Applied Acoustics 76 (2014) 310–318

Contents lists available at ScienceDirect

Applied Acoustics

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

Effect of coupling between passenger compartment and trunk of a car on coupled system natural frequencies using acoustic frequency response function

A. Seifzadeh [a,*], A. Pietrzyk [b], P. Göransson [a], R. Ramakrishnan [c]

[a] Aeronautical and Vehicle Engineering, MWL, Royal Institute of Technology, KTH, SE-100 44 Stockholm, Sweden
[b] NVH, CAE, Noise and Vibration Center, Volvo Car Corporation, Dept. 96720, Gothenburg PVÖS39, Sweden
[c] Department of Architectural Science, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada

ARTICLE INFO

Article history:
Received 6 November 2011
Received in revised form 5 August 2013
Accepted 7 August 2013
Available online 26 September 2013

Keywords:
Coupling
Passenger compartment
Trunk
Coupled system natural frequencies
Acoustic frequency response function

ABSTRACT

Conventional numerical techniques, used to study the acoustics of a car passenger cabin, treat the cabin as an isolated cavity excited by the cavity boundaries. Realistically, other cavity volumes such as the trunk communicate with the cabin through the holes in the parcel shelf of the car. An extended acoustic model of a car is formed by the cavity volumes of the passenger compartment and the trunk as well as air leakages through the holes provided for electrical devices and ventilation on the parcel shelf. In this study, the dynamic influence of air leakages between the passenger and trunk compartments on the first and second coupled system modes was investigated experimentally using acoustic frequency response function. The response to the acoustic excitation was measured for four different configurations of trim and holes of the parcel shelf. The natural frequencies of the first and second coupled system modes increased with increasing holes size with and without the trim of the parcel shelf. The experimental results were in good agreement with the reported results of coupling effects of double cavities connected by a neck. In the low frequency region since the wavelength is longer compared to the holes dimension, these holes act as point sources.

1. Introduction

A parcel shelf of a car, shown in Fig. 1, contains several holes for speakers and electrical devices and is covered by a trim. The trim is set back slightly above the parcel shelf to allow for air leakage while the side doors of the vehicle are closed. In addition, the trim itself contains holes for the air-flow. A passenger compartment with a trunk can be regarded as a double cavity connected through holes on the parcel shelf. From a practical point of view the relationship between the neck and the holes as well as the covering absorption material is of interest in NVH analysis as it can modify the natural frequencies of passenger cabin. In automobiles, investigation of the coupling effect between the passenger and trunk compartments plays a vital role in vehicle acoustic model especially at low frequency ranges because of its contribution to the booming noise.

Magalhacs and Ferguson developed a model analysis to calculate sound transmission through a panel between connected acoustic cavities [1]. The natural modes and natural frequencies of a cavity and plate have been investigated experimentally by others to study the acoustic characteristics of coupled structural-acoustic system [2–7]. To investigate the coupling effect of the system with specific acoustic characteristics, a theoretical model has been introduced [8,9]. Change in the natural frequencies of a vibrating panel in a rectangular cavity was investigated by Dowell and Voss [10]. Dowell, in subsequent investigation, also determined the acoustic natural frequencies of several connected cavities using simple formulas in terms of normal modes of the rigid-walled cavity [11].

Multiple cavities have been observed in other applications such as the hard disk drive systems in which the internal cavity of the drive, are divided into several sub-cavities by disks. The prediction of the natural frequencies and natural modes of the acoustic system, has received great attention during the design stages since the acoustical modal characteristics of the multiple cavities dominate the acoustic response of the system.

The effect of the Helmholtz resonator on the enclosure has been previously investigated by several researchers [12–15]. The extended acoustic model is formed by the cavity volumes of the passenger compartment and the trunk as well as air leakages between them. Fryman has idealized the dynamic characteristics of the

* Corresponding author. Current address: AMEC, Environment and Infrastructure, 160 Traders Blvd East, Suite 110, Mississauga, Ontario, Canada. Tel.: +1 647 302 0419.

E-mail address: alireza.seifzadeh@amec.com (A. Seifzadeh).

0003-682X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2013.08.002

Nomenclature

AFRF	acoustics frequency response function
c	speed of sound
f	natural frequency (Hz)
f_{10}	first natural frequency of the main cavity (passenger compartment uncoupled with trunk)
f_c^i	ith natural frequency of the coupled passenger and trunk compartments
h_n	height of the neck
H_{21}	ratio between height of cavity 2 and height of cavity 1
H_{n1}	ratio between height of neck and height of cavity 1
k	wave number of longitudinal wave
l_i	length of cavity i
VTF	velocity transfer function
ω	natural frequency [rad/s]
Ω	non-dimensional natural frequency
Ω_i	ith natural frequency of the coupled passenger and trunk compartments, normalized by the first resonant frequency of the passenger compartment uncoupled with the trunk
λ	wavelength of longitudinal wave

compartments by springs and simulated the effects of the air leakage by representative masses of the fluid enclosed [16]. Fryman's results showed that two extra Eigen modes should be considered if one used an extended finite element model of the vehicle. On the other hand, the simplified model (only passenger compartment) ignores the coupling effects as well as the influence of air leakage due to the holes between the two cavities and also ventilation ducts. Lee et al. investigated the effect of the neck connecting the two cavities as well as the effect of the size of the opening between cavities on the coupling natural frequencies of cavities [17]. Pietrzyk and Bengtsson [18] showed that the low frequency acoustic response of the passenger compartment (cavity) in sedans must also include the coupling between the cavity and the trunk. They investigated both acoustic (via holes in the parcel shelf or behind the backrest of the rear seat), and structural (via the parcel shelf itself, or the panel of the backrest) mechanisms. Their results showed that peaks in acoustic response of the cavity at low frequencies are due to both acoustic and structural phenomena.

The above literature review showed that the effect of air leakage between the passenger and the trunk compartments on the coupled system natural frequencies has not been experimentally investigated in a real car. In this study, the dynamic influence of air leakages in the passenger and trunk compartments as well as between these two volumes on the coupled system natural frequencies has been investigated experimentally using acoustic frequency response function (AFRF) in a real car. The responses to the acoustic excitation in both passenger and trunk compartments were compared for four different configurations of the trim and the holes of the parcel shelf. The importance of implementing the effect of air leakage between the two cavities in the finite element model of a car is thus investigated. To investigate the fluid-structure interaction effects on the acoustic frequency response function inside the car, the velocity transfer function of the rear window was measured. The results were compared to the published numerical analysis available for connected cavities [17].

2. The experiment

The basis, for the experimental investigation, is the modal analytical procedures used in structural-dynamic applications. The modal analysis model, shown in Fig. 2, can also be applied to cavity systems.

2.1. Experimental model

The physical system containing two cavities connected by the parcel shelf is formed by a fluid system enclosed by a rigid boundary. In the acoustic experiments, schematically shown in Fig. 2, the excitation of the fluid is achieved by a loudspeaker system. The resulting acoustical pressure fluctuations in the fluid can be determined by microphones. The acoustic pressures measured by microphones at defined points in the cavity are saved in Siglab as a complex dynamic pressure response. By dividing this complex value by the signal from the accelerometer connected to the membrane of the loud speaker, the complex value of the Acoustic Frequency Response Function (AFRF) is evaluated.

2.2. Experimental setup

The car was mounted on four air springs, as shown in Fig. 3 to simulate the real status of the car during measurements. During measurements, the four air springs were under load. The acoustic source, a loudspeaker, was placed on the foot bay next to the driver. An accelerometer was attached to the speaker diaphragm to measure the required response functions. The speaker setup is shown in Fig. 4.

The measurement systems consisted of six microphones, installed at different points in the car. Three half-inch microphones were located equidistant along the passenger compartment through an imaginary line in the middle of the passenger compartment. The three microphones were at the same height as that of the passenger's ear. The fourth microphone was located near the foot bay, the fifth was placed on the parcel shelf, and the sixth was located inside the trunk. The microphone setup is shown in Fig. 5. An accelerometer was installed on the rear window to measure the rear window velocity transfer function (VTF).

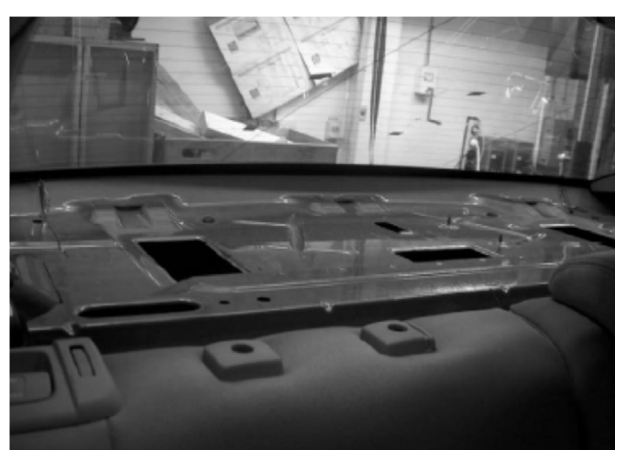

Fig. 1. Parcel shelf of a car with several holes for various devices.