Journal of Sound and Vibration 420 (2018) 204–226

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Vibroacoustic study of a point-constrained plate mounted in a duct

Swapnil L. Sapkale [a], Mahesh M. Sucheendran [b,*], Shakti S. Gupta [c], Shantanu V. Kanade [d]

[a] Department of Aerospace Engineering, Defence Institute of Advanced Technology, Pune, 411025, India
[b] Department of Mechanical and Aerospace Engineering, Indian Institute of Technology, Hyderabad, Telangana, 502285, India
[c] Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Uttar Pradesh, 208016, India
[d] College of Engineering, Pune, 411005, India

ARTICLE INFO

Article history:
Received 9 July 2017
Revised 21 January 2018
Accepted 22 January 2018
Available online 3 February 2018

Keywords:
Vibroacoustics
Plate vibration
Mode-localization
Duct acoustics
Transmission loss

ABSTRACT

The vibroacoustic study of the interaction of sound with a point-constrained, simply-supported square plate is considered in this paper. The plate is mounted flush on one of the walls of an infinite duct of rectangular cross section and is backed by a cavity. The plate response and the acoustic field is predicted by solving the coupled governing equations using modal expansion with the relevant eigenmodes of the plate dynamics and acoustic fields in the duct and cavity. By varying the location of the point constraint, the frequency characteristics of the transmission loss in the duct can be tuned. The point constraint can also alter the amplitude and spectral characteristics of the plate's response. Interestingly, some new peaks are observed in the response because of the excitation of unsymmetric modes which are otherwise dormant. Mode-localization phenomenon, which is the localization of vibration in specific regions of the plate, is observed for selected constrained points.

1. Introduction

Sound propagates as an unsteady pressure fluctuation in a fluid medium which is characterized by its speed, frequency and wave number. Such fluctuating pressure acting on an elastic structure, forces it to vibrate. This modifies the pressure field in the vicinity of the structure and beyond. For thin structures, this acoustic radiation can be comparable in magnitude to the elastic and inertial loads acting on the structure. Thus the radiation loading can significantly modify the forces acting on the structure. Since, the radiated acoustic pressure depends on the structure's velocity, a coupling between the pressure field in the fluid and the structure's response exists. This demands that both the domains have to be solved simultaneously. This is an example of two-way coupled problem, and approaches a more practical scenario of vibroacoustics [1].

Acoustics of ducts has been extensively studied because of its relevance in many engineering applications [2]. Noise from HVAC ducts is a practical situation where the vibroacoustics of thin plates is significant [3]. Use of light weight material for constructing the air-conditioning ducts can result in noise breaking out from the ducts leading to personnel discomfort. Considering the limitation of sound absorbers and active noise cancellation at low frequencies, Huang and Choy investigated the use of tensioned membrane backed by a cavity for sound reflection in a duct [4]. Huang also investigated the structural-acoustic interaction of plane sound waves with plates instead of membranes [5]. The plate velocity was computed for acoustically com-

* Corresponding author.
E-mail addresses: sl.sapkale@gmail.com (S.L. Sapkale), mahesh@iith.ac.in (M.M. Sucheendran), ssgupta@iitk.ac.in (S.S. Gupta), shantanuvk1@gmail.com (S.V. Kanade).

https://doi.org/10.1016/j.jsv.2018.01.043
0022-460X/

pact and non-compact plates for frequencies lower than the cut-on frequency of the duct. Results for root mean square velocity showed strong coupling between sound and flexural waves resulting in enhanced transmission loss in the duct. In a similar context Xie *et al.* [6] did the vibroacoustic analysis of irregular shaped cavity and thin plates. With the aim of noise control within the cabins, the vibroacoustic for plates surrounded by a light or heavy fluid was investigated. Acoustic metamaterials have been a topic of interest to researchers involved with the study of acoustics as is evident from the focus it has received recently [7]. Among their multiple applications, it has been proposed to use them for sound isolation using acoustically small structures. Huang *et al.* have proposed membrane and plate type acoustic metamaterials used for enhanced control of transmission loss [8]. Farooqui *et al.* investigated locally resonant patches for low frequency noise attenuation in ducts [9].

Another example of vibroacoustics, having detrimental effects on the life of aircraft, is the fatigue failure of its skin panels. Fatigue occurs when lightly damped resonant vibration modes of the panels fall within the excitation bandwidth of the acoustic input. Sonic fatigue problems range from cracking of secondary structures to flight safety critical failures of primary structures. Numerous examples of such failures exists in the aviation history, some of which are reported in the literature. An example of such an issue was reported for F-15 aircrafts by Levrea *et al.* [10]. The damage on the upper-outer wing skin of the aircraft is an example of sonic fatigue in primary structures. Bryan and Ahuja [11] and the references therein discuss about the problems of acoustic fatigue experienced by aerospace structures. Hence, the response prediction of thin plates subjected to acoustic loads is necessary for the development of fatigue-tolerant aerospace structures [12]. This is especially true in the case of hypersonic vehicles due to extremely high, unsteady, thermal and acoustic loadings involved [13]. Towards this, several experimental, numerical and theoretical studies have been conducted to determine the structural-acoustic response of plates. A method for testing thin panels to acoustic loads consists of placing them in a duct at grazing incidence to the incident sound [13–16]. To control the frequencies that are excited, the plate is sometimes backed by a cavity with rigid walls [6,17,18]. In the late 1990s, the Structural Division at Air Force Research Laboratory (AFRL) began a project called Durability Patch to evaluate experimentally the performance of damped, adhesively bonded patches to repair sonic fatigue damage in aircraft skin panels [19]. In a similar context, the progressive wave tube facility at NASA Langley Research Center, known as the Thermal Acoustic Fatigue Apparatus, has been used to support development of the thermal protection system for the Space Shuttle and National Aerospace Plane [20].

To understand the vibroacoustics of thin plates, various theoretical, numerical and experimental investigations have been carried out. Strawderman [21] investigated turbulence-induced plate vibrations for infinite and finite plates. They examined the effect of the fluid density on the coupling of the *in vacuo* plate modes. Sound radiation from turbulence-excited thin plates in the light fluid limit has been studied by Davies [22] using modal analysis and focused on the radiation damping contribution to the modal coefficients. This topic continues to get researchers' interest, since external flow remains a major source of cabin noise of commercial jet-powered aircraft during cruise flight. Liao and Ma carried out an in-depth analysis of vibration characteristic of rectangular plates in compressible, inviscid fluids [23]. They studied the dynamic characteristics of a thin plate placed at the bottom of a three-dimensional rectangular container filled with fluid. Rocha [24] investigated the impact of using different empirical models for the turbulent boundary layer wall pressure fluctuations on the radiated sound power and power spectrum of aircraft panels. Ostoich *et al.* investigated the coupled response of thin structures to hypersonic flows using direct numerical simulations which was computationally expensive [25,26]. Research towards development of computationally efficient reduced-order models from CFD and FEM solvers that identify and retain only the relevant physics is maturing and is being applied to coupled problems [27,28].

The vibration control of thin panels can be broadly classified as either active or passive. The active vibration control method uses feedback control systems for precise vibration control, however, they have limitations on practical implementation for aircraft panels. Passive vibration control methods like local stiffening, application of viscoelastic materials and adding a local mass have been used in various situations. Having a point constraint in the plate has a locally stiffening effect as can be seen from the analysis of such plates by Bapat and Suryanarayan [29]. Filoche and Mayboroda [30] discovered strong mode localization in a clamped plate made of an isotropic material having fixed points on an interior line perpendicular to the plate mid-surface. With the objective of comparing mode localization in isotropic material to that of the fiber-reinforced laminates, Sharma *et al.* [31] investigated constrained composite plates of varying fiber orientations. It was found that fixing the interior points divided the laminas into two independently vibrating regions, one in which the mode is active and the other in which the mode is completely/relatively silent which was dependent on the mode localization characteristics of their constituent laminas.

In an extensive study by Bapat and Suryanarayan [32] a multiple domain method for the free vibration analysis of rectangular plates with interior point supports was presented. Another formulation for the continuum representation of intermediate point supports in a single domain of a beam was presented in a subsequent study [33]. This approach, namely the fictitious foundation approach, was based on the use of a flexibility function, representing the distribution of a fictitious elastic foundation of the beam which is such that it has a zero value at the point support locations but assumes large values, resulting in negligible restraint over the rest of the beam span. The plate was divided into a number of sub-plates, and the force singularities, due to the point supports, appearing in the continuity conditions at the junctions were tackled by using the flexibility function approach [34]. The point support conditions were satisfied by representing the reactions at the point support locations as Fourier series expansion of two impulse functions [29]. The method proposed by Bapat and Suryanarayan will be used in modelling the point constrained plate.

In this paper, we are investigating the effect of having a point-constraint on a plate mounted in a duct on the transmission loss in the duct. We also investigate the vibration characteristics of the point constrained plate and compare it with that of an unconstrained plate. The geometry chosen is an idealized situation of a plate at grazing incidence in a duct with sound