



Numerical study of the effect of the corrugated baffle on the acoustic characteristics of the combustion chamber

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Abstract – Combustion instability caused by the amplification of sound waves is called acoustic or high-frequency instability, which can cause severe damage to the system. Adding baffles is one of the methods of passive instability control. Depending on the geometry of the chamber and the type of application, different baffles are used. In this research, the effect of the longitudinal corrugated baffle on the acoustic characteristics of the combustion chamber is investigated numerically. The quality of each baffle configuration is determined by examining their influence on the essential parameters such as natural frequency shift and damping factor. Modal and harmonic analyses for the acoustic field are conducted to investigate the effect of baffles installed in the combustion chamber. According to the obtained results, the addition of baffle shifts resonant frequencies. In other words, a combustor with baffles is more effective in controlling the instabilities than that without baffles. In addition, it increases the damping factor in the first–second circumferential (tangential) modes, making the system more stable. Also, a quantitative assessment of the acoustics by adding baffles shows that combustion chamber finds a better condition from stability point of view, and the bandwidth increase affects the combustion stability.

Keywords: Combustion chamber, Combustion instability, Corrugated baffle, Acoustic characteristics

1 Introduction

Combustion instability caused by the amplification of sound waves is called acoustic instability, which can cause contamination and severe damage to the combustion chamber.

The different types of instability are low and moderate and high-frequency combustion instability. When pilot-mode non-premixed combustion is established in aeroengine combustors, low-frequency combustion instabilities often develop under idle or sub-idle circumstances. Other forms of instabilities, such as azimuthal, transverse, and lean-limit instabilities, can develop under various cycle circumstances [1].

Under conditions of acoustic instability, the amplitude of pressure fluctuations inside the chamber increases. As a result, the amount of heat released in the chamber also increases. This dangerous situation can cause the combustion chamber's body to melt. Acoustic instability can be seen in the combustion chamber of various systems such as gas turbines, rockets, and jet engines [1]. For example, acoustic instability is an essential issue in developing the

combustion chamber of gas turbines for jet engines and rockets. Therefore, researchers have always considered it, and several efforts have been conducted to stabilize combustion instability which usually occurs near the injector faceplate [2].

Changing the fuel supply system and modifying the chamber geometry are two general ways to stabilize combustion. These two approaches have been widely used in various types of combustion systems. In addition, acoustic dampers are added to the system to stabilize combustion (damping combustion instabilities) by changing the geometry. The most common acoustic dampers include Helmholtz resonator, perforated liners, quarter- and half-wave tubes, and baffles. The present study uses baffles to damp acoustic instability [3]. Baffles are widely utilized as damping equipment to prevent high-frequency combustion instabilities inside the rocket combustion chamber [4]. Baffles and acoustic resonators are used as passive control devices to study the acoustic characteristics in combustion chambers and to predict acoustic field. Baffle design appreciably affects the damping capacity of the resonant modes, and thereby, the damping factor for resonant modes is changed exceedingly. If the baffles are not used, high-frequency combustion instabilities may increase heat transfer rates

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or resonance, resulting in poor propulsion performance and even severe damage to the injector faceplate and combustor wall.

The first notes on baffles were published in the book (AGARD R-820), covering work done during World War II [5]. The instrumentation available did not show pressure fluctuations but revealed significant changes in mean pressure. Wieber [6] investigated the acoustic behavior of a cold combustion chamber without fluid flow by considering different baffle patterns. Radial baffles were used in the combustion chamber. It was observed that radial baffles disrupt the acoustic field by preventing particles from moving in the tangential and radial directions; thus, transverse modes (radial and tangential) are more effectively damped than longitudinal ones.

Wieber concluded that the orientation of the baffles is essential on the behavior of the combustion chamber. Laudien et al. [7] conducted an experimental hot and cold acoustic bench test in the combustion chamber. They demonstrated that a two-blade baffle configuration might avoid spinning tangential modes, whereas a three-blade baffle pattern can damp the first and second tangential modes. The second tangent mode is unaffected by the four-blade baffle configuration. All tangent modes up to the fourth are affected by the five-blade baffle. Compared to the baffle-less chamber, this design lowers the resonant frequency, especially for the first and second tangential modes, and increases the damping rate by up to five times for the first two modes. Sohn et al. [8] numerically investigated the effect of a hub-blade configuration with five blades as a candidate baffle on the acoustic characteristics of the rocket combustion chamber. They have shown that increasing the baffle height increases the damping and the position of the hub has a significant effect on the damping of the first radial mode. Farshchi et al. [9] numerically and laboratory studied the acoustic characteristics of the rocket combustion chamber under the influence of radial baffles. They describe the methods used to determine the modes and acoustic frequencies of the rocket engine combustion chamber by considering the effect of different radial baffles. They showed that the baffle effect on the acoustic modes depends on the length of the baffles and weakly on the number of blades. Also, the conjugate spinning modes are decoupled and do not spin in any baffled combustor, independent of the number of blades.

You et al. [10] linearly studied the characteristics of combustion instability in a baffled combustion chamber. The theoretical formulation was based on a generalized wave equation. The effect of radial, circular baffles and the mechanisms by which baffles eliminate combustion instabilities were investigated. The effects of mean fluid flow, non-uniform temperature distribution, and combustion response on the different baffle designs in the rocket combustion chamber were examined. Zhao and Li [11] reviewed studies of acoustic dampers used in the aerospace industry. In this review, an experimental and numerical method was introduced to evaluate the quality of each damper, and different dampers were compared. Finally, potential destabilizing influences of baffles, challenges, and design issues for

applying various dampers were identified. Kim et al. [12] investigated the acoustic characteristics of combustion chambers with stabilizing equipment such as baffles and Helmholtz resonators using the finite element method. Several parameters were calculated to evaluate the quality of dampers, including natural frequency shift, damping factor for baffles, absorption, and conductivity coefficient for the resonator. The numerical results were compared to measured data from two different acoustic tests for baffle and Helmholtz resonators. They showed that the current method could reproduce quantitatively acoustic behaviors of the damping devices in terms of the quantified parameters if the wall damping model is appropriately adjusted.

Many numerical studies have performed acoustic analysis linearly. Poinsot [13] presented recent progress in thermoacoustic combustion instabilities in real and propulsion engines such as rockets or gas turbines. Combustion instability should be predicted and controlled since new mechanisms in real engines such as larger Reynolds numbers, higher pressures, power densities, multiple inlet systems, and complex fuels are necessary. Thus, in contrast with laboratory one, real systems experience more instability, such as azimuthal in gas turbines or transverse modes in rocket chambers. Zhao et al. [14] have recently reviewed active control approaches in stabilizing combustion systems in the aerospace industry. In this review, different methods of stability control were introduced and compared. Finally, the potential, challenges, and issues related to the design, application, and implementation of active combustion control strategies in a practical engine system were highlighted. In the mentioned studies, the effect of transverse baffles on combustion instability has not been investigated. Transverse baffles are primarily used in elongated chambers so that acoustic instability pressure fluctuations are controlled along the entire length of the chamber, and adverse effects on the fluid flow inside the chamber are not observed.

Therefore, the damping effect of this type of baffles needs to be investigated. Duan et al. [15] studied the effect of longitudinal baffled blades on the first-order tangential acoustic mode in a cylindrical chamber. The effect of the baffle on the amplitude of the pressure in the first tangential acoustic mode was investigated. With the increase in the number of the baffle, the amplitude of pressure in acoustic mode decreased. In another research, Duan et al. [16] investigated the effect of inner-surface baffles on the tangential acoustic mode and acoustic pressure oscillation in a cylindrical combustor. The longitudinal baffles are installed on the inner surface of the combustor wall to control the combustion instabilities. The first-order and second-order tangential modes are induced in the experiments.

The acoustic phenomenon inside the combustion chamber originates from three sources. The mixing of flows with two different temperatures (unipolar), the wall mechanical vibrations (bipolar), and the turbulent region of the mean flow inside the chamber (three poles) are the mechanisms affecting the acoustic pressure inside the combustion chamber [17]. Sohn et al. [18] have studied the effects of mean flow and shown that the mean flow velocity compared to other acoustic sources in the range of (0.0–2.1) Mach has

a negligible effect on the acoustic frequencies and mode shapes.

Sohn and Cho [19] addressed a spatially non-homogeneous temperature field in the combustor and evaluated the characteristics in terms of acoustic instability. They found that acoustic instability regularly causes considerable pressure fluctuations in the adopted combustor. The acoustic effects of the resonators are studied in terms of frequency tuning and damping capacity based on numerical findings for the combustor with current acoustic resonators fitted. Various fundamental works are still being pursued to understand acoustic instability, such as work conducted by Harrje and Reardon [20]. Under acoustic instability, pressure oscillations are amplified through in-phase heat addition/extraction from combustion, leading to acoustic resonance at specific acoustic modes of the chamber. It may lead to intense pressure fluctuation and excessive heat transfer to the combustor wall, such as solid and liquid propellant rocket engines, ramjets, and turbojet thrust augmenters. Other research works in this field can be addressed in [21–27].

Moreover, knowing the frequency characteristics and the combustion chamber structure is essential for stability analysis. However, the best baffle arrangement is obtained in the laboratory. There is no unique method to achieve the desired baffle design, but there are some general rules for designing baffle shapes. Therefore, various influential factors should be examined to select the appropriate baffle. The present study investigates the effect of corrugated transverse baffle designs used in the combustion chamber.

Due to the widespread use of corrugated baffles in industry and the lack of study in the open literature, this baffle type needs to be investigated. In the current research, acoustic behavior is investigated without considering the mean flow and temperature distribution in the combustion chamber. Also, since wall vibrations compared to the unipolar acoustic source are insignificant, wall vibrations are neglected in the present study. However, in applying the operating boundary conditions, which are very important to understand the simulation results, the dissipative effects of the wall are considered.

It is noted that unstable systems cannot work properly; combustion instability studies can also improve efficiency of combustion chambers. The primary purpose of this work is to study the effect of corrugated baffles on controlling the effect of the acoustic wave on the combustion process and reduce them. This purpose is admitted by numerical modeling of the wave propagation process in the experimental combustion chamber with baffles. It should be noted that the type of combustor system (liquid fuel combustion) used in our study is an industrial combustion chamber with two-stage combustion, and the type of combustion instability considered is low and moderate frequency instability. The results show that baffles cause damping of lateral oscillations in the combustion chamber. For this purpose, the combustion of acoustic air is considered. In the first step combustion flow field without baffles is analyzed. The process is analyzed again in the second step for the various baffle (unsteady flow), and system response is studied.

2 The governing equation

2.1 Acoustic

The acoustic cavity of the combustion chamber is calculated through linear acoustic analysis, which is obtained by solving the wave equation. For a homogeneous acoustic environment without loss and mean flow, the linear wave equation is:

$$\nabla^2 p - \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} = 0, \quad (1)$$

where p is the pressure changes resulting from the propagation of acoustic waves, t is the time, c_0 shows the speed of sound, and ∇^2 is the Laplace operator. The proposed wave equation is obtained from the mass and momentum conservation equations. All acoustic variables are considered periodically with a frequency of f . With this assumption, the unstable solution in the time domain can be converted to a stable solution in the frequency domain. Therefore, time-varying pressure fluctuations $p(X, t)$ are expressed by conjugate acoustic pressure $\hat{P}(X, t)$ as follows:

$$p(X, t) = \text{Re}\left\{\hat{P}(X, t)\right\} = \text{Re}\left\{\hat{P}(X)e^{-i\omega t}\right\}, \quad (2)$$

where ($\omega = 2\pi f$) is the angular frequency, and X is the displacement vector. By placing Equations (2) in (1), we get:

$$\nabla^2 \hat{P} - k^2 \hat{P} = 0, \quad (3)$$

where k represents the wave number, which is equal to ω/c_0 .

2.2 Acoustic cavity

The studied acoustic environment from around and at the end of its domain is limited to the body of the chamber and the free surface, respectively. The existing boundary conditions should be considered to solve the wave equation in the finite amplitude. Generalized boundary conditions can be defined using a reduced acoustic impedance, which is expressed as Equation (4) [28]:

$$\hat{Z} = \frac{\hat{P}}{\hat{U} \cdot n_f \rho c_0}, \quad (4)$$

where \hat{U} expresses the acoustic velocity vector (conjugate), ρ is the fluid density and n_f shows a normal unit vector at some points on the fluid boundary surface, perpendicular to the surface at that point; more precisely, it is perpendicular to the tangent plane of the surface at that point. Impedance is a complex frequency-dependent parameter that measures the ratio between acoustic pressure fluctuations and velocity at a specific frequency. In some particular cases, for instance, when ($\hat{U} \cdot n_f = 0$), i.e., on a rigid wall ($\hat{Z} \rightarrow \infty$), the reduced impedance is often replaced by its inverse, called an admittance, and is defined as its reciprocal $\hat{Y} = 1/\hat{Z}$. For a free surface boundary condition, impedance can be considered at the

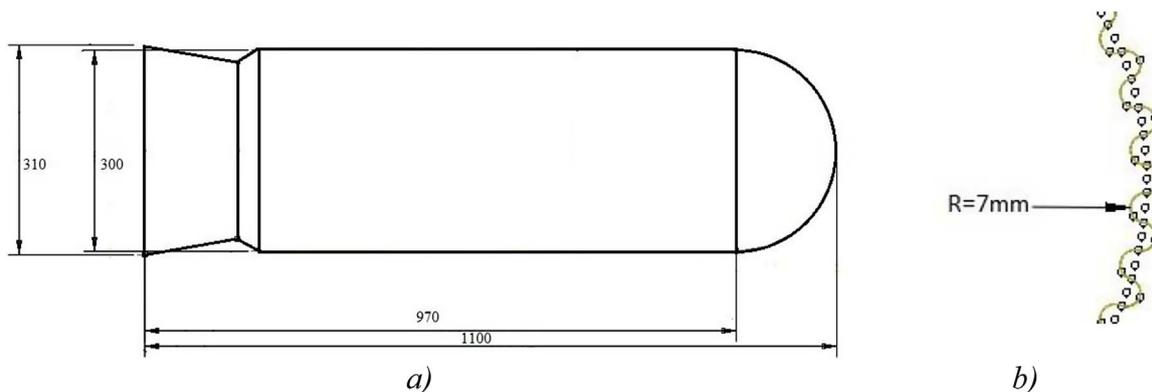


Figure 1. Dimensions of the considered system, (a) combustion chamber and (b) baffle.

end of the acoustic environment that does not reflect waves [29]. Due to the existence of heat loss and viscous stresses, acoustic waves are incompletely reflected, thus; to apply boundary conditions adjacent to the wall, the acoustic admittance model is used to describe the wall boundary condition, which is described as follows [29]:

$$\hat{Y} = C_y \frac{(1-i)\sqrt{\omega}}{\sqrt{2c_0}} (\sqrt{v} + (\gamma-1)\sqrt{\alpha_t}). \quad (5)$$

The model constant C_y quantifies the sensitivity of acoustic simulation to the wall damping model. Also, v is the kinematic viscosity, γ is gas constant and α_t represents the thermal diffusivity. The flow domain is intended for the acoustic air measurement under standard conditions i.e., $\rho = 1.21 \text{ kg m}^{-3}$, $\gamma = 1.4$, $c_0 = 340 \text{ ms}^{-1}$, $\alpha_t = 2.06 \times 10^{-5} \text{ m}^2\text{s}^{-1}$, $v = 1.46 \times 10^{-5} \text{ m}^2\text{s}^{-1}$ [29].

3 Modeling of the system

ABAQUS software is used to solve the wave equation numerically. The natural frequencies of the system can be tangential (1T, 2T, ...), radial (1R, 2R, ...), longitudinal (1L, 2L, ...), or mixed (1L1T, 1L1R, ...).

Figure 1 shows the dimensions of the combustion chamber and the baffle used for simulation. The baffled combustion chamber is also shown in Figure 2. It should be noted that Figure 1b is the crucial feature of the geometrical configuration of this study. Figures 1 and 2 are identical diagrams of a baffled combustion chamber.

The adopted number of elements is 1 483 597, and the type of mesh is selected AC3D4 for the simulation process.

4 Discussion and results

4.1 Validation

The modal analysis of the acoustic cavity for a cylinder conducted by Kinsler et al. [30] is performed to validate the solution accuracy. According to Table 1, it is clear that the simulation results obtained by pyramidal mesh have good accuracy. In Table 1, the analytical and numerical

frequencies of 1T are 592 and 593.76 Hz, respectively. And in the case of 2T, 982 and 921.17 Hz are shown.

According to the confirmation of ABAQUS computational ability for acoustic problems, geometry and finite element models are created.

4.2 Frequency response analysis

A sinusoidal acoustic wave generation source stimulates the acoustic environment at the point (distance of 15% of the diameter of the cylindrical part and zero angle) with an amplitude of 500 kPa. The system response to stimulation at the point (in the center of the cavity at an angle of 205.5°) is measured. The excitation frequency range is 400–1200 Hz. Figure 3 shows the system frequency response for the unbaffled and baffled systems.

According to Figure 3, the first and second tangent modes system intensifies, and the pressure amplitude increases sharply. Adding a baffle to the system reduces the acoustic pressure amplitude in unstable tangent modes and helps the system acts more efficiently, which the effect does seem to be significant. Also, it shifts the resonant frequency to the right in the unstable tangential mode. The frequency response results in Figure 3 show that both unbaffled and baffled peaks are found at 600 Hz or higher in 1T and at 1000 Hz or higher in 2T.

The contours of the first-second tangential modes for the unbaffled and baffled systems are shown in Figure 4.

In the contours presented in Figure 4, sections are cut from the middle of the acoustic environment. As can be seen, the baffle addition reduces the high-pressure area. As a result, the high-pressure areas in the baffled case are more concentrated towards the walls. Therefore, they can make the combustion more stable in the center area. Again, the damping coefficient increases as the bandwidth of each mode increases, and the installed baffle improves the combustion stability. Chamber damping can also be appreciably increased by using perforated acoustic liners.

4.3 Damping response analysis

In addition to the pressure amplitude, a baffle also affects the bandwidth around each mode. Figure 5 shows

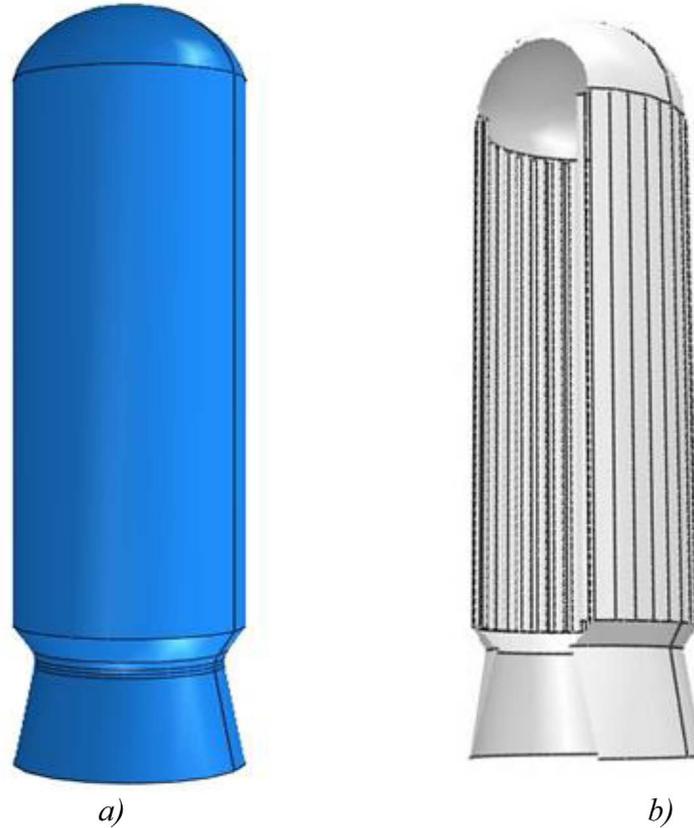


Figure 2. Schematic of combustion chamber: (a) unbaffled and (b) baffled.

Table 1. Resonance frequencies of the fully closed cylindrical chamber via analytical method [30] and numerical solution.

Mode	Analytical frequency (Hz) [30]	Pyramidal mesh	
		Frequency (Hz)	Error (%)
1L	322.4	324.42	0.5645
1T	592	593.76	0.2432
2L	644.9	648.15	0.2683
1L1T	674.1	676.32	0.0800
2L1T	875.4	877.91	0.2216
3L	967.3	970.64	0.1944
2T	982	981.17	0.2566
1L2T	1033.6	1033.0	0.4450
3L1T	1134.1	1135.7	0.7142
1R	1232.5	1235.5	0.1704

the effect of the baffle on the bandwidth of the first–second tangent modes.

The frequency response to the excitation and the damping factor for different cases are obtained from the harmonic analysis. To more reasonably qualify the damping effects of baffles, the flame dynamics such as flame transfer function (FTF; which is valid for low and moderate oscillation amplitudes, where the response is assumed to be linear) should be considered. The baffles acoustic damping effect is expressed by the damping factor (η), which is defined as follows [8]:

$$\eta = \frac{f_2 - f_1}{f_{\text{peak}}}, \quad (6)$$

where f_{peak} is the maximum frequency response of the pressure (p_{peak}) and f_1, f_2 , ($f_2 > f_1$) are the frequencies of the condition that the response of the pressure amplitude is equal to $\frac{p_{\text{peak}}}{\sqrt{2}}$.

Figures 5a and 5b show the normalized frequency response around the tangent modes, 1T and 2T, respectively. There is a significant difference between unbaffled/baffled at $\frac{1}{\sqrt{2}}$ in the range of normalized bandwidth of tangent mode, in damping factor either. According to Figure 5, adding a baffle increases the bandwidth around each mode. As a result, according to equation (6), the damping factor increases, making the system more stable. This can be more important in the design process to have more efficient combustion. As a result, the installed baffle is beneficial and improves combustion stability. Table 2 shows the values related to the damping factor and the frequency due to the addition of the baffle.

According to Table 2, adding a baffle increases the frequency and damping factor in the first and second tangential modes.

Figure 6 shows sections (a) and (b) of the damping factor for different C_y in two unbaffled and baffled chamber cases. The ratio of a damping factor of the baffled case to the damping factor (DF) of the unbaffled chamber is called the damping factor ratio (DFR). According to the obtained

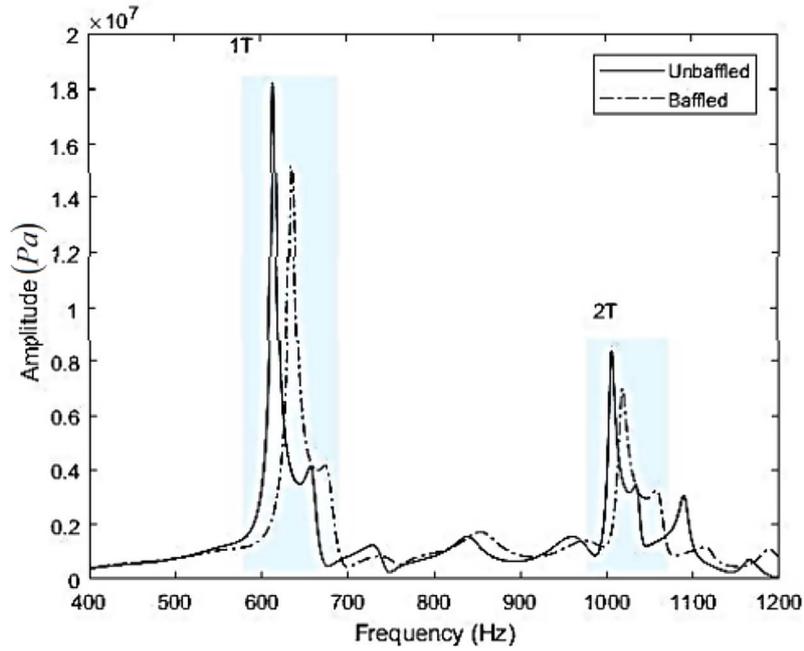


Figure 3. Frequency response of the system to harmonic excitation ($C_y = 6$).

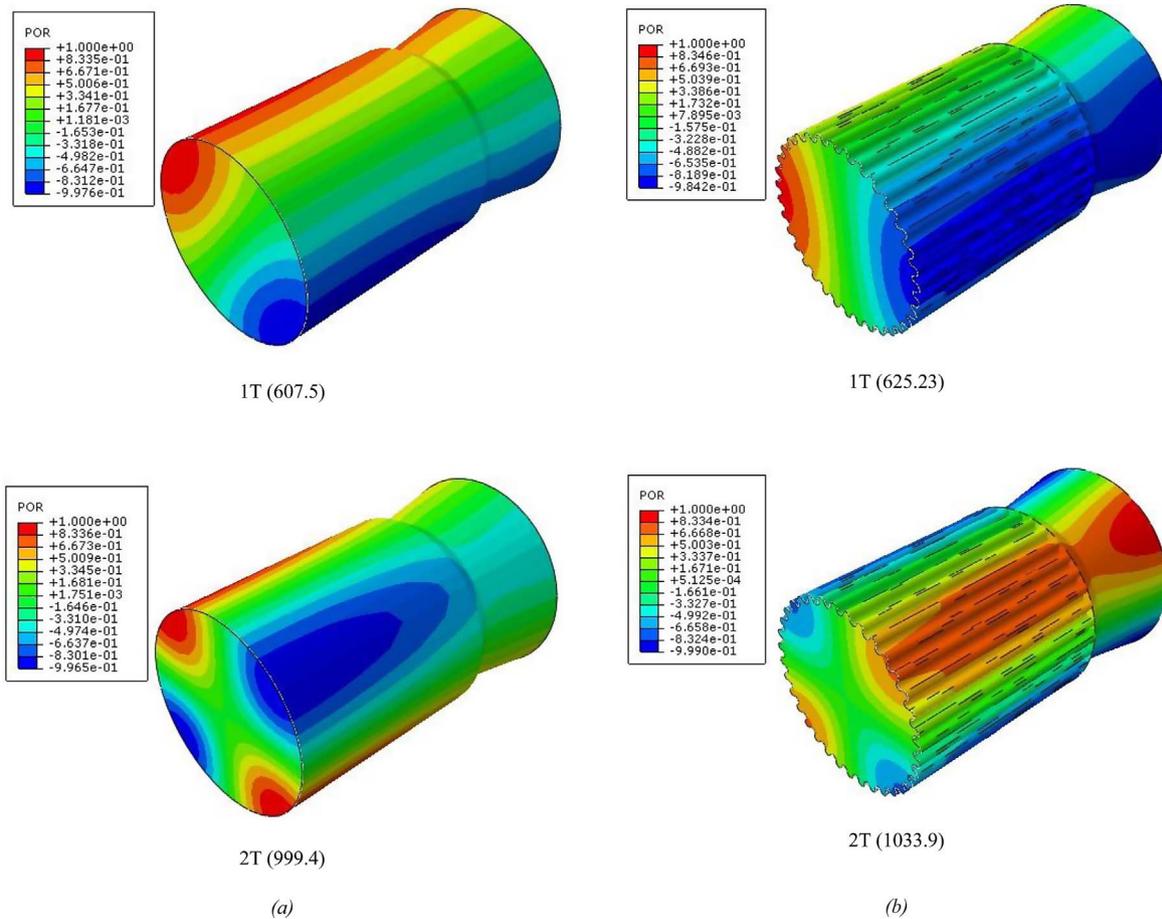
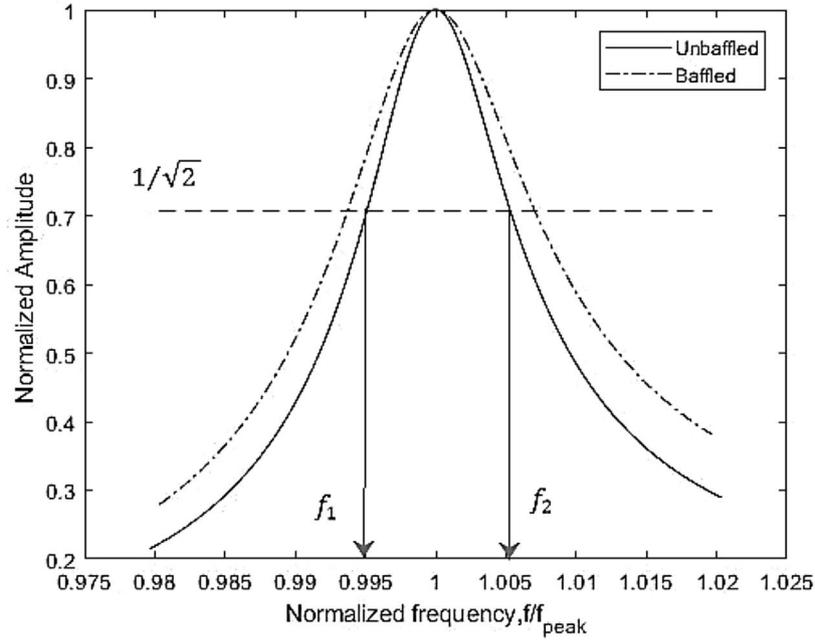
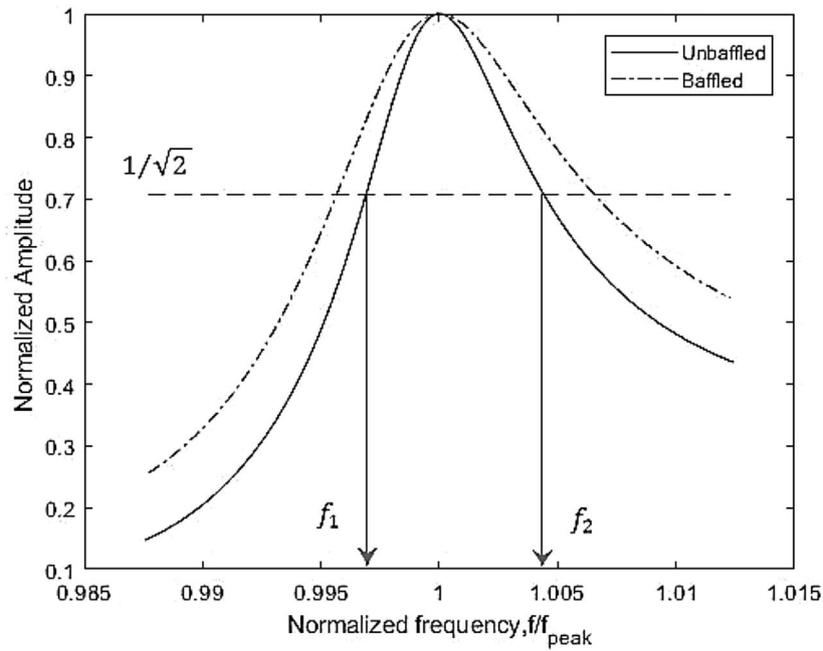


Figure 4. Pressure contours in the first and second tangential modes: (a) unbaffled and (b) baffled (the cross-section is parallel to the free end and at a distance of half the total height from the end).



(a)



(b)

Figure 5. Normalized bandwidth diagram around tangent mode, (a) first mode and (b) second mode.

Table 2. Comparison of acoustic characteristics of unbaffled and baffled systems ($C_y = 6$).

Mode	Unbaffled		Baffled	
	Frequency (Hz)	η	Frequency (Hz)	η
1T	607.5	1.041	625.33	1.3592
2T	999.4	0.767	1033.9	1.1138

results, the damping factor around the 1T and 2T modes increases linearly with the constant model increase. It is also observed that the damping factor of the baffled system (for most C_y values) always is higher than the unbaffled one. The model constant shows the sensitivity of the acoustic field to wall damping. As the damping factor of the system increases, the constant system, i.e., C_y increases; thus, at the boundaries, the energy dissipation of the acoustic wave

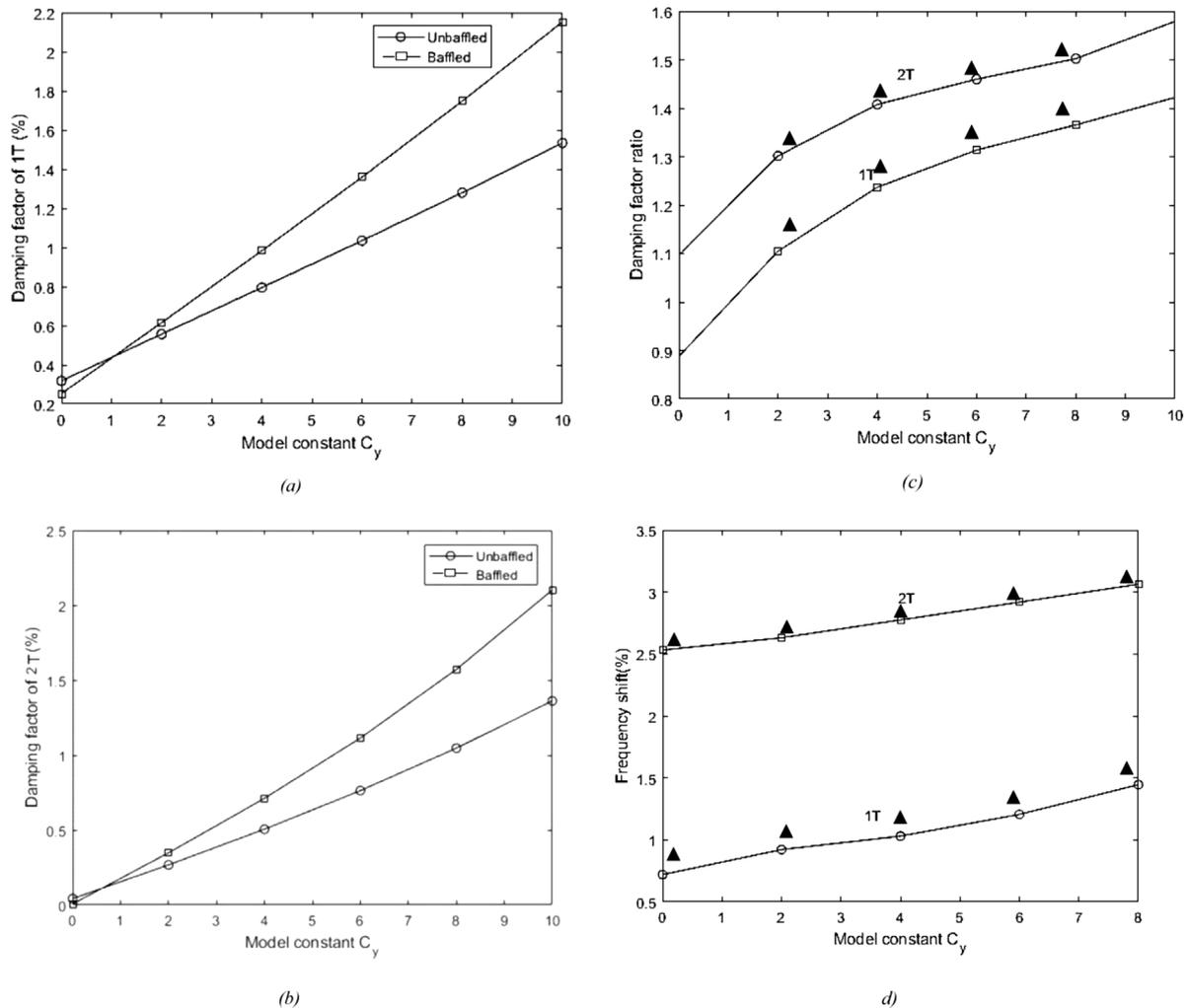


Figure 6. The effect of C_y (model constant) on acoustic characteristics: Damping factor ratio in terms of C_y around: (a) 1T mode, (b) 2T mode, (c) damping factor ratio around the first, second tangent modes in terms of C_y and (d) frequency shift versus C_y .

increases. It can be seen in Figures 6c and 6d: with the increase of C_y the natural frequency shift and the damping factor ratio resulting from adding baffles around 1T and 2T, modes increase slightly.

5 Conclusions

Baffles are plates connecting to the motor's injector plate and reducing interaction between acoustic waves and combustion effects. The linear acoustic behavior in the combustion chamber was investigated numerically. The transverse corrugated baffles were installed in the chamber. The effect of adding a baffle on the acoustic characteristics of the combustion chamber was studied. For this purpose, the modal and harmonic analysis of the acoustic field were used, taking into account the wall and the free surface boundary conditions. In addition, the damping effect of the baffles and constant system were compared with the resonance frequency shift and the damping factor.

By comparing the frequency characteristics of the baffled and unbaffled chamber, it was revealed that the amplitude peak decreased, and the characteristic frequency shifted to high frequency. Among other findings:

- The main purpose of baffles is to prevent high-frequency combustion instabilities inside the combustion chamber.
- Installing a corrugated baffle in the combustion chamber increases the damping factor and thus improves the combustion stability and reduces the high-pressure area. Also, it reduces the amplitude of the pressure response in the first–second tangent modes.
- The high-pressure areas in the baffled case are more concentrated towards the walls by adding the baffle. As a result, they can make the combustion more stable in the center area.
- The damping factor has a linear relation with the model constant. With increasing C_y , damping increases and makes the combustion more stable.
- The resonant frequency shift and the damping factor ratio are less sensitive to the model constant.

- Appropriate baffles in an unstable chamber can stabilize the combustion for the transverse acoustic mode.
- Stabilization of combustion reduces the interaction of acoustic waves and combustion by baffles and liners.

Conflict of interest

Author declared no conflict of interests.

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