FEASIBILITY STUDY OF SOUND POWER BASED ACTIVE NOISE CONTROL STRATEGIES FOR GLOBAL NOISE REDUCTION

Seong-Woo Kang and Yang-Hann Kim

Center for Noise and Vibration Control(NOVIC)
Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology(KAIST)
Science Town, Taejon 305-701, Korea

ABSTRACT The active noise control which regards the acoustic power as a target function to be minimized, is analyzed to test its feasibility of which simplifies the measurement system compared with the global acoustic energy based active noise control system. In fact, it is found that the acoustic power based active noise control strategy is equally likely as good as the global acoustic energy based active noise control method if the acoustic field of interest is diffusive or very low modal density one. In the intermediate modal density field, we also demonstrate that the power based control gives the similar results as the energy based control in terms of global sound energy reduction for the lightly damped enclosure which might be most important system in practical application. From all the theoretical and numerical considerations, it is shown that the availability of the acoustic power based control strategy is dependent on *the characteristics of the acoustic field to be controlled*; i.e., the modal density distribution, the degree of reverberation, and on *the strength of modal interaction of the control source with the primary source*; i.e., the location of control source.

1. INTRODUCTION

The acoustic quantity which represents the ability to generate sound, is *sound power*. The active control of radiated sound power requires the information local to the sources themselves. This control strategy has been studied mainly in sound radiation problem in free space (the practical engineering applications of active control will, in general, not be a free field). On the other hand, the physical quantity which has been mostly used in practice in sound field control, is *sound energy*, in particular a acoustic potential energy for the most of practical applications. The active global control of sound energy requires informations about the entire sound field, for example the mean-square pressure averaged over the control volume. This type of acoustic control strategy has been widely investigated for various systems; air-conditioning ducts and enclosed spaces are the typical examples.

The active control of sound power might be simpler than controlling sound energy since only the local information of the source; sound power of the souces, is required in the control scheme. This rather simple hypothesis basically comes from the realization of which the sound energy of field is nothing but an expression of the effects of sound sources, in other word, sound power of sources. The other expression of this hypothesis can be to ask to oneslf; *"Does the reduction of sound energy/sound power requires or produces the reduction of sound power/sound energy?"* To find an appropriate answer for the question, one need to investigate the law of energy conservation in an arbitrary acoustic system; that is, the relation between the input/output sound power to the system and the sound energy contained in the system. If there is a simple direct proportionality between these two variables, then the two control strategies would find the same optimal solution. However, the acoustic field is not in general, since there are wave interferences in the acoustic field besides of the energy accumulation due to the power outputs of sources. Therefore, one has to consider the two physical principles simultaneously; mutual source coupling and wave interference, to find the relation between these two control strategies in terms of somewhat unified dialogue.

In this paper, we have tried to find the links between the sound power based active control strategy (which has some advantages in practical implementation) and the sound energy based one. Numerical examples for the simple one-dimensional duct with finite termination impedance are also presented for having rather realistic comparisons of the aforementioned active control strategies.

2. ACOUTIC POWER CONTROL STRATEGIES

A. Acoustic power

The time average of acoustic power radiated by the collection of sources of which each strength is q_i and on which the acoustic pressure is loaded by p_i, can be expressed as

$$< W > = \sum_i < p_i\, q_i > \tag{1}$$

where subscript i denotes the individual source position.

For simple harmonic waves, we can rewrite the acoustic power radiated with complex quantities

$$< W > = \sum_i \frac{1}{2} \mathrm{Re}\,[\, p_i\, q_i^* \,] \tag{2}$$

The time averaged acoustic powers from the primary and secondary sources which generate the simple harmonic waves as illustrated in Fig. 1, can be expressed as

$$< W_P > = \frac{1}{2} \mathrm{Re}\,[\, p_p\, q_p^* \,] \tag{3a}$$

$$< W_S > = \frac{1}{2} \mathrm{Re}\,[\, p_s\, q_s^* \,] \tag{3b}$$

$$< W_T > = < W_P > + < W_S > \tag{3c}$$

where

$$p_p = p\,(\vec{r}_p\,) = G^p_{pp}\, q_p + G^p_{ps}\, q_s \tag{4a}$$

$$p_s = p\,(\vec{r}_s\,) = G^p_{sp}\, q_p + G^p_{ss}\, q_s \tag{4b}$$

and the subscripts P, S and T represent the primary, secondary source and the total source power respectively.

Substitution of Eqs. (4a) and (4b) into (3a) to (3b) gives the acoustic powers in terms of the source strength and acoustic characteristic function between the both source position(i.e., G^p_{ij} where i, j = p or s).

$$< W_n > = q_s^*\, D_n\, q_s + q_s^*\, E_n\, q_p + q_s\, E_n^* q_p^* + q_p^*\, F_n\, q_p \quad \begin{cases} n = P & \text{for primary source power} \\ n = S & \text{for secondary source power} \\ n = T & \text{for total power} \end{cases} \tag{5}$$

where

$$D_P = 0 \tag{6a}$$
$$E_P = \frac{1}{4} G^{p*}_{ps} \tag{6b}$$
$$F_P = \frac{1}{2} R^p_{pp} \tag{6c}$$

and

$$D_S = \frac{1}{2} R^p_{ss} \tag{7a}$$
$$E_S = \frac{1}{4} G_{sp} \tag{7b}$$
$$F_S = 0 \tag{7c}$$

R represents the real part of G.
From the Eq.(3c), the coefficients D_T, E_T and F_T are as follows

$$D_T = D_P + D_S \tag{8a}$$
$$E_T = E_P + E_S \tag{8b}$$
$$F_T = F_P + F_S \tag{8c}$$

B. Active minimization

One can obtain the optimal secondary source strength to minimize the $< W_S >$ and $< W_T >$ which are quadratic with respect to the secondary source strength

$$q_{so}^{< W_n >} = (-)\frac{E_n}{D_n} q_p \qquad \begin{cases} n = S & \text{for secondary source power} \\ n = T & \text{for total power} \end{cases} \tag{9}$$

where $q_{so}^{< W_n >}$ means the optimal secondary source strength to minimize the time averaged sound power $< W_n >$ and the complex coefficients D_n and E_n are described in Eqs. (6) to (8). We can see that the optimal secondary source strength is linear transformation of the primary source strength as in the energy based control strategy. However the complex coefficient($- E_n/D_n$) in this case is simpler than one in energy based control case, since the local characteristic relation between the each source, not the global characteristic relation, is necessary. Therefore we can qualitatively deduce the fact that the power based control scheme might have simpler control structure than the energy based one.

When the secondary source is driven by $q_{so}^{< W_S >}$, it acts as the best *active sound absorber*. On the other hand, when the secondary source takes the complex strength $q_{so}^{< W_T >}$, it is not a sound absorber but a total *sound power minimizer*.

If acoustic reciprocity exists between each point in the acoustic field then under the optimal situations which minimize the total acoustic power of the two sources, the radiated power of the secondary source is exactly zero [1]. In other words, the secondary source neither radiates nor absorbs any net acoustic power. In fact, the source only modifies the radiation characteristics of the primary source to have the least radiation efficiency. It can be observed by substituting Eq. (9) into Eq. (5), that is

$$< W_S (q_{so}^{< W_T >}) > = \frac{| G^p_{ps} |^2 - | G^p_{sp} |^2}{R^p_{ss}} | q_p |^2 = 0 \tag{10}$$

if the acoustic reciprocity is guaranteed only between the two source positions, in other words, $G^p_{ps} = G^p_{sp}$. The result can be used to the practical application [2]. If one considers a multi-source case, in which all the primary sources are acting in phase, it can be also shown that the sound power output of each secondary source is zero.

3. NUMERICAL EXAMPLES

We compared the acoustic power control strategies with the acoustic energy based one. Figs. 3 and 4 illustrate the sound energy and the sound power fields before and after the global energy control(E_p–Control), total power control(W_T–Control), and secondary source power control (W_S–Control), are accomplished in a sample one-dimensional duct for the various termination conditions(Fig. 2). In the Figs. 3 and 4, $< W_T >$ and $< E_p >$ represent the total acoustic power and the global time averaged acoustic potential energy respectively.

From the Figs. 3a and 4a, we can see that the results(i.e., reductions of the global sound energy) of the total sound power control strategy(W_T–Control), approach to ones of the sound energy control(E_p–Control) as the acoustic field becomes reverberant.

It is clear from the results presented in the Figures, that power absorption by the secondary source(W_S–Control) is not a major mechanism of active control in intermediate modal density field. On the contrary, the method shows worse results than those of the other methods in terms of energy and power reduction.

In all control strategies and corresponding figures, the frequency regions in which are not controlled actively are due to the effect of the secondary source locations; weak modal interaction with the modes by the primary source.

4. CONCLUDING REMARKS

The sound energy and sound power based active control strategies were investigated by having one's attention on the latter which is easier to implement in practical circumstances than the former one. The two control strategies have some different aspects in each optimal situations in general. But if the acoustic field are very low modal density one or diffuse one(i.e., lightly damped and high modal density field), there is a direct proportionality between the sound energy and the sound power, so that the two control schemes give the same result although the best result will be limited evidently by the various factors of control configuration and the characteristics of the acoustic field. The sample numerical example showed the potential of the sound power based control strategy in the lightly damped intermediate modal density field.

However, it is worth to recall that the practical application of sound power based active noise control strategies is to be only feasible if one could measure the sound power of control source or sources. This might be done by placing an intensity probe in front of the control speaker. This just means that the measurement system for the active power control is not as simple as expected, or as practical as anticipated, due to its sophistication and cost. This contradiction is certainly a brawback of power based active noise control strategies.

REFERENCES

1. M.E.Johnson and S.J.Elliott. (1993). "Measurement of acoustic power output in the active control of sound," J. Acoust. Soc. Am. 93, 1453-1459.

2. S.-W. Kang and Y.-H. Kim, "A comparison of sound energy and sound power based active noise control strategies," submitted to J. Acoust. Soc. Am. 1993.

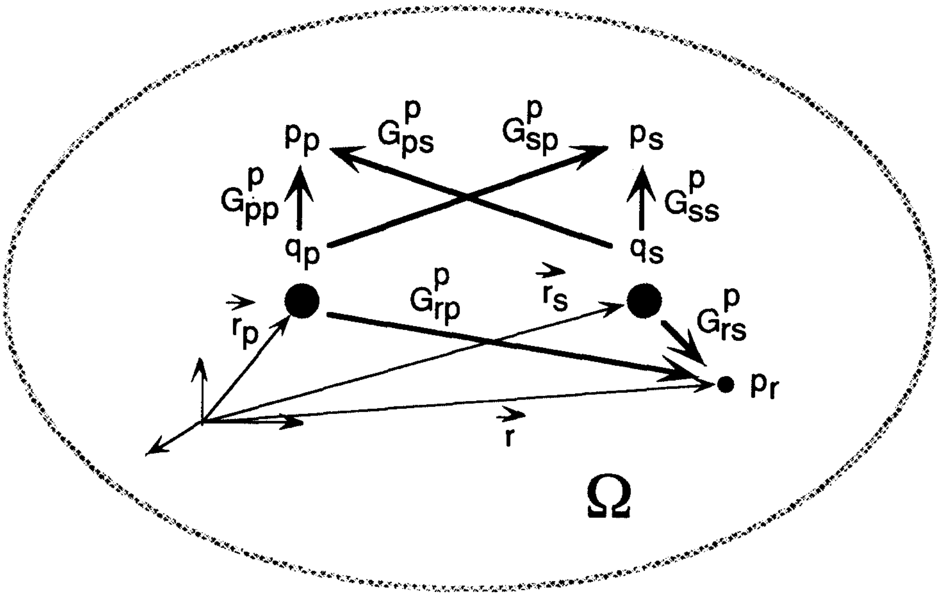

Fig. 1. The acoustic model which is composed with a primary source(q_p) at $\vec{r}_p$ and a secondary source(q_s) at $\vec{r}_s$ in the arbitrary domain(Ω).

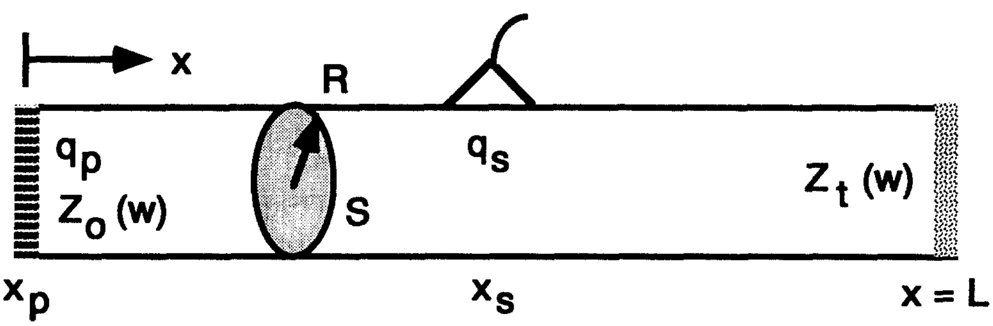

Fig. 2. One-dimensional finite circular duct with primary source impedance $Z_o(\omega)$ and termination impedance $Z_t(\omega)$ which has two compact sources; a primary source(q_p) at $x = x_p$ and a secondary source(q_s) at $x = x_s$; $L = 1$, $x_p = 0$, $x_s = 0.4$, $R = 0.08$ (unit: meter) and, $q_p = 2\times10^{-3}$ m^3/s.

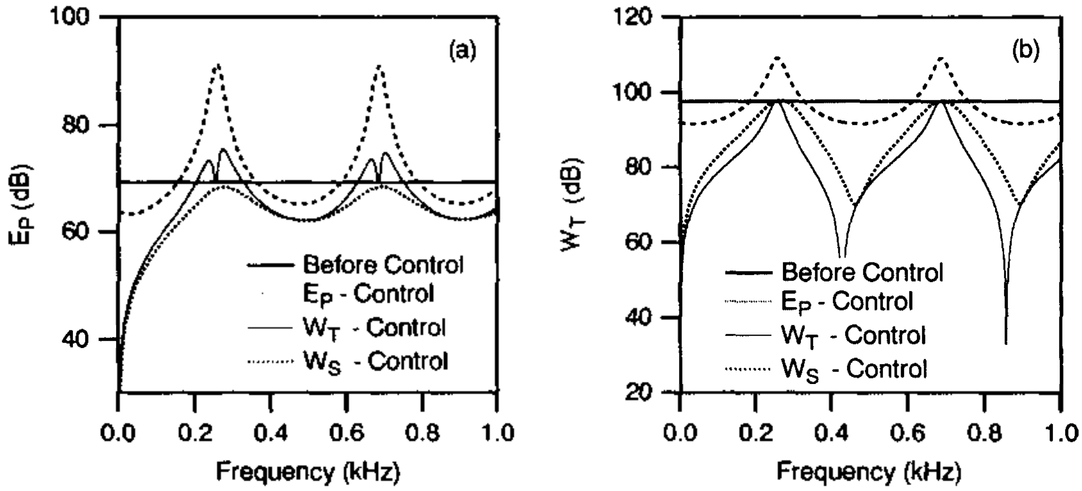

Fig. 3. Sound energy and sound power distributions before and after the energy based active control (E_p–Control), total power based one (W_T–Control), secondary source power or intensity based one (W_S–Control), are accomplished in the one-dimensional duct(Fig. 2) with primary source impedance $Z_o/\rho c = 0.2+j\cdot 3$ and termination impedance $Z_t/\rho c = 1+j\cdot 0$; anechoic end condition.

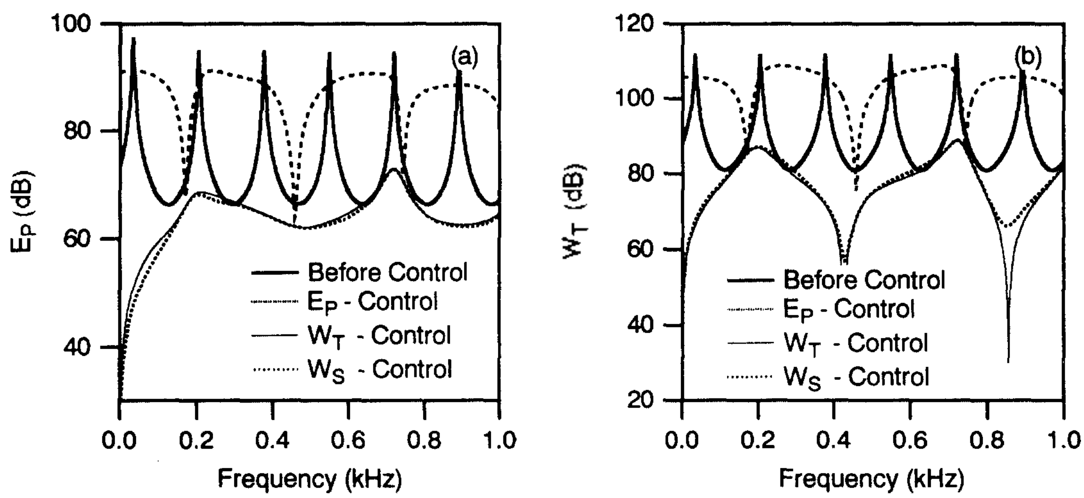

Fig. 4. Sound energy and sound power distributions before and after the energy based active control (E_p–Control), total power based one (W_T–Control), secondary source power or intensity based one (W_S–Control), are accomplished in the one-dimensional duct(Fig. 2) with primary source impedance $Z_o/\rho c = 0.2+j\cdot 3$ and termination impedance $Z_t/\rho c = 0.2+j\cdot 3$; lightly damped end condition.