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ACTIVE MINIMIZATION OF ENERGY DENSITY IN THREE-DIMENSIONAL ENCLOSURES

Performance Report

Dec. 1993- Dec. 1994

Principal Investigator

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I. Introduction

The objective of this research project is to further investigate and develop a novel approach for actively controlling the sound field in enclosures. Typically the acoustic field in an enclosure has been controlled by minimizing the sum of the squared pressures from several microphones distributed throughout the enclosure. The approach being investigated in this project involves minimizing the acoustic energy density at the sensor locations, rather than the squared pressure. Previous research[1] in a simple one-dimensional enclosure showed that improved global attenuation of the acoustic field is often obtained by minimizing the energy density, rather than the pressure. The current project builds on the previous research by extending the method of controlling the acoustic energy density to three-dimensional enclosures. The results will establish if improved control can still be expected in a more general enclosure. Pending successful results, the method could be applied to control problems such as attenuating the acoustic noise in an aircraft fuselage, an automobile cabin, or other general enclosures.

The research project was set up as a two-year project designed to achieve both numerical and experimental results. The primary focus of the first year of research (now being completed) was on the analytical/numerical modeling of the method of controlling the acoustic energy density. During the second year, the research focuses on experimental verification of the approach and extending our understanding of the method.

II. Overview of Tasks Completed or in Progress

In the research plan submitted for the project, there were several tasks outlined for the first year of the project. The project research is being largely performed by John W. Parkins, a Ph.D student in the Graduate Program in Acoustics at The Pennsylvania State University. Dr. Scott D. Sommerfeldt has been overseeing the project. He has been involved in a number of aspects of the research and in guiding students in their research efforts related to the project. During the past year, the following has been accomplished.

1) John Parkins has done a literature review on the subject of controlling enclosed sound fields.
2) Analytic/numerical models have been developed to estimate the effectiveness of the various types of control being investigated. These include controlling the global potential energy, the squared pressure at discrete sensor locations, and the acoustic energy density at discrete sensor locations. (These models and the results obtained are discussed below.)
3) A three-dimensional enclosure has been constructed for performing the research. The dimensions are 1.93 m $\times$ 1.54 m $\times$ 1.22 m. There are some additional improvements planned for the enclosure. However, we are scheduled to move to a new laboratory space in December 1994, and will wait until after the move to finish the improvements.
4) The hardware necessary to estimate the acoustic energy density in a three-dimensional field has been developed. A two-microphone technique is used for each direction, so

that a total of six microphones will be used for each sensor.

5) The DSP software for controlling the acoustic energy density in an enclosed field is currently nearing completion, and should be fully debugged and ready for use in December 1994.

III. Significant Research Results

There have been several significant results associated with the research performed during the past year outlined in this section. One of the major accomplishments has been the development of a model of the control approach. This model has aided greatly in developing a better understanding of the control mechanisms associated with controlling the energy density. The numerical model allows the user to specify the number of modes to be included in the model. We have found empirically that retaining one thousand modes in the model yields convergence for the modal summations. (Retaining two hundred modes produces results within about 1 dB of the converged solution, and can be used to quickly obtain general results.) The model also allows the user to specify the dimensions of the enclosure, the damping coefficient, and the locations of the sources and sensors. Any number of sensors and sources can be used, with the current limitation that the number of sensors must be greater than or equal to the number of sources. It is planned to modify the model in the near future to be able to remove this restriction.

There are several results that can be obtained from the model developed. One available output is the globally integrated potential energy in the enclosure as a function of frequency. The three control methods of minimizing the global potential energy, the squared pressure, and the energy density are all simulated in the program. This provides a measure of how effective the control approach is globally for each of the control methods being considered. A second output available is the spatial dependence of the pressure and energy density that results for each of the control methods. This allows the user to quickly determine spatial features, such as localized areas of attenuation and effects due to good or poor source/sensor locations.

Significant insight has been gained into the spatial dependence associated with sensor placement for controlling the energy density or the squared pressure. For axial modes, there will be nodal planes where the pressure vanishes, which represent poor locations for placing the sensors. On the other hand, the energy density is constant throughout the volume for an axial mode, so that there are no poor locations for placing the sensor. (Axial modes correspond to the previous one-dimensional research.) For tangential modes, there will be nodal planes in two directions, which again represent poor locations for placing the pressure sensors. The energy density is not constant for tangential modes, but instead of nodal planes, there are only energy density nodal lines, located where the pressure nodal planes intersect. As a result, there are poor locations where one can put the energy density sensor. However, these poor locations constitute a considerably smaller portion of the total enclosure volume than the pressure nodal planes. Similarly, for oblique modes, there are pressure nodal planes in all three directions. However, for energy density, there are only nodal points, where three orthogonal pressure nodal planes cross. The implication of this result is that if a small number of sensors are to be used, there is a much lower probability that an energy density sensor will be in a poor locations than there is for a pressure sensor. The simulation results that have been performed support this conclusion. If a small number of sensors are used, the method of minimizing the energy density will generally result in superior results. However, if a larger number of sensors are used, the point is reached where it makes little difference if energy density sensors are used or

pressure sensors are used.

An additional finding of the research is that when larger numbers of sensors are used, N energy density sensors will generally give performance comparable to about $4N$ pressure sensors. This suggests that fewer sensor sites can be used when using energy density, although perhaps not fewer total sensors, since energy density sensors involve multiple sensors. In many practical applications, the available locations for sensors can be rather limited. Since energy density sensors have less dependence on sensor location, they can be placed at the allowed locations and effective control can often be achieved with fewer sensor sites.

During the past year, the question was posed as to what the optimal sensor configuration would be if one had a given number of error sensors to minimize the global potential energy. Initially, a one-dimensional field was considered with two sensors that could be pressure and/or velocity sensors. It was found that the optimal configuration for two pressure sensors corresponds to having the sensors spaced $\lambda/4$ apart, where λ is the acoustic wavelength. However, a collocated pressure sensor and velocity sensor (i.e., energy density sensor) corresponds exactly with the two pressure sensors spaced $\lambda/4$ apart. A very important distinction, though, is that the pressure sensor spacing is frequency dependent, such that there is a different optimal configuration for each frequency of interest. Since the energy density sensor uses collocated sensors, no such frequency dependence exists for controlling the energy density. As a result, it may be argued that for one-dimensional fields, energy density sensors are the optimal discrete sensors to use for controlling the global acoustic field. A current research effort is to extend this analysis to three-dimensional fields to determine the optimal sensor configuration for four sensors. Our hypothesis is that the optimal configuration is to have four pressure sensors spaced $\lambda/4$ apart in the three orthogonal directions. If this hypothesis is true, the optimal configuration would be equivalent to the results obtained for an energy density sensor. Such a finding would suggest that energy density sensors may be the optimal discrete sensor for controlling three-dimensional enclosed sound fields.

To measure acoustic energy density requires a measure of both the pressure and particle velocity. During the past year, work has progressed to be able to measure all three particle velocity components for a three-dimensional field. A two-microphone technique has been adopted, similar to that used to measure acoustic intensity. The previous research in one-dimensional fields used a pair of phase-matched B&K microphones to obtain the velocity estimate. In an attempt to develop an inexpensive energy density sensor, a large number of Lectret LT 1207 A34 microphones were tested to find pairs of microphones that were closely matched. Analysis and testing have also shown that the phase matching of the microphones is not as critical for obtaining the energy density as it is for obtaining the acoustic intensity. As a result, by using pairs of microphones that are fairly closely phase-matched, they can be calibrated and used for estimating the energy density. There have been two alternate approaches developed for estimating the particle velocity from the microphone outputs. The velocity is proportional to the time integral of the spatial gradient of the pressure. One approach developed uses analog circuitry to subtract the outputs from the microphones (estimating the pressure gradient) and then to do an analog integration. The resulting signal is proportional to the particle velocity. The second approach does all the processing digitally. Both microphone signals are input to the DSP board, where they are subtracted and the result is digitally integrated. Both approaches have been tested experimentally and lead to favorable results. It has been found that the digital approach does generally work somewhat better, but both approaches are acceptable.

IV. Projected Research for 1995.

Experimental verification of the numerical results is scheduled to begin in January 1995. The necessary hardware and software developments are nearing completion, and should be in place by that time. Experimental configurations that correspond to numerical configurations studied will be tested to determine the agreement between theory and experiment. We anticipate that the experimental results obtained will provoke additional questions that we will also pursue analytically/ numerically to gain additional insights into the mechanisms associated with controlling acoustic energy density.

V. Abstracts of Publications

1. S. D. Sommerfeldt and J. W. Parkins, "Active control of energy density in three-dimensional enclosures," presented at 127th Meeting of the Acoustical Society of America, Cambridge, MA, June 1994.

   Attenuating the sound pressure at a microphone in an enclosure typically results in a relatively small region of control, often referred to as a zone of silence. In an effort to increase the region of control for practical applications, as many as 30-50 microphones have been used to achieve a broader region of control. An alternative control method for achieving global control of the field, based on sensing and minimizing the total energy density at discrete locations, has been developed. Previous work using this method in one-dimensional enclosures has indicated that significant improvement in overall attenuation is possible. This improvement can be attributed to the fact that sensing the energy density monitors all of the modes of the enclosure, and thereby avoids the spillover problem which often plagues control systems that minimize only pressure. The work reported here extends the energy density approach to three-dimensional, rectangular enclosures. Numerical results are presented to compare the global attenuation achieved by minimizing the energy density and acoustic pressure at single and multiple discrete locations. These results are also compared with the control that one would achieve by minimizing the total potential energy in the enclosure.

2. S. D. Sommerfeldt and J. W. Parkins, "An evaluation of active noise attenuation in rectangular enclosures," *Proceedings of Inter-Noise 94*, Yokohama, Japan, pp. 1351-1356, August 1994.

   A number of current problems of interest in active noise control involve the need to control the sound field in an enclosure. Attenuating the sound pressure at a microphone in the enclosure typically results in a relatively small region of control, often referred to as a zone of silence. In an effort to increase the region of control for practical applications, as many as 32-48 microphones have been used to achieve a broader region of control. In an attempt to simplify the control architecture, an alternative control method for achieving a more global control of the field has been developed. The method is based on sensing and minimizing the total energy density at discrete locations, rather than the squared pressure as has been done previously.

   Previous work using this energy density method in one-dimensional enclosures has indicated that significant improvement in the overall attenuation may be possible. This improvement can be attributed to the fact that sensing the energy density provides the capability of observing all modes contributing to the acoustic field. As a result of the increased

observability, the spillover problem that often leads to localized control when minimizing the pressure field is largely avoided.

In this paper, the energy density control approach is extended to three-dimensional rectangular enclosures. Numerical results are presented to compare the attenuation of the global potential energy that can be achieved by minimizing the energy density and the acoustic pressure in the enclosure. These results are also compared with the control that one would achieve by minimizing the total potential energy in the enclosure, which has been suggested as the optimal theoretical solution.

3. J. W. Parkins and S. D. Sommerfeldt, "Sensor location considerations for active noise control in enclosures," presented at 128th Meeting of the Acoustical Society of America, Austin, TX, November 1994.

Minimizing the squared pressure at a discrete point(s) is one method of achieving global control in an enclosure, but this strategy will fail when the error sensor(s) lie close to nodal planes of the pressure field. In this case, the secondary modes dominate the pressure measurement, and the active control will create a minimum with little consideration given to the dominant mode. Subsequently, primary mode amplification may result, and the total potential energy in the enclosure will increase. A control based on energy density, on the other hand, can generally sense the dominant mode when the error sensor is close to a pressure field nodal plane, due to its dependence on velocity as well as pressure. Nodal patterns of the energy density field consist of nodal lines and nodal points that lie on the pressure field nodal planes. At these locations, energy density measurements will also be dominated by the secondary modes, and may cause primary mode amplification. Computational results of pressure and energy density fields will be presented which provide insight to optimal error sensor placement for the two aforementioned control methods.

4. S. D. Sommerfeldt and J. W. Parkins, "Active control in three-dimensional enclosures using multiple secondary sources and error sensors," presented at 128th Meeting of the Acoustical Society of America, Austin, TX, November 1994.

The use of multiple secondary sources and multiple error sensors can significantly improve global attenuation whether one employs a control method based on the squared pressure or energy density. A single source positioned close to a pressure node will be inefficient at exciting the corresponding mode, therefore the secondary modes will dominate the pressure field, and attenuation is unlikely at the related frequency. Increasing the number of secondary sources improves the probability that at least one source will not lie close to a pressure node, thereby mitigating this problem. Problems also arise when error sensors are close to nodes. Adding multiple error sensors increases the probability that the sensors will be able to observe the dominant modes, which will yield improved attenuation. Using a greater number of error sensors than secondary sources will yield a determined control system, with a unique optimal solution. If more sources are used than sensors, an underdetermined control system will result which can be uniquely solved by adding more constraints to the system, such as minimum effort. The performance of the energy density versus squared pressure control methods are compared as they relate to the use of multiple secondary sources and multiple error sensors.

VI. Media Reports

1. "Actively pursuing quieter spaces," Penn State Intercom, Nov. 10, 1994. The research on actively controlling acoustic energy density was featured in this one page article in the *Focus on Research* section. (Penn State Intercom is a weekly publication for the faculty and staff of Penn State.)

2. Our research on active control of energy density was briefly reported in the Technology Bulletin section of Design News. (July 25, 1994).

3. Our research on active control of energy density was briefly reported in the Industry Outlook section of Aviation Week and Space Technology. (August 29, 1994).

VII. Reference

1. Nashif, P. J. "An energy-density-based control strategy for minimizing the sound field in enclosures," M.S. thesis, The Pennsylvania State University, University Park, PA (1992).