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PREDICTION OF BREAKOUT NOISE FROM END PLATE OF AN EXPANSION CHAMBER USING COUPLED FE/BE ANALYSIS

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Abstract

Sound pressure levels of breakout noise due to flexible end plate of an expansion chamber are computed using coupled FE/BE analysis; boundary element method was used to obtain the pressure driving the end plate; coupled analysis was used to predict the vibration of the end plate, considering acoustic loading on both of its sides; acoustic pressure in the exterior field was computed using Rayleigh's integral. Inclusion of the chamber cavity in the geometry of the solution domain enabled consideration of actual pressure distribution over the end plate and acoustic loading on the interior side of the end plate. Cases corresponding to very high and very low values of the radiated sound pressure levels of breakout noise were analyzed. Conditions of coincidence were identified corresponding to the highest value of radiated sound pressure level of breakout noise. At coincidence, three conditions are fulfilled simultaneously. First, the excitation frequency and the natural frequency of vibration of the end plate are equal. Second, the excitation frequency and the resonance frequency of the chamber cavity are equal. Third, the mode-type of vibration of the end plate (axisymmetric or diametral) and nature of distribution of the driving pressure (axisymmetric or otherwise) match with each other. Based on these observations, precautions to be taken while designing expansion chamber mufflers are suggested so the breakout noise can be kept to a minimum.

Keywords: Coupled FE/BE analysis, breakout noise, expansion chamber, end plate

1. INTRODUCTION

Expansion chamber is an important acoustic element that is used in reactive mufflers. To save cost and weight, it is usually constructed from thin sheet metal. Hence, flexibility of the wall and the end plate is considerable. So they respond to acoustic excitation from within and thus radiate air-borne sound to the surrounding. This is termed as *breakout noise*. Breakout noise puts a limit on the insertion loss obtainable from a muffler, if it is not accounted for in the design. Importance of breakout noise in muffler design is discussed in the literature [1-4], but no rigorous study on this problem, to our knowledge, is reported.

Literature on expansion chamber as a noise-controlling device is rich. However, it only aims at studying the acoustic performance of expansion chamber mufflers with different configurations [5-9]. The flexibility of the walls and the end plate are not accounted for in most such analyses. There is no discussion in literature, to the authors' knowledge, dealing exclusively with the breakout noise from the end plate of an expansion chamber.

Literature on acoustic excitation of flexible structural members and subsequent transmission of sound is based on the assumption of plane wave incidence [10-13]. A plane wave, incident upon the junction of an expansion chamber and tail pipe, cannot remain plane at the junction. Because, a plane wave field cannot satisfy boundary conditions imposed by the discontinuity [14]. Also, higher order modes can be cut-on in the expansion chamber at higher frequencies. In case of acoustically short chambers, higher order modes that cut-on at the junction of the inlet tube and the expansion chamber do not die out before reaching the junction of the tail pipe and the expansion chamber [14,15]. Thus, assumption of uniform acoustic pressure driving a flexible endplate is not valid, in general. Method to compute the driving pressure for the end plate, presented in [16], is useful only for a circular geometry. For an arbitrary shaped expansion chamber, no such method is thus far reported.

This paper reports a study on prediction of breakout noise from the end plate of an expansion chamber muffler, using coupled FE/BE analysis; the boundary element method is used to obtain the pressure driving the end plate; coupled FE/BE analysis is used to predict the vibration of the end plate, considering acoustic loading on both sides; acoustic pressure in the exterior field is computed using Rayleigh's integral. Finite element equations for the end plate and the boundary element equations for the chamber cavity and the exterior field are coupled by the boundary conditions at the interfaces. Solution of the coupled equations provides response of the end plate, accounting for acoustic loading on both sides of the end plate. Sound pressure level at a certain point in the exterior field is computed using Rayleigh's integral, over a range of excitation frequencies.

2. COUPLED FE/BE ANALYSIS OF AN ACOUSTIC CAVITY

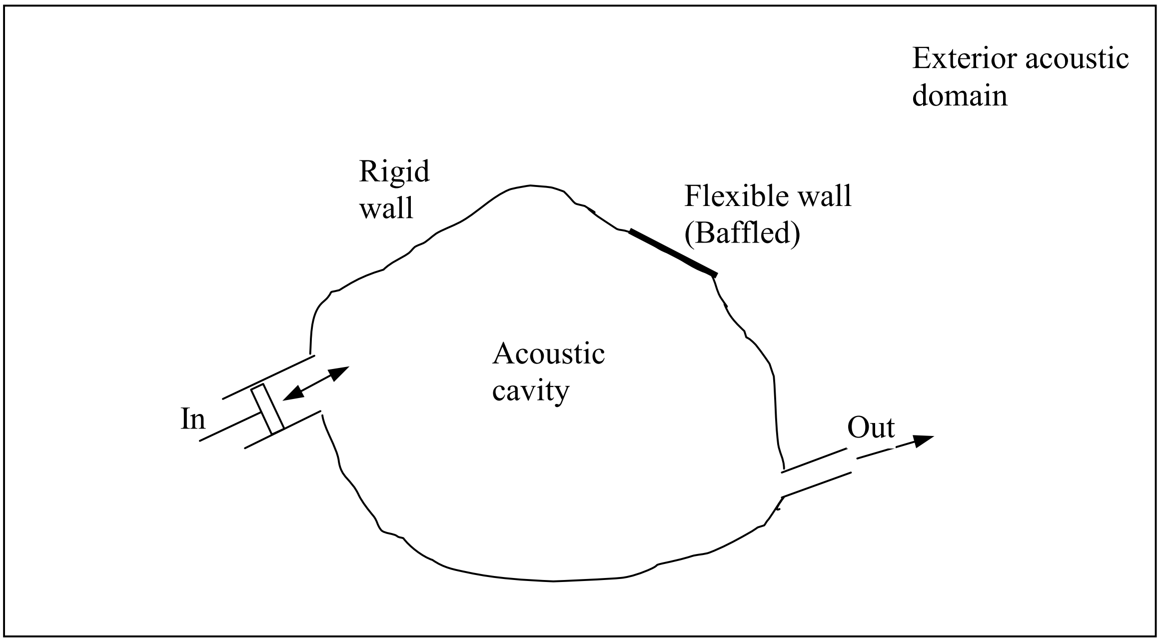

Figure1. Geometry of the problem

Figure 1 shows an acoustic cavity with two openings, marked as *In* and *Out*. The enclosure-wall is rigid except for a flexible portion, as shown. The flexible portion of the wall is assumed flat and baffled. Further, it is considered *thin*, so the classical plate theory can be applied. The rigid baffle is not shown in the figure. A harmonically reciprocating piston at the inlet drives the cavity, with a known value of acoustic pressure on its surface. A state of plane wave propagation is assumed at the inlet tube. The outlet termination is assumed to be anechoic and therefore the noise radiated to the surrounding from the tail pipe is not considered. In reality, the noise radiated from the tail pipe end and the breakout noise will combine, resulting in reduced insertion loss. The flexible part of the enclosure-wall will be excited due to the acoustic field inside the cavity. There will be acoustic loading on both sides of the portion of the wall under consideration. The problem is to estimate the sound pressure level at a point in the exterior field, due to the vibration of the flexible wall. This essentially involves estimation of the amplitude and distribution of driving pressure over the wall and obtaining its response, accounting for the acoustic loading on both sides. Sound pressure level at any point in the exterior field can then be obtained using Rayleigh's integral.

Analytical approach to solve such a problem leads to lengthy mathematical equations and may have to be eventually approximated [10, 11]. Therefore, many researchers have discussed the advantages of coupled FE/BE analysis for problems of structure-fluid interaction, similar to the one under consideration [13, 17-21]. Hence, a coupled FE/BE analysis was used in the present case. This method comprises of finite element analysis for the structural part and boundary element method for the acoustic domains, coupled at the interfaces by suitable boundary conditions.

The method of analysis presented here, for the problem stated above, neglects existence of the outlet tube while computing the response of the end plate and radiation field in the exterior. Moreover, structural or any other damping of the end plate is neglected, while radiation damping due to the fluid-structure interaction is included in the formulation. Furthermore, effects due to flow and viscosity of gases flowing through the expansion chamber are neglected.

The major steps in implementation of the analysis can be summed up as follows:

1. Entire wall of the cavity is assumed rigid. Plane wave pressure, of known amplitude and frequency, is considered at the inlet. Nodal values of the pressure at the inner surface of the flexible portion of the wall are computed using the boundary element method. These are taken as the values of the *driving pressure* for the flexible wall.
2. Coupled FE/BE analysis for the acoustic domains and the flexible wall is carried out using the values of the driving pressure obtained from step 1.
3. Radiated sound pressure, at a selected point in the exterior field, is computed using the values of displacement of the end plate obtained from step 2.
4. Steps 1 through 3 are repeated for discrete frequencies, in a range of frequencies with suitable step size.

The stiffness, mass and acoustic-loading matrices obtained from FE analysis of the end plate are independent of the excitation frequency. However, the matrices in BE analysis are frequency-dependent and therefore need to be computed at all values of the input excitation frequencies. The BE-matrices at any frequency are used twice, once each at steps 1 and 2.

3. BREAKOUT NOISE FROM END PLATE OF AN EXPANSION CHAMBER

The formulation described in earlier sections was applied to predict the breakout noise from the flexible end plate of an expansion chamber used in reactive mufflers with rigid walls. Though the formulation is valid for geometry of any arbitrary shape of the cavity, a simple expansion chamber was considered. A 3-D analysis was performed for the axi-symmetric case, for ease of comparison of some of the results with those available in the existing literature.

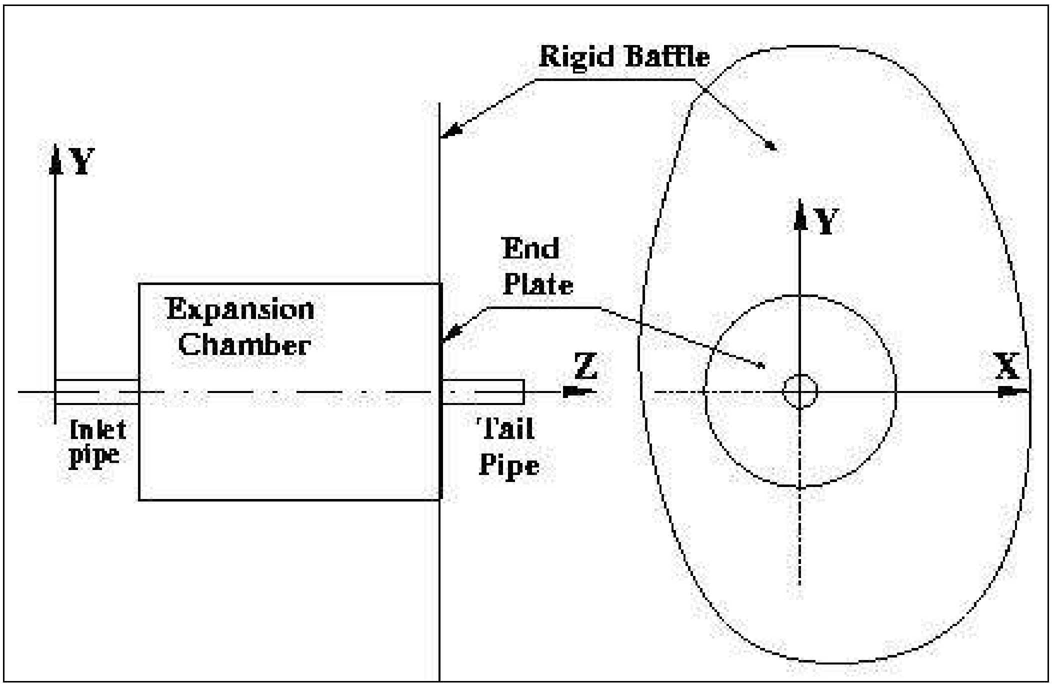

Figure 2. Geometry and solution domains of the problem

Figure 2 shows a schematic of the expansion chamber with end plate fitted in a rigid baffle of infinite extent- a thick line identifies the end plate. Sound pressure level at a selected point in the exterior field, due to vibration of the end plate, was computed. Right-handed coordinate system is followed, with origin at the center of the inlet to the expansion chamber and z-axis coinciding with the axis of the expansion chamber and pointing towards the exterior field. The outer edge of the end plate was treated as fixed and the inner one, free.

4. RESULTS AND DISCUSSION

As the insertion loss is generally measured at a distance of 1 *m*, the sound pressure level of the breakout noise was computed at a point, 1 *m* away and on the axis of the end plate. Computations were carried out at frequencies over a frequency range of 20 *Hz* to 2 *kHz*, with a step size of 20 *Hz*. The plot is shown in Figure 3.

The greatest value of the radiated sound pressure at 420 Hz, corresponds to the condition of coincidence, when $\omega = \omega_{EP}$, $\omega = \omega_{Ex,}$ and the type of modes of vibration of the end plate and nature of distribution of the driving pressure are matching. At the coincidence, the type of mode of vibration of the end plate and nature of distribution of the driving pressure are both axi-symmetric. At 100 and 1620 Hz, one of these three conditions is not fulfilled resulting in comparatively lower values of the radiated pressure. At 360 Hz, two of the conditions are not met that resulted in still lower value of the breakout noise. At 920 Hz, the value of the radiated pressure is the lowest, as none of the three conditions are met. Thus, it is the coincidence, as mentioned earlier, that governs the value of the radiated pressure of the *break out noise*.

It is worthwhile to put some general observations as follows. Due to the circular cross-section and concentric inlet, excitation of only axi-symmetric duct modes was found. This is in line with the established results, found in literature [22, 23]. So also the excited modes of the end plate were axi-symmetric. Hence high values of the radiated pressure were corresponding to the axi-symmetric modes (circular modes) of the end plate.

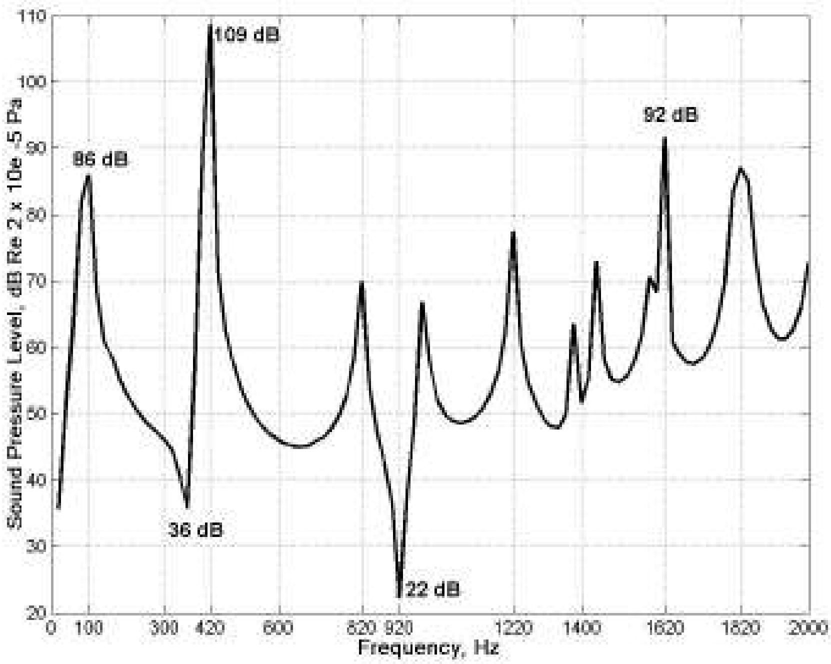

Figure 3. Breakout noise level at a point 1 m away from the centre of the end plate and on the axis of the end plate.

5. CONCLUSIONS

An attempt has been made to predict the breakout noise from the end plate of an expansion chamber using coupled FE/BE analysis. The phenomenon of the breakout noise is presented in quantitative terms and its dependence on the system parameters is analyzed.

The breakout noise levels corresponding to certain frequencies in the range considered was quite high, reaching a value of 109 *dB* at 420 *Hz*. The high value of the breakout noise at this frequency corresponds to the coincidence when the excitation frequency is closer to some of the eigen-frequencies of the end plate and the expansion chamber, simultaneously, and the pressure distribution over the end plate matches with the corresponding mode-type of the end plate. The pressure distribution and the corresponding mode-type were both axisymmetric.

There are three conditions governing the coincidence: frequency of acoustic excitation being equal to one of the natural frequencies of the end plate and the chamber cavity and the driving pressure distribution matching the corresponding mode-type of vibration of the end plate. The mode matching is important in deciding the coupling between the end plate and the acoustic medium. Breakout noise level at frequencies of 100 *Hz* and 1620 *Hz* is high compared to that of other frequencies in the range considered. But it is not as high as that under the condition of coincidence at 420 Hz. This is attributed to the lack of one of the conditions stated for the coincidence. At 100 Hz, excitation frequency is not equal to resonance frequency of the chamber, resulting in lower values of the driving pressure. At 1620 Hz, though the resonance frequencies of the end plate and the expansion chamber are both equal to the excitation frequency, corresponding mode of the end plate did not match with the pressure distribution. For other cases, the noise level is not very significant - for conditions far from the coincidence, it is negligible.

The predicted values of the breakout noise suggest that the phenomenon cannot be neglected and it can be intense under the condition of coincidence. Hence, a check must be applied at the design stage for probable coincidence between the eigen frequencies of the end plate and the expansion chamber, and the presence of corresponding frequency components in the spectrum of the noise to be controlled. Further, the type of corresponding modes of vibration and location of the inlet to expansion chamber should be observed. Because, the nature of distribution of the driving pressure over the end plate at higher frequencies (on cut-on of higher modes) are decided by the location of the inlet to the expansion chamber.

The driving pressure varies over the surface of the end plate, though the variation is small at lower frequencies. This justifies the inclusion of the chamber cavity in the solution domain, at the cost of high computational time. This also facilitates consideration of acoustic loading on the inner side. Due to the generality of the FE/BE formulation used, the analysis presented here is applicable to an expansion chamber of any complex geometry and locations of the inlet and outlet tubes.

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