Control of Low Frequency Enclosed, Harmonic Sound Fields with Active Absorbers

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Introduction

Low frequency harmonic sound fields in enclosures can be controlled by a simple active absorber driven by an analog inverting amplifier. The control performance of a single and of multiple active absorbers is assessed in a rigid and in a damped rectangular room using total acoustic potential energy. The relationship between absorbed sound power and the feedback gain of a single active absorber is derived. The theory is shown to be in close agreement with experiment.

Prediction of Control Performance

The active absorber as shown in Figure 1 consists of a microphone located immediately adjacent to a loudspeaker. The microphone signal is used to drive the loudspeaker's volume velocity q_0 via a high-gain inverting power amplifier with gain G, thereby causing the pressure p_0 at the microphone to be driven towards a minimum. By analogy with passive absorbers, the behaviour of the active absorber can be completely described by its input impedance Z_A, which includes the impedance Z_ac of the loudspeaker given by the electro-acoustic analogy [2]

$$Z_\mathrm{A} = \frac{Z_\mathrm{ac}}{1-G} \; . \qquad (1)$$

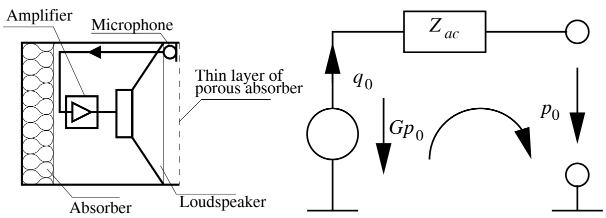

Figure 1: Sketch and electro-acoustic equivalent circuit of the active absorber

The solution to the inhomogeneous wave equation for the sound pressure $p(\vec{r})$ at a given point $\vec{r} = (x, y, z)$ in a rectangular room of the volume $V = l_x l_y l_z$ is normalised here by the volume velocity of the source q and written as a transfer impedance Z_T between source position $\vec{r}_\mathrm{S}$ and receiver position $\vec{r}$ as

$$Z_\mathrm{T}(\vec{r}_\mathrm{S}, \vec{r}) = \frac{p(\vec{r})}{q} = \frac{j\omega\varrho}{V} \sum_{n=0}^{\infty} \frac{\Psi_n(\vec{r}_\mathrm{S})\Psi_n(\vec{r})}{{k_n}^2 + j2k\delta_n/c - k^2} \; . \qquad (2)$$

The set of orthogonal eigenfunctions Ψ_n used for the rectangular rigid room can be found in [3]. Damping is accounted for by making use of complex eigenvalues K_n (valid for low damping) which are simplified here as ${K_n}^2 \approx {k_n}^2 + j2k\delta_n/c$ where the damping constant δ_n is a function of the complex wall admittance β as described in [4].

The sound field $\mathbf{p}$ written in matrix form (boldface letters) due to a superposition of N point sources with volume velocities $\mathbf{q}_\mathrm{S}$ and M point absorbers with volume velocities $\mathbf{q}_\mathrm{A}$ [1] using the transfer impedances $\mathbf{Z}_\mathrm{Sr}$ between the sources and the receiver positions and $\mathbf{Z}_\mathrm{Ar}$ between the active absorbers and the receiver positions from Equation (2) is given by

$$\mathbf{p} = \mathbf{Z}_\mathrm{Sr}\mathbf{q}_\mathrm{S} + \mathbf{Z}_\mathrm{Ar}\mathbf{q}_\mathrm{A} \; . \qquad (3)$$

The volume velocities $\mathbf{q}_\mathrm{A}$ of the active absorbers are unknown but can be derived by the fact, that they are related with the solution of the sound pressure $\mathbf{p}_\mathrm{A}$ at the active absorbers' positions by their impedances $\mathbf{Z}_\mathrm{A}$

$$\mathbf{p}_\mathrm{A} = \mathbf{Z}_\mathrm{SA}\mathbf{q}_\mathrm{S} + \mathbf{Z}_\mathrm{AA}\mathbf{q}_\mathrm{A} = -\mathbf{Z}_\mathrm{A}\mathbf{q}_\mathrm{A} \; . \qquad (4)$$

Solving Equation (4) for $\mathbf{q}_\mathrm{A}$ and inserting the result into Equation (3) yields the solution for the total sound field

$$\mathbf{p} = (\mathbf{Z}_\mathrm{Sr} - \mathbf{Z}_\mathrm{Ar}(\mathbf{Z}_\mathrm{AA} + \mathbf{Z}_\mathrm{A})^{-1}\mathbf{Z}_\mathrm{AS})\mathbf{q}_\mathrm{S} \; . \qquad (5)$$

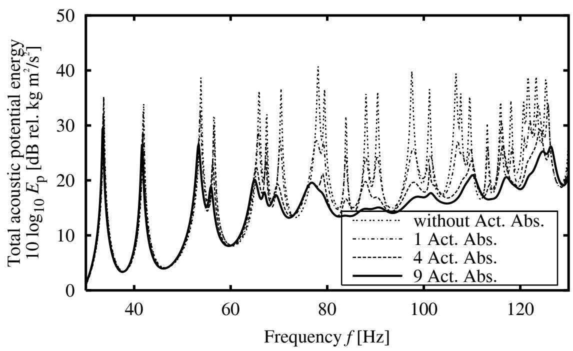

Figure 2: Total acoustic potential energy of a single source in a rigid-walled room ($V = 5 \times 4 \times 3\,\mathrm{m}^3$) before and after control with a single active absorber and a rectangular grid of 4 and 9 active absorbers distributed over one room surface

As shown in Figure 2 several modes of the room are reduced by more than 10 dB even with a single active absorber. The reduction of the total acoustic potential energy is higher for a larger number of active absorbers, however, the performance per unit absorber above a certain number of active absorbers starts to decrease [4]. The reduction in total acoustic potential energy is significantly smaller than in a rigid room when passive damping is introduced (Figure 3).

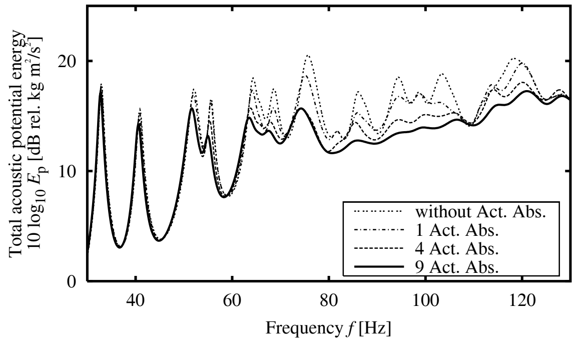

Figure 3: Total acoustic potential energy of a single source in a damped room ($V = 5 \times 4 \times 3\,\mathrm{m}^3$, $\beta \approx 0.01$) before and after control with a single active absorber and a rectangular grid of 4 and 9 active absorbers distributed over one room surface

Equation (6) gives the sound power which is absorbed by a single absorber in the presence of a single source. It shows that as well as being influenced by the radiation resistance $\Re\{Z_A\}$, the absorbed sound power is also depending on the location of the absorber and the source

$$W_A = -\frac{|q_S|^2}{2}\Re\{Z_A\}\frac{|Z_T(\vec{r}_S,\vec{r}_A)|^2}{|Z_A + Z_T(\vec{r}_A,\vec{r}_A)|^2}\,. \qquad (6)$$

Finding the maximum absorbed sound power for each frequency leads to an expression for the optimum gain of the active absorber

$$G_{opt} = 1 - \frac{|Z_{ac}|}{|Z_T(\vec{r}_A,\vec{r}_A)|} \qquad (7)$$

which is drawn in Figure 4 for varying amounts of damping.

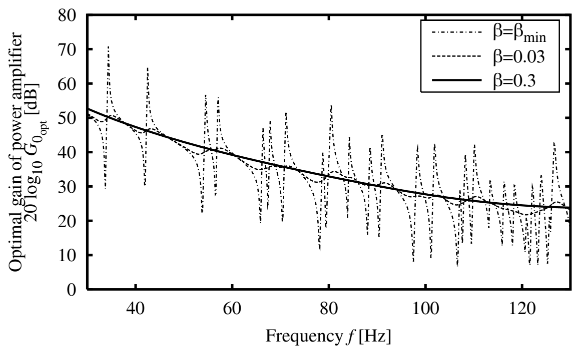

Figure 4: Optimum gain for maximum absorbed sound power W_A of a single active absorber and a single source in diagonal opposite corners of a room ($V = 5 \times 4 \times 3\mathrm{m}^3$) for varying amounts of passive damping

Experimental Results

The use of multiple active absorbers involves the mutual interaction between different absorbers, but also the presence of passive absorption greatly affects control performance. Significant reductions in total acoustic potential energy in the room are obtained by increasing the total number of active absorbers uniformly distributed over one surface of the room. The experiments show the reduction due to nine active absorbers in the rigid-walled room in Figure 5 where up to 28 dB reduction can be achieved for certain room modes. Figure 6 shows an example for the damped room, where the performance decreases to a maximum of 7 dB.

The experimental results for the reduction of total acoustic potential energy before and after control for nine active absorbers match predictions to a reasonable degree.

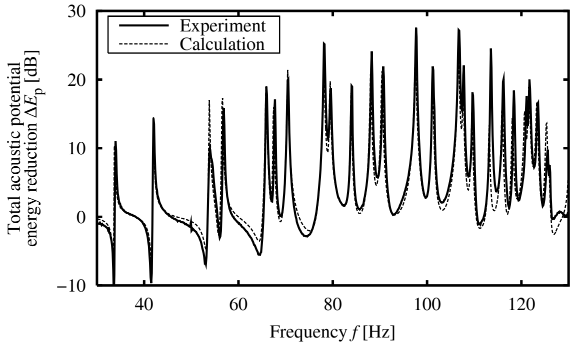

Figure 5: Reduction of total acoustic potential energy of a single source in the rigid-walled room due to a rectangular grid of 9 active absorbers distributed over one room surface

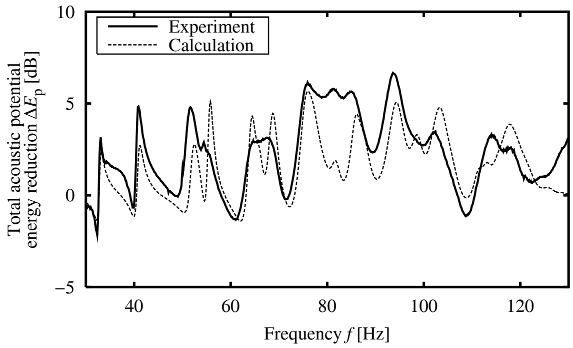

Figure 6: Reduction of total acoustic potential energy of a single source in the damped room ($\beta \approx 0.01$) due to a rectangular grid of 9 active absorbers distributed over one room surface

References

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