Journal of Sound and Vibration 363 (2016) 181–198

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Acoustic resonances in a 3D open cavity with non-parallel walls

S. Ortiz [a], L.M. González [b], C. González Díaz [a], U.P. Svensson [c], P. Cobo [a,*]

[a] Instituto de Tecnologías Físicas y de la Información (ITEFI), CSIC, Serrano 144, 28006 Madrid, Spain
[b] Escuela Técnica Superior de Ingeniería Naval, Universidad Politécnica de Madrid, Plaza Cardenal Cisneros, 28040 Madrid, Spain
[c] NTNU – Norwegian University of Science and Technology, Department of Electronics and Telecommunications, NO-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 13 March 2015
Received in revised form
5 November 2015
Accepted 6 November 2015
Handling Editor: D. Juve
Available online 28 November 2015

ABSTRACT

This paper extends the Image Source Model (ISM) to an open cavity with non-parallel walls by including edge diffraction. Explicit expressions are deduced for the calculation of the IS positions for two non-parallel walls. The addition of the other two walls is done iteratively, while the floor is taken into account in the same way as in a rectangular cavity with parallel walls. The edge diffraction effect is included in the model by generating first order diffraction components for each IS. This model is then used to calculate the impulse response at any point inside or outside the open cavity. The time response at such a point is obtained by the convolution of the impulse response and the source waveform. The acoustic resonance frequencies of the open cavity are extracted from the peaks of the Frequency Response Function (FRF), obtained as the Fourier transform of the corresponding time response between a point source and any point in the cavity. The acoustic resonance frequencies estimated by the ISM+edge diffraction are validated by comparison with those provided by a Finite Element Method (FEM) and the ones measured experimentally, differing less than 1.6 percent and 2.7 percent, respectively. As a comparison, resonance frequencies estimated with the pure ISM differ by 5.7 percent from the measured ones.

1. Introduction

The interaction of a flow with an open cavity is of certain interest both in aeroacoustics and noise control [1,2]. A horizontal flow over an open cavity induces acoustic waves, either by a feedback mechanism between the upstream and downstream edges or by triggering its resonant modes. An energy exchange between acoustic waves and vorticity arises, with a net transfer in favour of the acoustic type. Thus, the main consequence of the flow over the open cavity is the generation of cavity noise [3]. High amplitude cavity tones are radiated by, for instance, the wheel well and auxiliary power

Abbreviations: ed, edge diffraction; ed-spr, edge diffraction specularly; FEM, Finite Element Method; FRF, Frequency Response Function; IS, Image Source; ISM, Image Source Model; LA, Limit Anticlockwise; LC, Limit Clockwise; PML, Perfectly Matching Layer; PO, Polygon Originated; PVE, Potentially Visible Edges; PVP, Potentially Visible Polygons; PVS, Potentially Visible Set; spr-ed-spr, specularly edge diffraction specularly; VCP, Virtual Crossing Point

* Corresponding author. Tel.: +34 91 5618806; fax: +34 91 4117856.
E-mail address: pedro.cobo@csic.es (P. Cobo).

http://dx.doi.org/10.1016/j.jsv.2015.11.013

unit compartments during the airplane landing and take off operations, the bogie section and the shallow cavity accommodating the pantograph of a high speed train, or the open sunroofs and open windows of a car driven at high speed.

The mechanisms underlying the radiation of cavity tones in a shear flow were well elucidated by Rossiter [2] and Plumbee et al. [1]. Rossiter considered that cavity noise is the result of acoustic feedback. An acoustic pulse is generated when the vortices that shed periodically from the upstream edge of the cavity convect downstream and impinges the aft wall of the cavity. Plumbee et al. suggested that it is the shear layer that provides a broadband source to excite resonant modes of the cavity. Both approaches provide an expression to calculate the frequencies of the generated cavity tones, as a function of the cavity dimensions (length, width and depth) and the Mach number (ratio of the flow velocity to the sound velocity).

Therefore, both the frequency and the amplitude of the cavity tones should be a function of the Mach number, M. Koch [4] and Hein et al. [5] claimed that the dependence of the frequency on the flow velocity can be neglected at low Mach numbers. Lauterbach et al. [6] have also demonstrated that the correlation between cavity tone resonance frequencies and flow velocity is very weak for $0.05 < M < 0.3$. They observed that, in this Mach number range, the resonance frequencies of the tones generated at a scaled bogie section in a wind tunnel were, essentially, independent of the flow velocity. Notice that $M = 0.3$ corresponds to a flow velocity of roughly 103 m/s, or 370 km/h.

For noise control purposes, it is crucial to predict in advance the frequency response of an open cavity. Thus, in the low subsonic regime, if the flow can be neglected, the more complex aeroacoustic problem can become a simpler, purely acoustic problem. This hypothesis was assumed by Koch [4] and Hein et al. [5] to calculate the resonance frequencies of 2D and 3D rectangular open cavities by solving numerically the wave equation by the Finite Element Method (FEM). To avoid reflections at the numerical boundaries of the computational grid, a Perfectly Matching Layer (PML) condition was employed [7]. González et al. [8] compared the resonance frequencies of a 2D open cavity predicted by this FEM–PML method with those measured experimentally inside an anechoic room, obtaining excellent agreement.

This FEM–PML method performs simulations in the frequency domain providing the acoustic resonance frequencies of the cavity by eigenvalue analysis of a stiffness matrix. The computational cost of such an FEM method increases rapidly with frequency. A more efficient method at high frequencies, which is formulated in the time domain, is the Image Source Model (ISM). Ortiz et al. [9] applied this method to calculate the impulse response between any source–receiver pair in a 3D rectangular open cavity. The time response at any point is then obtained by the convolution of this impulse response with the loudspeaker waveform. The FRF between the source–receiver pair can then be simply obtained by transforming this time response to the frequency domain by taking the Fourier transform. The significant peaks of this FRF were identified as the acoustic resonance frequencies of the cavity. The experimentally measured resonance frequencies inside the 3D cavity showed a reasonable agreement with those computed by the ISM model. The experimentally measured modes were also compared with the computed modes showing a good accord, except for near the cavity opening, due to the lack of edge diffraction in the ISM model. The resonance frequencies of the 3D rectangular open cavity computed by ISM were also compared with those predicted by the FEM–PML method with relative errors less than 3 percent [10].

A rectangular 2D or 3D open cavity without including the edge diffraction effect is a rather simplified model of a real cavity. Thus, the main purpose of this paper is to add edge diffractions effect to the ISM model of an open cavity with non-parallel walls. The acoustic resonance frequencies provided by this model will then be compared with those given by the FEM–PML model and those that are experimentally measured in an anechoic room.

The outline of the paper is as follows. First, the details of the application of the ISM and FEM–PML models to analyse the acoustic field in an open cavity with inclined walls are given in Section 2. After that, the experimental measurements carried out inside and outside the open cavity are described in Section 3. The comparison of the measured frequency resonances with these provided by the ISM and FEM–PML models is then presented in Section 4. The main conclusions of this study are summarized in Section 5.

2. Models

Let us consider a cavity with non-parallel lateral walls and depth D, open at the top side. The floor and opening of the cavity are rectangular with dimensions (L_b,W_b) and (L_t,W_t) respectively, see Fig. 1. A three-dimensional Cartesian coordinate system (X,Y,Z) with the origin at the centre of the cavity floor, is also shown in Fig. 1. The front and rear walls subtend an angle θ_f with the plane XZ, and the lateral walls form an angle θ_l with the plane YZ. A point source S is positioned at the front wall of the cavity, with coordinates (x_S,y_S,z_S). The problem consists of calculating the sound signal for the receiver R, with coordinates (x_R,y_R,z_R), at any point inside or outside the open cavity. A baffle is situated around the open wall of the cavity in order to give well defined single edges at the opening, rather than the double edges resulting from an opening without baffle.

2.1. Image Source Model and first order edge diffraction

The time signal measured at the receiver R will be

$$y(t,\mathbf{r}) = x(t) * h(t,\mathbf{r},\mathbf{s}), \tag{1}$$