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Finite element analysis for acoustic characteristics of combustion stabilization devices

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ABSTRACT

The present study has proposed a numerical methodology based on harmonic analysis of the convective Helmholtz equation to predict acoustic characteristics of combustion chambers with passive stabilization devices such as baffle and acoustic resonators. In order to resolve complex geometries of the acoustic damping devices, a three-dimensional Galerkin finite element method with four-type hybrid elements is adopted. The acoustic energy dissipation in the laminar wall boundary layer is taken into account by a wall damping model based on acoustic admittance. Special effort is devoted to obtain quantified parameters for comparative evaluation of acoustic damping capacities: (1) eigenfrequency shift and damping factor ratio for baffles, and (2) absorption coefficient and conductance for acoustic resonators. The numerical results have been compared with measured data from two different acoustic tests for baffle and Helmholtz resonators, respectively, and demonstrate that the present method is capable of reproducing quantitatively acoustic behaviors of the damping devices in terms of the quantified parameters if the wall damping model is appropriately adjusted.

1. Introduction

High-frequency combustion instability is generated by resonant coupling between unsteady combustion processes and acoustic oscillations within combustion chambers. In general, it is accompanied by high-amplitude pressure oscillations and excessive heat flux to the chamber wall, which cause severe damage to the hardware. The combustion instability has been one of the most serious problems in the development of aerospace and industrial combustion systems including rocket engines [3,23] and gas turbines [13].

The driving mechanism of combustion instability varies significantly depending on the particular injection/combustion system and involves complex phenomena such as turbulence, chemical kinetics, flame dynamics, and their interactions with acoustics. In spite of the long history of the research, therefore, neither general design rules of inherently stable combustion system nor reliable numerical tools to predict accurately combustion instability have yet been established. In order to resolve the undesirable thermo-acoustic problems, it is a prerequisite to analyze acoustic characteristics of the combustion chamber including discrete acoustic eigenfrequencies and their modal shapes which affect greatly the selection and design of damping devices such as baffles and acoustic resonators. For the elucidation of the acoustic characteristics, acoustic tests under non-reacting condition have been widely carried out since they can provide an effective way to evaluate the chamber's eigenfrequencies exhibited during hot-firing tests. Moreover, the acoustic tests are very useful for preliminary design of passive damping devices as well as for obtaining physical insights into their damping mechanisms.

Experimental procedures of acoustic tests with various damping devices were extensively reviewed by Laudien et al. [11]. In their work, useful parameters have been employed to measure quantitatively acoustic damping behaviors: (1) eigenfrequency shift and damping factor for baffles, and (2) absorption coefficient and acoustic conductance for various acoustic resonators. Following the experimental procedure, Sohn and Park [19] investigated comparatively absorption coefficients of three-type resonators (half-wave, quarter-wave, and Helmholtz resonators) to provide design criterion of each resonator on the optimal damping. Similarly, Kim et al. [8] evaluated absorption coefficient and acoustic conductance of multiple Helmholtz resonators from acoustic tests of a model chamber to address geometric and number effects on damping capacity of the resonators. As a remarkable progress, Zhao and Morgans [26] have developed an advanced technique of real-time

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Nomenclature

A_{ch}	cross-sectional area of chamber
C_Y	model constant for wall damping
c	speed of sound in the medium
f	frequency
i	imaginary complex number, $\sqrt{-1}$
k	wave number, ω/c
l	orifice length of Helmholtz resonator
$\triangle l$	mass correction for orifice length
$\mathbf{M}$	Mach number of the mean flow
N_R	number of Helmholtz resonators
$\mathbf{n}_f$	outward unit vector normal to boundary surface
$\hat{P}$	acoustic pressure (complex variable)
p'	pressure fluctuation
Re	real part of the complex valued quantity
r	resistance
S	cross-sectional area of orifice
t	time
$\hat{\mathbf{U}}$	acoustic velocity vector (complex variable)
V	cavity volume of Helmholtz resonator
$\mathbf{x}$	position vector
$\hat{Y}$	admittance (complex variable)
$\hat{Z}$	reduced impedance (complex variable)

Greek symbols

α_t	thermal diffusivity
δ	absorption coefficient
γ	polytropic gas constant
η	damping factor
ν	kinematic viscosity
ξ	conductance
ρ	density
χ	reactance
ω	angular frequency, $2\pi f$

Subscripts

i	ith resonator
peak	peak response
R	Helmholtz resonator
total	total for multiple resonators
0	time-averaged variable

tuned passive control by varying the neck area of the multiple Helmholtz resonators with focus on actual combustion system exhibiting multi-harmful modes.

Many numerical studies have also been carried out for linear acoustic analysis. You et al. [24] have investigated the effects of mean flow, nonuniform temperature distributions, and combustion response on the baffle design for a rocket combustion chamber using normal mode expansion and spatial averaging techniques on a generalized wave equation. Sohn et al. [20] have performed a harmonic analysis based on a three-dimensional FEM of the Helmholtz equation for acoustic tuning of a gas–liquid scheme injector as a half-wave resonator. Searby et al. [18] have proposed a hybrid approach to predict the damping efficiency of acoustic resonators accounting for viscous and thermal dissipation. In their work, analytical formulations derived for the laminar dissipation of acoustic energy in the boundary layer of a forced resonator, are used in conjunction with acoustic pressure field which is obtained individually by a three-dimensional modal analysis of the Helmholtz equation.

As for acoustic resonators, more specific studies have been performed. In addition to conventional wave equation and Navier–Stokes equations, Lattice Boltzmann method in time domain has been applied to investigate fluid dynamics in resonator orifice and detailed acoustic damping performance has been evaluated such as square-shaped and rounded orifices [6,7,25]. Richards et al. [16] summarized passive methods to improve the stability of low-emission combustors in stationary power gas turbines and suggested the possible application of acoustic dampers not widely used in stationary engines to increase the stability. To overcome the narrowband characteristics of conventional resonators, Barrow et al. [2] suggested a Helmholtz resonator with oscillating volume to increase the effective frequency range and good agreement has been achieved. These studies could provide more precise informations on dissipation phenomena in orifice entrance region and feasible guidelines for the fine design of acoustic resonators.

From a practical point of view, optimal design of acoustic resonators still remains as a very difficult task because they are narrowband absorbers which have to be tuned precisely to target frequency of the harmful acoustic modes. It is especially true when geometrical and structural restrictions of actual combustors result inevitably in irregular shapes of resonators which differ from the conventional ones of Helmholtz and quarter-wave resonators [17]. In this context, the present study is motivated to develop a reliable acoustic simulation tool for design and analysis of combustion chamber with various passive control devices, especially acoustic resonators. A numerical procedure based on harmonic analysis of the Helmholtz equation is devised analogously to the experimental one of acoustic tests. In order to resolve complex geometries of the combustor and passive control devices, a three-dimensional Galerkin FEM has been employed with four-type hybrid elements. Special effort is devoted to numerically obtain the absorption coefficient and acoustic conductance, which have been quantified as indicators for optimal tuning and damping capacity of the resonators by the experimental works [8,11,19]. It has been widely recognized that the damping behaviors of acoustic resonators are significantly affected by acoustic losses due to viscous and thermal boundary layers in the orifice wall. Therefore, an appropriate modeling of the acoustic loss mechanism has been a critical task of this work. Since the dissipation of acoustic energy in the wall boundary has not yet been modeled in the framework of multidimensional acoustic simulations, a wall damping model is proposed based on a theoretical formulation of admittance and incorporated into the present FEM Helmholtz solver. To the best knowledge of the authors, the present study is one of the leading attempts to evaluate numerically the absorption coefficient and acoustic conductance of acoustic resonators by the multi-dimensional acoustic simulation and to validate them against experimentally measured data.

In this paper, calculations under cold-flow configuration have been performed for two different acoustic tests with a rocket combustion chamber with a hub-and-six-blade baffle and an impedance tube with multiple Helmholtz resonators, respectively. The numerical results have been compared with the measurements in terms of the aforementioned damping parameters: (1) frequency shift and damping factor ratio for baffle, and (2) absorption coefficient and acoustic conductance for Helmholtz resonators. Throughout this paper, the modeling effects of the acoustic energy dissipation in the wall boundary layer on these damping parameters are critically discussed.