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# Numerical evaluation of acoustic characteristics and their damping of a thrust chamber using a constant-volume bomb model

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**Abstract** In order to numerically evaluate the acoustic characteristics of liquid rocket engine thrust chambers by means of a computational fluid dynamics method, a mathematical model of an artificial constant-volume bomb is proposed in this paper. A localized pressure pulse with a very high amplitude can be imposed on specified regions in a combustion chamber, the numerical procedure of which is described. Pressure oscillations actuated by the released constant-volume bomb can then be analyzed via Fast Fourier Transformation (FFT), and their modes can be identified according to the theoretical acoustic eigenfrequencies of the thrust chamber. The damping performances of the corresponding acoustic modes are evaluated by the half-power bandwidth method. The predicted acoustic characteristics and their damping for a special engine combustor agree well with the experimental data, validating the mathematical model and its numerical procedures. A small-thrust liquid rocket engine chamber is then analyzed by the present model. The First Longitudinal (1L) acoustic mode can be excited easily and is hard to be damped. The axial position of the central constant-volume bomb has little influence on the amplitude and damping capacity of the First Radial (1R) and 1L acoustic modes. Tangential acoustic modes can only be triggered by an off-centered constant-volume bomb, among which the First Tangential (1T) mode is the strongest and regarded as the most harmful one. The amplitude of the 1L acoustic mode is smaller, but its damping factor is larger, as a constant-volume bomb is imposed approaching the injector face. These results are contributed to evaluate the acoustic characteristics and their damping of the combustion chamber.

## 1. Introduction

Combustion instabilities have been experienced in many development programs of liquid rocket engines, which are manifested as transient large-amplitude pressure oscillations in the thrust chamber exceeding around 10% of the averaged chamber pressure. Based on the characteristic frequency of

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pressure oscillations, combustion instabilities can be classified as low-frequency (chugging), intermediate-frequency (buzzing), and high-frequency (acoustical) modes.[1] High-frequency combustion instability generally results from thermal-acoustic coupling, which is the most destructive for its extensive damage to the chamber and injector face.[1,2]

Research has shown that high-frequency combustion instability can generally occur when oscillatory energy supplied by unsteady combustion heat release is sufficiently greater than the loss of oscillatory energy damped in the chamber.[1] Acoustic combustion instability can be retrained by increasing damping, as well as by decreasing or breaking down thermal-acoustic coupling for a concerned acoustic mode. Thus, it is important to determine the acoustical modes and their damping characteristics for a thrust chamber. The popular method for predicting acoustic characteristics of a combustion chamber is to solve linear or nonlinear pressure wave equations,[3–7] in which acoustic modes can be obtained by the Helmholtz analysis. For a linear model, the pressure disturbance grows without a bound and is unphysical, while nonlinear models can obtain the limit cycle behavior in real situations.[5–7] However, both linear and nonlinear models require an accurate definition of the mean flow and response functions, which are limited to apply to cases with complex chamber geometries. The Finite Element Method (FEM) can be employed to analyze acoustic fields in complex geometries by solving the Helmholtz equation with a Neumann boundary condition.[8–10] However, it is difficult for the FEM to handle the flow and combustion process occurring in a chamber, which in fact has an important effect on acoustic characteristics.

The detailed processes of flow, combustion, and propagation of pressure wave can be solved based on the Computational Fluid Dynamics (CFD), which is somehow superior to the Helmholtz analysis of the FEM. Both linear and nonlinear disturbances can be handled in this method, which can also predict the effects of geometry variations and mean flow on acoustic characteristics. Using the CFD method, pressure oscillations have to be excited in a chamber first, and then acoustic characteristics can be obtained by analyzing the recorded time series of the pressure oscillations. Therefore, artificial disturbance models are usually employed in CFD to excite pressure oscillations, which have been developed by different researchers known as models of oscillating velocity disturbance,[11–13] mass flow rate disturbance,[14] energy disturbance[15], and pressure disturbances[16–22] as well as pressure pulse.[20–22] They have then been successfully applied to analyze chamber acoustic properties and acoustic damping of various passive devices by researchers such as Abdelkader[16] and Taro et al.,[17] and to stimulate combustion instability by Kim,[18] Grenda,[19] Habiballah,[20] Zhuang,[21] and Urbano et al.[22] However, it must be indicated that artificial disturbance is not indispensable for self-sustained combustion instabilities in a combustion chamber predicted by CFD.[23–25]

In summary, there are two main approaches to obtain pressure oscillations in a combustion chamber using the CFD method: one is to excite decaying oscillations by an artificial disturbance model, and the other is to realize self-excited combustion instability without artificial perturbations. Based on such pressure oscillations, the acoustic characteristics and the phenomenon of combustion instability in a combustion chamber can be investigated numerically. However, because it is hard to achieve self-excited combustion instability, artificial disturbances are more feasible to evaluate the acoustic characteristics and their damping in a thrust chamber, and often used in industries. For the existing artificial disturbance models, such as the models of mass flow rate, energy, velocity, and pressure, a specific acoustic mode is needed, and a resonant-mode oscillation is then trigged. The amplitudes of pressure pulse models are limited to a small value, which are capable to excite a specific acoustic mode, usually a single-frequency mode. In practice, an artificial disturbance method that can simultaneously excite the multi-acoustic modes of a chamber is a pressing need to determine which acoustic mode is the easiest to be excited and which one is the most difficult to be attenuated in the acoustic modes in a given chamber. Therefore, an artificial model must be applied with a large-amplitude pressure pulse and then drive the nonlinear acoustics process of pressure propagations. However, all the existing disturbance models do not possess all of the above traits, which will be further analyzed in Section 2 of the present paper.

Thus, a numerical constant-volume bomb model for a high-amplitude pressure pulse is proposed in this paper. The non-reactive turbulent flows in a chamber are numerically simulated by CFD. Multi-frequency pressure oscillations are excited by the present numerical constant-volume bomb model imposed on a limited region in the chamber. Acoustic modes and their corresponding damping characteristics are analyzed by both the Fast Fourier Transformation (FFT) analysis and the half-power bandwidth method. Furthermore, the effects of the forced geometrical regions on the excited pressure oscillations are further discussed.

## 2. Numerical method

Acoustic properties in a typical configuration of a thrust chamber in a liquid rocket engine are numerically investigated in this paper. The chamber is initially filled with quiescent air with a temperature of 298 K and a pressure of 0.1 MPa. A pressure pulse is then imposed on the mean pressure in a small region, and then fluid flows and pressure oscillations in the chamber are induced. Such turbulent flows with pressure oscillations are numerically simulated by using Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations, and the acoustic properties of the chamber can be obtained by analyzing the excited pressure oscillations. Based on the $k$-$\varepsilon$ two-equation turbulent model, the governing equations in a general form for the turbulent flows in the chamber are written as follows[23]:

$$\frac{\partial(\rho\varphi)}{\partial t}+\frac{\partial(\rho\varphi u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\Gamma_\varphi\frac{\partial\varphi}{\partial x_j}\right)+S_\varphi \tag{1}$$

where $\varphi$, $\Gamma_\varphi$, $S_\varphi$ and $u_j$ represent the conservation variables, the convective flux coefficient, the source terms, and the velocity in the $j$th direction, respectively; $\rho$, $t$, $x_j$ denote density, time and coordinate axis in the $j$th direction in the Cartesian coordinate system, respectively. These variables are shown in details in Table 1.

In Table 1, $p$, $T$, $k$, $\varepsilon$, and $Y_i$ represent pressure, temperature, turbulent kinetic energy, turbulent dissipation rate and mass fraction of the $i$th species, respectively; $\lambda$ denotes heat conductivity coefficient, while $c_p$ is specific heat at constant pressure; $\mu_e$ denotes the effective viscous coefficient, which contains the laminar viscous coefficient $\mu$ and the turbulent