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Technical note

Prediction of noise inside an acoustic cavity of elongated shape using statistical energy analyses with spatial decay consideration

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A B S T R A C T

In this paper, Statistical Energy Analysis (SEA) is used to predict the interior noise of an acoustic cavity of elongated shape. The disadvantage of the conventional SEA method, which quantifies the response in terms of the energy averaged over each subsystem, is overcome by introducing a one-dimensional spatial decay relation, through which information about the acoustic energy variation in the elongated direction is taken into account. The modified SEA is experimentally validated using a 1:5 scaled space station prototype, having the longitudinal dimension much larger than the cross-sectional dimension. It is also compared with a model reported in the literature. It is shown that, in the region where the acoustic pressure level decays at a constant rate, the two models agree well with each other and are capable of estimating the acoustic pressure variation along the space station cabin. However, near the end walls where the decay rate of the acoustic pressure level is not constant, the proposed model provides better accuracy.

1. Introduction

The overwhelming noise to which astronauts are exposed in space station becomes a growing concern in long-term space travel missions. Excessive noise interferes with communication, disrupts concentration and reduces operation performance, impacting on the well-being of the crew on board. A systematic acoustic control strategy for the quietness of the space station should therefore be developed in the design stage to avoid remedial actions after launch.

Prediction of the acoustic pressure level as well as its distribution inside the space station is an indispensable part of a successful implementation of the acoustic control strategy. There are various prediction tools available for interior noise problems: Boundary Element Method [1] and Finite Element Method [2] are suitable for low frequency noise prediction; SEA [3] is appropriate for high frequencies; and some hybrid methods [4–7], which bridge the gap between low and high frequency ranges, are developed for mid-frequency problems. It is the objective of this paper to predict the interior noise of a space station at high frequencies where explicit prediction tools like BEM or FEM become computationally expensive.

Standard SEA formulation has been well documented in many textbooks, for example Lyon [8] and Craik [9]. The condition that allows the implementation of SEA is that, at high frequencies, energy is distributed uniformly within each subsystem. In connection with this assumption, it is fairly acceptable to use a single quantity, usually the mean energy, to quantify a subsystem response. This ensemble representation, however, becomes an obstacle to observing the spatial variation in the subsystem as the difference in energy level could only occur between different subsystems. An example in which such a need is required would be the design of a space station, where the information about the acoustic energy distribution in the compartment would be crucial for designers to plan a less noisy sleeping area for astronauts. A space station compartment constitutes intrinsically an air volume and thus it is a straightforward practice to subdivide this air volume into a number of SEA subsystems. However, considerable debate arises over the validation of this practice. Fahy [10] made a comment on the validity of subdividing an air volume into SEA subsystems. In that note, one major concern is that the contiguous subsystems, defined by the artificially introduced interfaces, are not weakly coupled because these interfaces represent no geometry or material discontinuities. The subsystems, in this case, vibrate in a global manner and the system behaviour should not be interpreted in terms of coupled 'local' subsystems. It is suggested that the practice of subdivision may only be justified within limited frequency band.

Apart from subdividing a system, solution to the spatial information could also be pursued through post-processing the SEA result. This, in turn, relies on a priori knowledge of the acoustic characteristics of the subsystems. This supplementary information,

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in fact, could be acquired from the subsystem itself. For instance, the interior noise problem of a vehicle in which the main body features an acoustic cavity of elongated shape could benefit from acoustic knowledge on corridors. It is found, in room acoustics, that the acoustic pressure in a room that has one dimension dominant over other dimensions exhibits a certain decay pattern, starting from the point where the source is placed [11]. Forssén et al. [12] made use of this information and introduced a constant decay relation, derived by Redmore [13] for a corridor, to the standard SEA model to predict the acoustic pressure level in a railway train. Validation on a scale model showed that the modified SEA model could be able to visualize the acoustic variation across the train compartments. Despite the improved accuracy, discrepancy was still identified at the terminating boundaries where the effect of end walls of the enclosure is substantial. Indeed, Kang [14] demonstrated that in long enclosures the reverberation time increases sharply to a maximum and then decreases slightly with the increase of source-to-receiver distance. This variation eventually results in a longitudinal acoustic pressure decay expression different from that derived by Redmore. Picaut et al. [15] then developed an expression, based on a diffusion model, to quantify the variation of the acoustic energy in a long room, with experimental result showing that the model allows for the spatial variation to be predicted with a better precision.

In this paper, an improved SEA model would be developed by introducing the spatial sound pressure decay relation [15] into the standard SEA framework for predicting the interior noise of a space station of elongated shape. Inheriting the appealing feature of the SEA, the modified approach allows an efficient handling of the complex system whilst providing sound pressure variation within the main cavity. The paper is structured as follows: Section 2 gives a description of the prototype of the space station for scale model validation; a modified SEA model to which the spatial variation relation of the acoustic pressure is introduced would be developed in Section 3; in Section 4, the model is validated in the scale model and conclusions are drawn in Section 5.

2. Description of the space station model

A 1:5 scale model of a space station is depicted in Fig. 1. The major part of the prototype consists of two rectangular air cavities aligned in a row, representing the crew compartment in a space station. In view of the similar cross sections of the two air cavities, it is assumed that they constitute a single long air cavity, with its length being the sum of the lengths of the two cavities and the cross-sectional area being the average of those of the two cavities. The long air cavity is coupled, through a circular opening with a radius of 0.07 m, to an irregular-shaped cavity on top inside which a loudspeaker is placed to represent the noise emitted by the air ventilation system, a major noise generator in space stations [16]. Except the arc part, which is made of a 10 mm thick aluminum structure, the walls enclosing the air volume are made of 30 mm thick acrylic panels. A Cartesian coordinate system is used with the origin set at the middle of the far end wall of the long cavity. The geometry information about the two air volumes is given in Table 1.

Table 1
Geometry information of the two air volumes.

	Volume	Surface area
Long air cavity	$1.8 \times 0.35 \times 0.4\ m^3$	$2.98\ m^2$
Irregular air cavity	$0.027\ m^3$	$0.584\ m^2$

3. Formulation of the problem

For calculating the system response using SEA, the whole prototype is divided into two subsystems, being respectively, the irregular air cavity (subsystem 1) and the long air cavity (subsystem 2). The former, hosting a noise source inside, has an irregular shape, while the latter is a rectangular cavity having one dimension much larger than the others. The two subsystems are coupled through an acoustic opening that represents the passage for air ventilation, and it is assumed that the acoustic energy is by no means transmitted through other paths but this opening. The objective of this work is to predict the acoustic pressure level in the cabin and its spatial variation in the longitudinal direction. This is accomplished by, first solving the standard SEA model for subsystem energy of the cabin, and then introducing a spatial variation relation, based on the expression of the acoustic energy decay in a long cavity developed by Picaut et al. [15], to the subsystem.

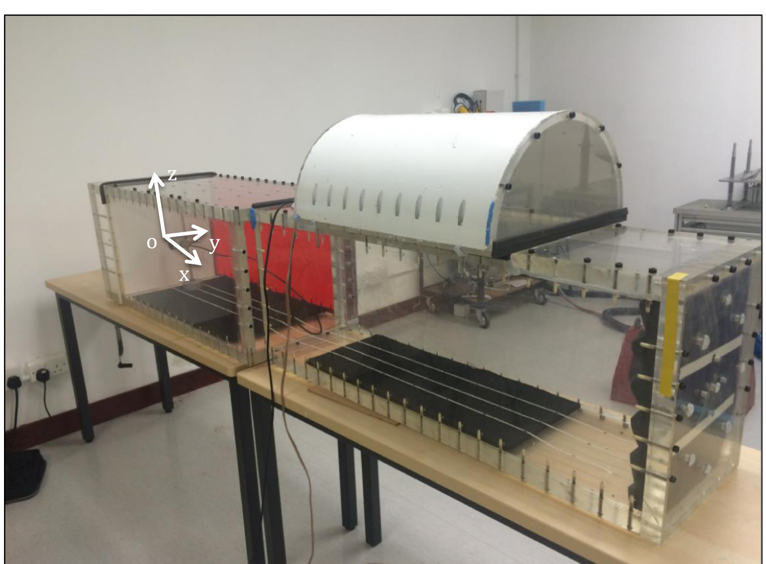

Fig. 1. The 1:5 scale model of the space station prototype.