calculated by solving the Helmholtz equation (frequency-domain approach) based on the predicted liner impedance. Although their works attack a different practical problem, the idea is essentially the same as that in the expert subsystem of the current paper. Both deal with an inverse problem, one in the time domain and the other in the frequency domain.

B. Liners with Controllable Impedance

By now we have established the expert subsystem with which we can approximate a desired acoustic field if we can control the impedance properties. The standard approach of controlling impedance properties is a mechanical approach, which is to control the geometric parameters of the liner, for example, the diameter and/or depth of the Helmholtz resonators in an array, so that the required impedance properties can be achieved.[5] Because the impedance properties also depend on the liner material properties, a potential approach of controllable impedance might be developed through the control of material properties or microstructures of the materials. The liners with controllable impedance are critical components in the adaptive noise control system and merit further investigation. However, our main purpose of the current study is to demonstrate the feasibility and potential of the coupling of a CAA time-domain method with an optimizer for the purpose of adaptive noise control, we will not get into any specific approaches for controllable impedance in this paper. Instead, the three-parameter impedance model of the Helmholtz type (see Ref. 6) is used for the purpose of the demonstration:

$$Z(\omega) = R_0 - i(X_{-1}/\omega + X_1\omega) \tag{2}$$

Note that the general concept of the adaptive noise control system works for all kinds of liners with controllable impedance.

III. Numerical Implementation and Results

To test the feasibility of the coupling concept, we implement the concept for a two-dimensional problem as shown in Fig. 2. All of the variables used in this paper are dimensionless with $L = 0.012$ m as the length scale, $a_0 = 340$ m/s as the velocity scale, $\rho_0 = 1.29$ kg/m^3 as the density scale, L/a_0 as the timescale, $\rho_0 a_0^2$ as the pressure scale, and $\rho_0 a_0$ as the impedance scale.

The acoustic field of interest lies in the region of 80×40 confined in the dashed lines and is bounded by an impedance wall of two segments of equal length, denoted as segments 1 and 2, at $y = 0$. The impedance is assumed to be characterized by the three-parameter model as in Eq. (2) but takes different values for the impedance parameters for the two segments. Note that, when this model is used for a case with a mean flow, it is assumed that the mean flow effects are included in the three parameters.[6,7] When the same values are used for the three parameters R_0, X_{-1}, and X_1 in the cases of different mean flow conditions, they represent different liners. Initially, the acoustic velocity components are zero everywhere and the broadband acoustic pressure has a cylindrical Gaussian distribution of the form

$$p_0(R) = e^{-BR^2} \tag{3}$$

where R is the distance to the pulse center S at $x = 30$ and $y = 10$ and $B = 0.04\,\ln 2$.

The problem formulated is numerically solved by a CAA code in the time domain with a seven-point-stencil upwind optimized dispersion-relation-preserving method.[8] The accuracy is sufficient for both the temporal and spatial scales of the current problem. A nonreflecting radiation boundary condition[9,10] is applied at the left, right, and upper boundaries. It has been substantiated that numerical reflection is virtually zero at these boundaries. At the lower boundary, Tam's broadband time-domain impedance boundary condition (see Refs. 6 and 7) is applied. For the three-parameter impedance model in Eq. (2), the time-domain impedance boundary condition is derived as

$$\frac{\partial p}{\partial t} = R_0 \frac{\partial v_n}{\partial t} - X_{-1} v_n + X_1 \frac{\partial^2 v_n}{\partial t^2} \tag{4}$$

where p and v_n are the acoustic pressure and the normal acoustic velocity (positive when pointing into the liner) at the impedance wall, both being time-domain variables. The CAA time-domain code will be incorporated in the optimization process to predict the acoustic field given the noise source, the mean flow condition, and the values for the impedance parameters.

The optimization process is schematically illustrated in Fig. 3. As a discretized special case of Eq. (1), the objective function used in the current optimization process is defined as the sum of the local differences over all of the nodes in the computational domain at a certain time, for example, $t = 25$, as

$$D_1 = \frac{\sum_j \sum_i |p_{\text{cur}} - p_{\text{des}}|_{i,j,t=25}}{\sum_j \sum_i |p_{\text{des}}|_{i,j,t=25}} \tag{5}$$

where the desired acoustic pressure p_{des} is assumed to be known and the current acoustic pressure is computed by the CAA time-domain code.

As discussed in Sec. II, constraints may be imposed to the optimization problem from the practical considerations of a real controllable-impedance substance. In the current problem, the three-parameter model in Eq. (2) is used. Because this model analogously represents a damped mechanical vibration system of resistance R_0, stiffness $-X_{-1}$, and mass X_1, all being greater than or equal to zero, we can assume that the physical constraints for the three parameters are $R_0 \geq 0$, $X_{-1} \leq 0$ and $X_1 \geq 0$. Mathematical analysis shows that the constraint $X_{-1} < 0$ is also required for the stability of the broadband time-domain impedance boundary condition.[6]

The MATLAB function fmincon is used to minimize the objective function that is caculated by an in-house FORTRAN program. Every time upon being called by fmincon, the FORTRAN program numerically calculates the acoustic field with the impedance parameters that it receives as inputs using the CAA time-domain code. It then calculates the relative averaged difference between the two fields as defined in Eq. (5). The difference is returned to fmincon as the value of the objective function. Many calls may be needed before the optimization process is terminated when the magnitude of the directional derivative in the search direction is less than 2×10^{-9} while all of the constraints are satisfied. The small magnitude indicates the optimization accuracy.

To test the optimization process, several desired acoustic fields are proposed for three different mean flow conditions: no mean flow; a uniform mean flow, $M_x = 0.8$ and $M_y = 0$; and a sheared mean flow, $M_x(y) = 0.8 \sin[(\pi/2)(y/40)]$ and $M_y = 0$. For each of the mean flow conditions, the desired acoustic fields for unperturbed and perturbed cases are specified as follows. For the unperturbed cases, the desired acoustic fields are calculated by the CAA code for a given set of impedance parameters shown as exact in Table 1.

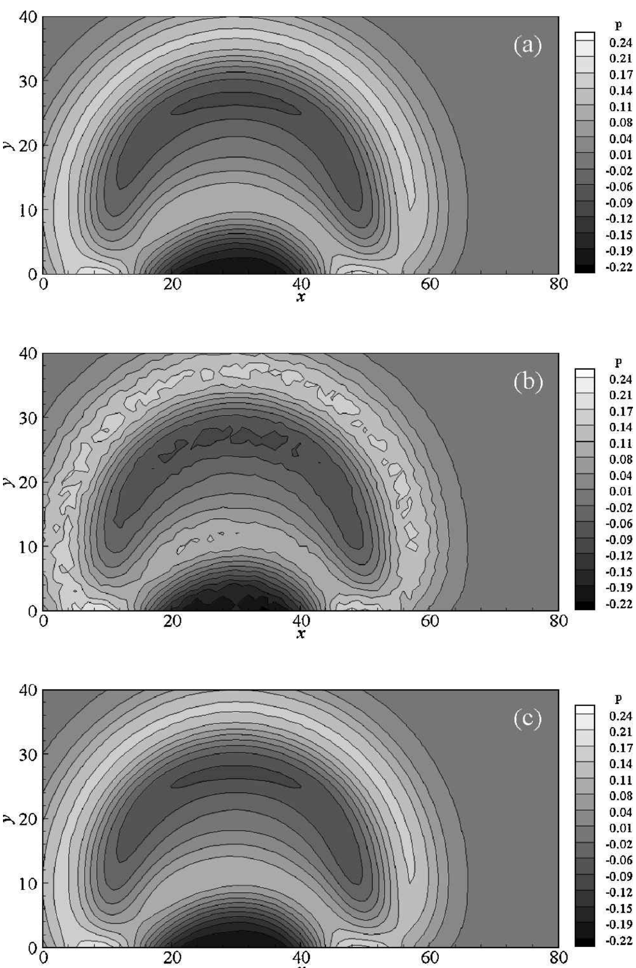

Fig. 4 Acoustic pressure fields at $t = 25$ without mean flow: a) unperturbed desired, b) perturbed desired, and c) optimized (resultant) for the perturbed desired.

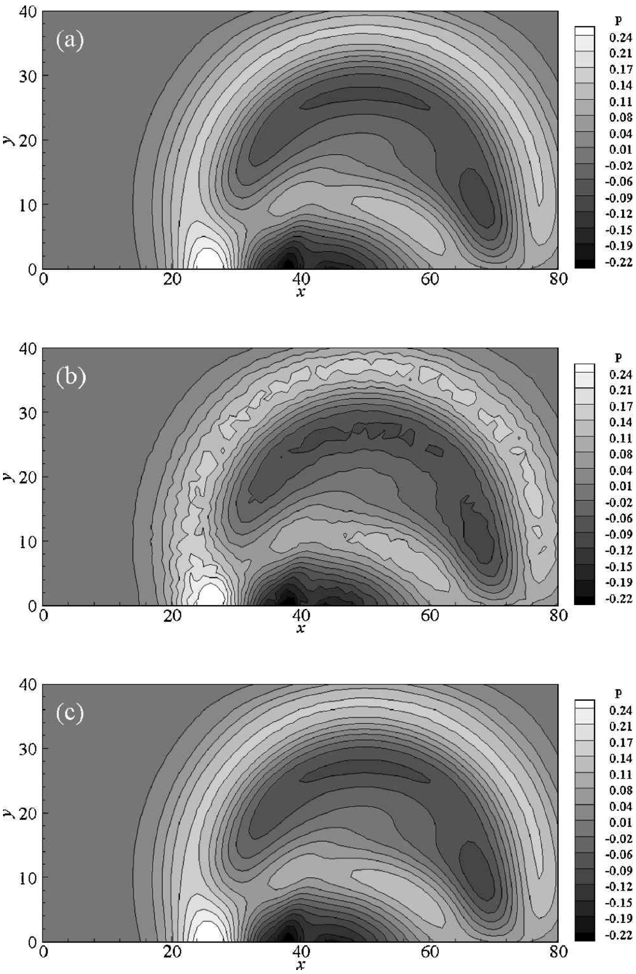

Fig. 5 Acoustic pressure fields at $t = 25$ with a uniform mean flow of $M_x = 0.8$ and $M_y = 0$: a) unperturbed desired, b) perturbed desired, and c) optimized (resultant) for the perturbed desired.

These desired acoustic fields for unperturbed cases are shown in Figs. 4a, 5a, and 6a, respectively, for the three mean flow conditions. For the perturbed cases, the desired acoustic fields are defined as the addition of the desired acoustic fields of the corresponding unperturbed cases and a uniformly distributed random perturbation within 10% of the local acoustic pressure. These desired acoustic fields for the perturbed cases are shown in Figures 4b, 5b and 6b. Figure 7a shows another desired acoustic pressure field achieved by uniformly decreasing by 10% the local acoustic pressure of the unperturbed desired acoustic field with the sheared mean flow in Fig. 6a. After obtaining the desired acoustic fields for all of the cases, we then reverse the process to find out the required impedance parameters by using the optimization process.

For all of the desired acoustic fields, we quite arbitrarily choose $R_0 = 1$, $X_{-1} = -1$, and $X_1 = 1$, only to satisfy the physical constraints, as the initial guess for all of the simulated cases. Note from Table 1 that the values of the initial guess are sufficiently far away from the optimized impedance parameters. Other initial guesses have also been tried, and essentially the same results have been obtained. Therefore, we would like to say that the global optimum is achieved. The optimization was performed on a personal computer with an Athlon XP 1800+ CPU at 1533 MHz and 512-MB memory. It took about 10 min of CPU time for each of the simulated cases. The optimization results are shown in Table 1.

In Table 1, unperturbed optimized is used for the unperturbed cases and perturbed optimized is used for the perturbed cases. For the unperturbed cases, the resultant acoustic pressure fields with these optimized impedance parameters are visually undistinguishable from those shown in Figs. 4a, 5a, and 6a, respectively, and thus are not presented. The values of the impedance parameters for the

Table 1 Values for the impedance parameters

Cases	Segment	R_0	X_{-1}	X_1	D
All, exact	1	0.20000000	−0.47576471	2.09383333	
	2	0.10000000	−0.23788235	1.04691667	
No mean flow					
Unperturbed optimized	1	0.19999880	−0.47576529	2.09383775	6.01E−07
	2	0.09999081	−0.23788437	1.04693702	
Perturbed optimized	1	0.19766536	−0.47855838	2.11890414	5.00E−02
	2	0.12036436	−0.23173582	0.98874926	
Uniform mean flow					
Unperturbed optimized	1	0.19999997	−0.47576475	2.09383192	5.18E−07
	2	0.09999943	−0.23788338	1.04692421	
Perturbed optimized	1	0.19583255	−0.47632917	2.10251175	5.08E−02
	2	0.10042433	−0.23866052	1.04792525	
Sheared mean flow					
Unperturbed optimized	1	0.19999945	−0.47576487	2.09383427	2.42E−07
	2	0.09999810	−0.23788297	1.04692207	
Perturbed optimized	1	0.20011584	−0.47660989	2.09708747	5.04E−02
	2	0.09269976	−0.24189526	1.07151848	
Modified optimized	1	0.30733303	−0.46104729	2.04534607	8.96E−02
	2	0.16058164	−0.22220306	0.93715973	

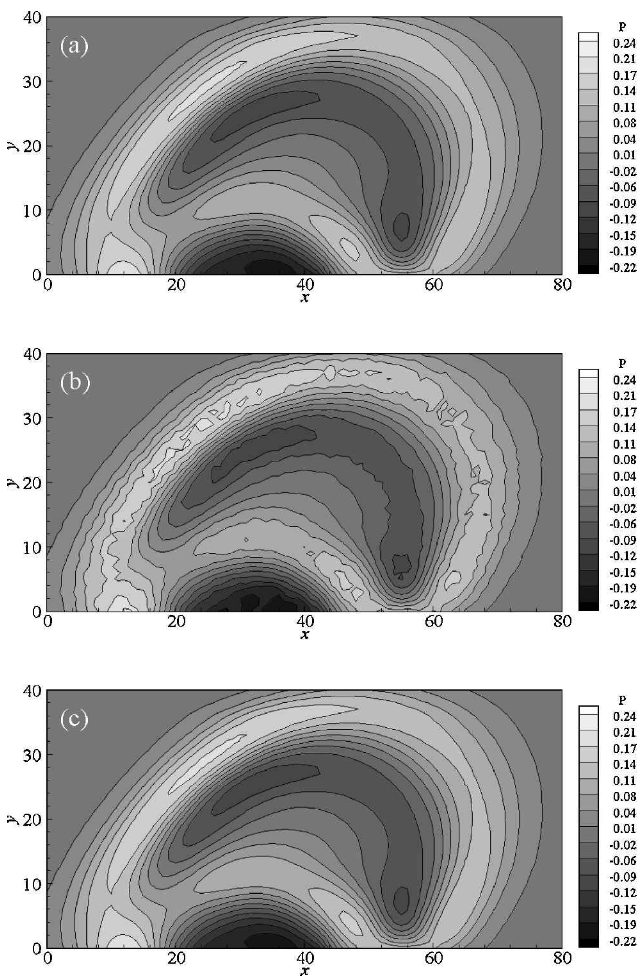

Fig. 6 Acoustic pressure fields at $t = 25$ with a sheared mean flow of $M_x(y) = 0.8\sin[(\pi/2)(y/40)]$ and $M_y = 0$: a) unperturbed desired, b) perturbed desired, and c) optimized (resultant) for the perturbed desired.

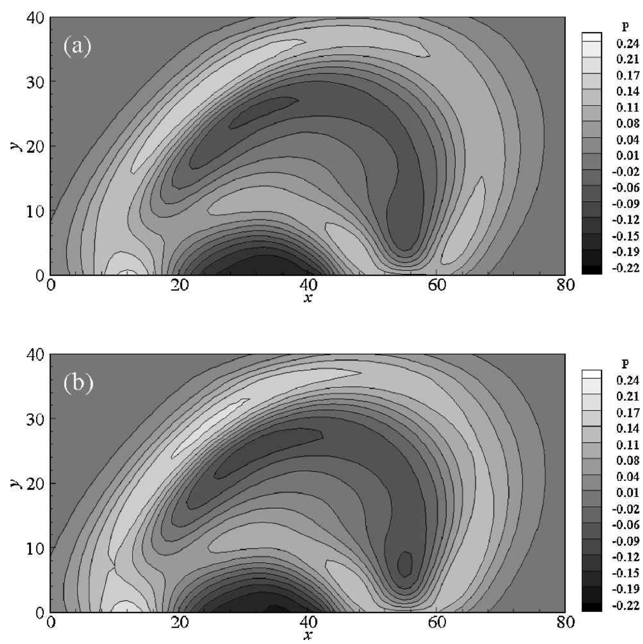

Fig. 7 Acoustic pressure fields at $t = 25$ with a sheared mean flow of $M_x(y) = 0.8\sin[(\pi/2)(y/40)]$ and $M_y = 0$: a) modified desired and b) optimized (resultant) for modified desired.

unperturbed cases are very accurately reproduced by the optimization procedure. It is shown in Table 1 that the objective function, or the relative averaged difference, defined in Eq. (5) is in the order of 10^{-7} for the three unperturbed cases, as compared to zero, the theoretically obtainable value. The small magnitudes of the relative error substantiate the accuracy of the optimization procedure. For the perturbed cases, the resultant acoustic fields with these optimized impedance parameters are shown in Figs. 4c, 5c, and 6c for the three different mean flow conditions. Note that these acoustic fields (Figs. 4c, 5c, and 6c) still resemble the desired acoustic fields for the unperturbed cases (Figs. 4a, 5a, and 6a). The resemblances can also be found with a comparison between the corresponding optimized impedance parameters for the perturbed cases (perturbed optimized in Table 1) and those impedance parameters (exact in Table 1) used to produce the desired acoustic fields for the unperturbed cases. These close resemblances result from that the averaged effects of the random perturbations in the desired acoustic fields for the perturbed cases nearly vanish.

For the desired acoustic pressure field shown in Fig. 7a, however, the averaged effect of the modification will not vanish. As might be expected, the resulting values of the impedance parameters (modified optimized in Table 1) are quite different from those (exact in Table 1) used to produce the desired acoustic field for the unperturbed case. As a result, the difference is also more obvious between the current acoustic pressure field shown in Fig. 7b and the unperturbed (unmodified) desired one shown in Fig. 6a.

For the perturbed or modified cases, an acoustic field that is identical to the desired one is even physically impossible, and thus it is reasonable that the minimized objective function is not as small as for the unperturbed cases. However, it is believed that the accuracy is good due to the small magnitude in the directional derivative and the evidence shown for the unperturbed cases.

IV. Conclusions

We have developed a conceptual design for adaptive noise control system through the coupling of a CAA time-domain method with an optimizer. Although the concept works for all kinds of liners with controllable impedance, a three-parameter (broadband) impedance model is used for the purpose of demonstration of the concept. The CAA time-domain method with the broadband impedance boundary condition serves as an accurate and efficient tool for simulating a broadband noise problem in time domain. Incorporating the CAA code with the optimizer, we have shown that the optimization procedure is able to predict the optimum impedance properties accurately and effectively for various desired acoustic fields and mean flow conditions.

References

[1]Parrott, T. L., Watson, W. R., and Jones, M. G., "Experimental Validation of a Two-Dimensional Shear Flow Model for Determining Acoustic Impedance," NASA TP 2679, May 1987.

[2]"Optimization Toolbox for Use with MATLAB®," Ver. 2.2, MathWorks, Natick, MA, 2002.

[3]Watson, W. R., Jones, M. G., and Parrott, T. L., "Validation of an Impedance Eduction Method in Flow," *AIAA Journal*, Vol. 37, No. 7, 1999, pp. 818–824.

[4]Watson, W. R., Tracy, M. B., Jones, M. G., and Parrott, T. L., "Impedance Eduction in the Presence of Shear Flow," AIAA Paper 2001-2263, May 2001.

[5]Ahuja, K. K., and Gaeta, R. J., Jr., "Active Control of Liner Impedance by Varying Perforate Orifice Geometry," NASA CR-2000-210633, Dec. 2000.

[6]Tam, C. K. W., and Auriault, L., "Time-Domain Impedance Boundary Conditions for Computational Aeroacoustics," *AIAA Journal*, Vol. 34, No. 5, 1996, pp. 917–923.

[7]Zheng, S., and Zhuang, M., "Application and Verification of Broadband Time Domain Impedance Boundary Conditions in Multi-Dimensional Acoustic Problems," AIAA Paper 2002-2593, June 2002.

[8]Zhuang, M., and Chen, R. F., "Applications of High-Order Optimized Upwind Schemes for Computational Aeroacoustics," *AIAA Journal*, Vol. 40, No. 3, 2002, pp. 443–449.

[9]Tam, C. K. W., and Webb, J. C., "Dispersion-Relation-Preserving Finite Difference Schemes for Computational Acoustics," *Journal of Computational Physics*, Vol. 107, No. 2, 1993, pp. 262–281.

[10]Tam, C. K. W., and Dong, Z., "Radiation and Outflow Boundary Conditions for Direct Computation of Acoustic and Flow Disturbances in a Nonuniform Mean Flow," *Journal of Computational Acoustics*, Vol. 4, No. 2, 1996, pp. 175–201.

W. J. Devenport
Associate Editor