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ACTIVE CONTROL OF RADIATED SOUND POWER FROM A BAFFLED, RECTANGULAR PANEL

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1. INTRODUCTION

Reduction of radiated sound power is a desirable design objective in Active Structural Acoustic Control (ASAC), since sound power, unlike e.g. the sound pressure at a few far field positions, is a measure of the overall sound radiation. This paper describes active control of radiated sound power from a rectangular baffled panel radiating into free field, by minimisation of an accurate sound power estimate.

Pairs of piezoceramic patches bonded to the panel have been used as secondary sources, and the active control strategy has been investigated for pure tone excitation over a broad frequency range (60-600 Hz). Frequency domain simulations have shown that minimising an estimate of the radiated sound power obtained by discretised integration of the far field intensity with an array of eleven error microphones in front of the panel, is very close to minimising the actual radiated power from the panel. The Multiple Error Filtered-X LMS Algorithm has then been used in a practical setup to control secondary vibration sources in order to minimise such a microphone array estimate, and the actual reductions of radiated power from the panel have been determined with an intensity probe.

2. FREQUENCY DOMAIN MATRIX MODEL

The central part of the frequency domain model is the approximation of the sound radiation from the panel by an array of elementary sources. Each source is much smaller than the wavelength in air, radiates into free field and has a complex volume velocity corresponding to the panel normal velocity at the source position [1]. If $\mathbf{p}$ and $\mathbf{v}$ are vectors containing the complex pressures and normal velocities at each source position then $\mathbf{p}$ can be written as $\mathbf{p} = \mathbf{Z}\mathbf{v}$, where $\mathbf{Z}$ is a matrix of complex transfer impedances from source velocities to source pressure contributions, since the sound pressure at each source is the sum of contributions from all sources. The total radiated sound power is found as the sum of the power contributions from each source [2]:

$$W=\frac{S}{2}\mathrm{Re}\{\mathbf{v}^{\mathrm{H}}\mathbf{p}\}=\frac{S}{2}\mathrm{Re}\{\mathbf{v}^{\mathrm{H}}\mathbf{Z}\mathbf{v}\}=\frac{S}{4}\mathbf{v}^{\mathrm{H}}(\mathbf{Z}+\mathbf{Z}^{\mathrm{H}})\mathbf{v}=\frac{S}{2}\mathbf{v}^{\mathrm{H}}\mathrm{Re}\{\mathbf{Z}\}\mathbf{v}=\mathbf{v}^{\mathrm{H}}\mathbf{R}\mathbf{v} \qquad (1)$$

Here S is the elemental source area, superscript $^{\mathrm{H}}$ denotes the conjugate transpose and $\mathbf{R}=(S/2)\,\mathrm{Re}\{\mathbf{Z}\}$ is a real, symmetric radiation resistance matrix, dependent on the geometry of the panel. This matrix is easily calculated for a rectangular baffled panel (see [1] or [3]).

A far field estimate of the radiated sound power is found by a discretised integration of the far field intensity over a hemisphere in front of the panel, with an array of microphones. Each far field pressure is a sum of contributions from each panel elementary source, enabling the vector $\mathbf{p}_f$ of complex far field pressures to be written as $\mathbf{p}_f=\mathbf{D}\mathbf{v}$, where the elements of matrix $\mathbf{D}$ are complex transfer impedances. If the microphones cover areas of equal size S_f, an estimate of the power can be found as

$$W_f=\frac{S_f}{2\rho c}\mathbf{p}_f^{\mathrm{H}}\mathbf{p}_f=\frac{S_f}{2\rho c}\mathbf{v}^{\mathrm{H}}\mathbf{D}^{\mathrm{H}}\mathbf{D}\mathbf{v}=\mathbf{v}^{\mathrm{H}}\mathbf{R}_f\mathbf{v} \qquad (2)$$

where $\mathbf{R}_f=(S_f/2\rho c)\mathbf{D}^{\mathrm{H}}\mathbf{D}$. The panel normal velocity distribution can be approximated by a finite sum of structural modes, each with a given complex amplitude [4]. The panel is excited by a primary source (a point force) and a number of secondary sources (pairs of piezoceramic patches bonded to the panel). Each modal amplitude is found by superposition of the contributions from each source. If $\mathbf{a}$ is a vector of the modal amplitudes then $\mathbf{a}=\mathbf{a}_{\mathrm{prim}}+\mathbf{C}\mathbf{u}$, where $\mathbf{a}_{\mathrm{prim}}$ contains the primary source contributions, $\mathbf{u}$ is a vector of complex control signals for the secondary sources and $\mathbf{C}$ is a matrix of transfer functions between control signals and modal contributions of the secondary sources. The elements of $\mathbf{a}_{\mathrm{prim}}$ and $\mathbf{C}$ for a simply supported panel can be found in [5] and [6] or [3].

Each normal velocity is a function of all modal amplitudes so that $\mathbf{v}=\mathbf{\Phi}\mathbf{a}$, where the elements of the matrix $\mathbf{\Phi}$ depend on the mode shapes and elemental source positions. The radiated sound power can now be written as

$$W=\mathbf{a}^{\mathrm{H}}\mathbf{\Phi}^{\mathrm{H}}\mathbf{R}\mathbf{\Phi}\mathbf{a}=\mathbf{u}^{\mathrm{H}}\mathbf{C}^{\mathrm{H}}\mathbf{M}\mathbf{C}\mathbf{u}+\mathbf{u}^{\mathrm{H}}\mathbf{C}^{\mathrm{H}}\mathbf{M}\mathbf{a}_{\mathrm{prim}}+\mathbf{a}_{\mathrm{prim}}^{\mathrm{H}}\mathbf{M}\mathbf{C}\mathbf{u}+\mathbf{a}_{\mathrm{prim}}^{\mathrm{H}}\mathbf{M}\mathbf{a}_{\mathrm{prim}} \qquad (3)$$

where $\mathbf{M}=\mathbf{\Phi}^{\mathrm{H}}\mathbf{R}\mathbf{\Phi}$. Since $\mathbf{M}$ must be positive definite ($W\geq 0$), this standard Hermitian quadratic form has a unique minimum for an optimal set of secondary source control signals [7]:

$$\mathbf{u}_{\mathrm{opt}}=-[\mathbf{C}^{\mathrm{H}}\mathbf{M}\mathbf{C}]^{-1}\mathbf{C}^{\mathrm{H}}\mathbf{M}\mathbf{a}_{\mathrm{prim}} \qquad (4)$$

By inserting this optimal control signal vector in eq. (3), the minimum radiated power with a given configuration of secondary sources may be calculated. A set of control signals to minimise the far field power estimate can be determined in a similar way. By inserting this control vector in eq. (3), the actual radiated power after minimisation of the far field estimate is found.

3. SIMULATIONS

The frequency domain model has been implemented on a computer and used for active control simulations. A simply supported 430x260x1.5 mm aluminium panel configured with a primary source and two secondary piezoceramic sources has been modelled. Both primary and secondary sources have been positioned away from nodal lines of the panel modes in the examined frequency range, to ensure coupling to as many modes as possible. No further attempt has been made to optimize the source configuration.

Figure 1 shows the spectrum of the radiated sound power from the panel without control and with control by minimisation of three different cost functions: the actual radiated power and power estimates using three or eleven microphones distributed equally on a hemispherical surface in front of the panel. Minimising the actual radiated sound power results in a benchmark that can be used to evaluate the results of minimising the microphone array power estimates. When minimising the actual radiated power, considerable reductions of radiated power (up to 60 dB and typically 20-30 dB) are obtained at panel resonance frequencies throughout the investigated frequency range. At low frequencies (below 200 Hz) large reductions (12-20 dB) are also obtained between resonances, since the sound radiation is due to a few well-separated structural modes which can be controlled by the secondary sources.

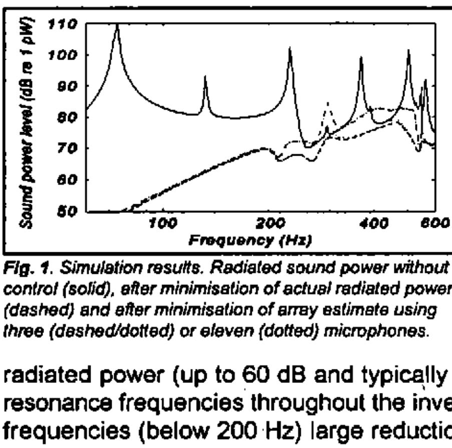

Fig. 1. Simulation results. Radiated sound power without control (solid), after minimisation of actual radiated power (dashed) and after minimisation of array estimate using three (dashed/dotted) or eleven (dotted) microphones.

Minimising the power estimate obtained with three microphones works well below 200 Hz, where the results are almost identical to those of minimising the actual power. Above 200 Hz using three microphones is clearly not sufficient to sample the more complex radiated sound field adequately. At some frequencies the radiated sound power is actually increased by up to 8 dB when the estimate is minimised. Increasing the number of microphones to eleven results in a very accurate power estimate. Minimising this estimate results in power reductions less than 1 dB from the optimal reductions obtained by minimisation of the actual radiated power, at all frequencies. This indicates that the reductions of sound power obtained by minimising the estimate from the array with eleven microphones are very close to what can maximally be obtained with the given configuration of secondary sources.

4. EXPERIMENTAL INVESTIGATIONS

An experimental setup with a baffled panel similar to that of the simulations has been built in an anechoic chamber. The Multiple Error Filtered-X LMS algorithm has been implemented on a DSP-board and used to control the two secondary piezoceramic actuators of the panel in order to minimise the power estimate determined with the array of eleven microphones. The actual radiated sound power with and without control has been measured with an intensity probe. Figure 2 shows the spectrum of the radiated sound power with and without control. The results are quite similar to those of the simulations, except that the reductions are smaller (30, 14 and 22 dB at the first three resonances). This is probably due to larger damping of the resonances in the experimental case. Around 450 Hz the active control is seen to increase the radiated sound power. This is caused by corruption of the sound power estimate due to unwanted sound radiation from the baffle. At high frequencies (above 400 Hz) reductions of about 8 dB are obtained.

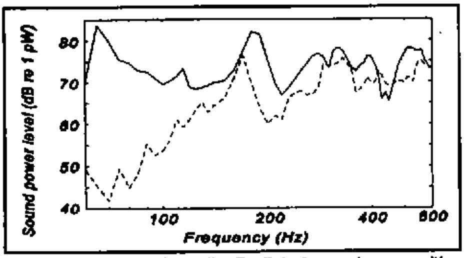

Fig. 2. Experimental results. Radiated sound power without control (solid) and with control (dashed), minimising eleven microphone power estimate.

5. CONCLUSIONS

Active control of radiated sound power from a rectangular baffled panel by minimisation of an accurate power estimate using piezoceramic actuators has been investigated. Computer simulations have shown that minimising a power estimate obtained by discretised integration of the far field intensity with an array of eleven microphones is very close to minimising the actual radiated sound power. Practical experiments with such an array have shown that substantial reductions of radiated sound power can be obtained over a broad frequency range using few piezoceramic actuators, provided that an accurate estimate of the sound power is avaliable for minimisation.

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