THERMO-ACOUSTIC STUDIES OF COMBUSTION CHAMBER WITH ACOUSTIC DAMPER

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ABSTRACT: In gas turbine combustors, there is always a pressure fluctuation. In such combustion chamber a growing acoustic wave is also observed. A coupling between acoustic wave and unsteady heat release causes combustion instability. When the combustion instability occurs, large amplitude of sound with high level of vibration is observed in combustion chamber which also causes structural damage to the engine. Now a day most of the chambers developed are having combustion instability problem. To overcome such instabilities and improve the combustion system operability, Helmholtz resonator system is considered as a passive absorber. The present work focuses on the combustion instability by solving coupled dynamics equations and generalising the relations between the input and output parameters using neural network model. The pressure and velocity distribution are illustrated in this paper, phase diagram of acoustic velocity and pressure are found out. Solid model of combustion chamber is used to do modal analysis.

Index terms: Combustion chamber, Helmholtz resonator, acoustic amplitude, coupled dynamics.

1. INTRODUCTION

To reduce the emissions in the gas turbine lean premix combustion process is often used in which air and fuel are mixed prior to burning. but it causes combustion instability. Combustion instability occurs by the coupling between acoustic wave and unsteady heat release [1]. Combustion instability is one of the most major problem in gas turbine, rocket motor etc. Gas turbine play a crucial role in power generation. In this context, the operation should be stable and free from vibration. Thermoacoustic stability is a important factor in the development and implementation for a new combustor. The result for linear and nonlinear thermoacoustic assessment are compared. The growth rate of the thermoacoustic instability is predicted by linear assessment whereas the the limit cycle amplitude is predicted by the nonlinear stability method [2]. A large amplitude of pressure oscillation cause noise and structural vibration [3]. Combustion can be unsteady phenomena, combustion also makes sound, the burner actually makes sound. So, the sound that is generated by the combustion, they travel to the walls get reflected and come back. And this sound when it come back they affect flame and flame become unstable unsteady. Now the unsteady flame produces further sound. So, this kind of sets up a feedback where in the sound actually makes the flame unsteady and the unsteady flame makes sound. combustion instability generally seen in most of the combustion chamber and also leads to structural damage. The combustion instabilities occur in systems such as aero engines, ramjet, after burner etc. Self-excited oscillation with a high level of amplitude can be created depends upon the phase of coupling [4]. In general, combustion add energy to the acoustic field if it is in phase with pressure fluctuation and if the pressure oscillation is out of phase with acoustic field then we actually have damping. Combustion will take away the acoustic energy. We can control combustion oscillation by adding an energy source out of phase with oscillation of heat release [5]. Thermoacoustic instability is a major problem now a day for a gas turbine since it

also causes undesirable vibration in combustion chamber and rises fatigue concern [6].
To control these instabilities, the coupling between acoustic wave and unsteady heat release which causes instabilities should be broken. The two techniques, to control acoustic instabilities, are active control and passive control. Helmholtz resonators are used as a passive damper. It consists of a cavity which is connected to combustion chamber by means of a short neck. At resonance, the fluid enters in the cavity compress and expand, while a mass of the fluid in the neck oscillate [7]. Volume of air in the neck is oscillate because of the springiness of the air inside the cavity. Helmholtz resonator is widely used to damp acoustic oscillation in the combustor.

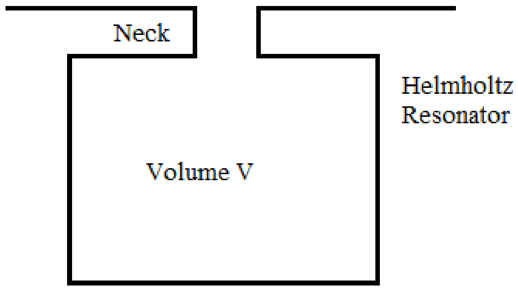


Figure 1: Helmholtz resonator

Helmholtz damper increase the acoustic dissipation and which result in decrease in the amplitude of pressure oscillation. Such resonators are used to reduces the mechanical vibration. Helmholtz are passive damper which is used in gas turbine combustor. The design of passive damper increase the stable zone of machine [8]. Helmholtz resonator is used in wide range of combustor to damp the acoustic wave. A low frequency noise is generally reducing. However, it is effective at small frequency band. Now to reduce the low frequency noise, multiple Helmholtz resonator array system is used by Dizi wu [9].
Some test has been done with non-reactive flow in the combustion chamber. Resonator geometry also important, some test on design and performance of the resonator to damp instability is also conducted [10]. The coupling between heat release and acoustic field tends to increase acoustic amplitude, this interaction can be mimicked by a feedback excitation with the help of loudspeaker and microphones [11]. In 1878, Rayleigh gives a criterion to determine thermoacoustic instability.

$$\int_T \int_V p'(x,t)q'(x,t)dxdt > \int_T \int_V \Phi(x,t)dxdt$$

This equation gives important relation between the pressure oscillation and unsteady heat release which cause thermoacoustic instability. The left hand side of the above equation shows the coupling between heat release rate q' and pressure oscillation p' during the one oscillation cycle of time duration T and inside the control volume V. Thus, the coupling add energy to the system. The dissipation in the acoustic field, which is not taken into account in the original criterion, is described by the wave energy dissipation Φ in the right-hand side of equation. Rayleigh gives the condition for thermoacoustic instability which state that, if the energy added to the system that is left hand side of the equation overcome the total energy dissipation, the acoustic energy is increase in the combustion chamber and it leads to combustion instability. Now we can control combustion instability by increasing the acoustic energy dissipation. We can use Helmholtz resonator to increase the acoustic energy dissipation i.e. increase the right hand side in the Rayleigh criterion and which tends to reduces the amplitude of pressure oscillation.
The aim of this work is to reduce acoustic affect in the combustion chamber with the help of a side branch resonator known as Helmholtz resonator, which is actually used to minimize the coupling effects of acoustic wave and unsteady heat release. We are using the coupled dynamics equations of the Helmholtz resonators and combustion chamber to see pressure and velocity distribution across the combustion chamber and also see the phase diagram to conclude the stability.

2. MATHEMATICAL MODELING

A thermosacoustic model of Helmholtz resonator and a combustion chamber which are coupled with each other is described in this section. We will see the dynamics of Helmholtz resonator and combustion chamber separately.

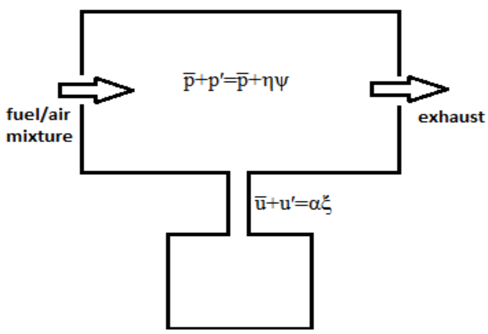


Figure 2: Model consist of combustion chamber(Top) and Helmholtz resonator(Bottom)

2.1 Dynamics of Combustion Chamber

The pressure, velocity and heat release are decomposed into two fluctuating, also referred as acoustic part and mean part. The mean part is constant whereas the fluctuating part is small. The acoustic pressure distribution is given as $p'(x,t) = \sum_{i=0}^{\infty} \eta_i(t)\psi_i(x)$, where the basis function ψ_i are defined by acoustic eigen mode of the system without acoustic source. As an approximation, only the eigenmode with the largest growth rate is considered and all other eigenmodes are neglected, which corresponds to a Galerkin approach. The interaction between the fluctuating heat release rate and the acoustic pressure as well as the acoustic flux across the control surface excluding the damper is captured by introducing a linear damping term k_0. For negative values of k_0, the constructive interaction is larger than the energy dissipation which leads to thermoacoutic instability of the undamped system [12].

$$\frac{d^2}{dt^2}\eta + \kappa_0 \frac{d}{dt}\eta + \omega^2\eta = 0 \qquad (1)$$

Where η(t) is the participation factor of Galerkin approach, ω is Eigen frequency. Now by introducing nonlinear terms [8]

$$\frac{d^2}{dt^2}\eta + \left(\kappa_0 + \kappa_1\eta^2 + \kappa_2\left(\frac{d}{dt}\eta\right)^2\right)\frac{d}{dt}\eta + \omega^2\eta = -\in\chi\frac{d}{dt}u' \qquad (2)$$

The Van-der-Pol type terms with positive parameters k_1 and k_2 ensures boundedness of η for bounded acoustic velocities u'. The parameter $\chi > 0$ depends on fluid properties whereas $\in > 0$ depends on the location of the Helmholtz damper [10].

2.2 Dynamics of Helmholtz Damper

A Helmholtz resonator is similar to bottle shape. The cross section area of the bottle is much larger as compare to cross section area of neck. Then the pressure perturbation is assumed to be uniform inside the bottle. Therefore, the gas in the bottle is assumed to be acoustic spring whereas the gas oscillating in the neck is assumed to be acoustic mass.

Assuming the flow to be uniform and frictionless, the dynamics of the acoustic velocity in the neck of the damper can be derived using the unsteady Bernoulli equation between a point at the entrance and a point at the exit of the neck as [10]

$$\frac{d^2}{dt^2}u' + \zeta\left|\bar{u} + u'\right|\frac{d}{dt}u' + \omega_d^2 u' = \frac{\omega_d^2}{\chi}\frac{d}{dt}\eta \qquad (3)$$

where $\bar{u}$ is the mean flow due to the continuous volume flow $\bar{Q}$, ω_d is the eigen frequency of the damper and $\zeta > 0$ is a damping efficiency

2.3 Coupled Dynamics

Coupling the two system described by (2) and (3). The acoustic velocity is normalized as, and new parameter are defined as $\xi = \frac{\chi}{\omega}u$, and new parameter are defined as $q = \frac{k_0}{\omega}, c_1 = \frac{k_1}{\omega} > 0, c_2 = \omega k_2 > 0, d = \frac{\zeta\bar{u}}{\omega} > 0, \delta = \frac{\zeta}{\chi} > 0$

Therefore, the coupled dynamics of (2) and (3) is obtain as

$$\ddot{\eta} + (q + c_1\eta^2 + c_2\dot{\eta}^2)\dot{\eta} + \eta = -\in\dot{\xi} \qquad (4)$$

$$\ddot{\xi} + |d + \delta\xi|\dot{\xi} + \xi = \dot{\eta} \qquad (5)$$

Now converting these second order differential equation, equation (4) & (5) into first order ordinary differential equation and arrange them in matrix form.

$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{pmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ -1 & -q & 0 & -\in\\ 0 & 0 & 0 & 1\\ 0 & 1 & -1 & -|d+\delta x_3|\end{bmatrix}\begin{pmatrix}x_1\\ x_2\\ x_3\\ x_4\end{pmatrix} + \begin{pmatrix}0\\ -c_1x_1^2x_2 - c_2x_2^3\\ 0\\ 0\end{pmatrix}$$

$$\dot{X} = AX + B$$

Where,

$x_1 = \eta$, $x_2 = \dot{\eta}$, $x_3 = \xi$, $x_4 = \dot{\xi}$.

$\dot{x}_1 = x_2, \dot{x}_3 = x_2$.

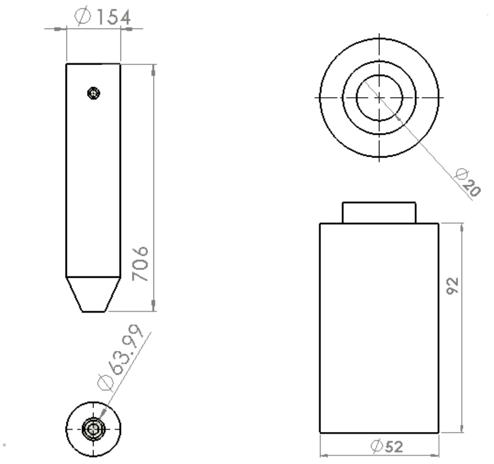
And solve this using matlab we will get pressure & velocity distribution with time and phase diagram for the different values of d and q.

3.RESULTS AND DISCUSSION

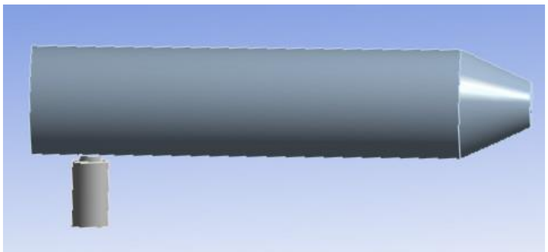
Initially the structural modes of the combustor with resonator are predicted from 3D modelling and analysis.

3.1 3D modelling

The combustion chamber along with resonator is modelled in Solidworks 2016 and imported into Ansys workbench for modal analysis. Figure 3 shows the dimension and model of the system under consideration.



(a) (b)



(c)

Figure 3: (a) solid model of combustion chamber (b) Helmholtz resonator resonator and (c) assembly.

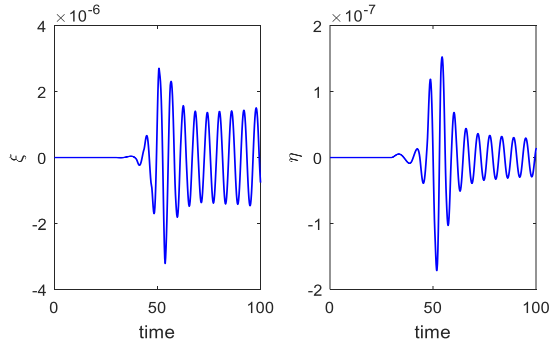
Modal analysis has been done on the combustion chamber with Helmholtz resonator. The material used is structural steel. Analysis has been done by arresting the radial direction displacement of the combustion chamber. The natural frequency of first few modes is shown in Table 1.

Table 1: Frequency of Combustor and Resonator

Mode	Frequency[Hz]
1	1343.7
2	1361.5
3	2752.2
4	4598.2
5	4598.3

By solving the coupled equations we have following results. Initial condition is taken as: - X=[1e-20;1e-20;1e-20;1e-20];

Figures 4 to 6 show the time responses and phase diagrams at three different values of q and d. For the Fig 4 we get the stable limit cycle and pressure oscillation is also found to be reducing whereas in the Fig 5 we found the same but increase in amplitude of limit cycle is observe and the velocity wave fluctuate more as compare to previous one. In Fig 6 we have taken negative value of q which shows instability, a growing pressure oscillation observe and limit cycle is also found to be unstable.



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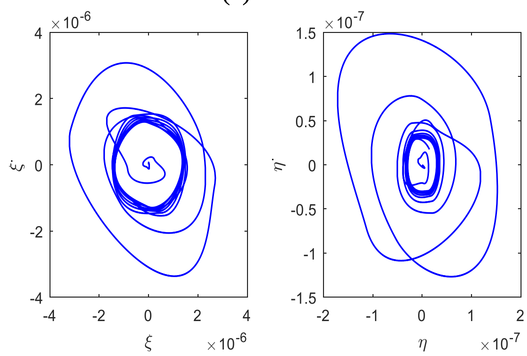
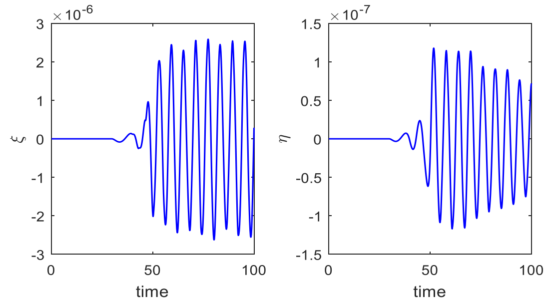
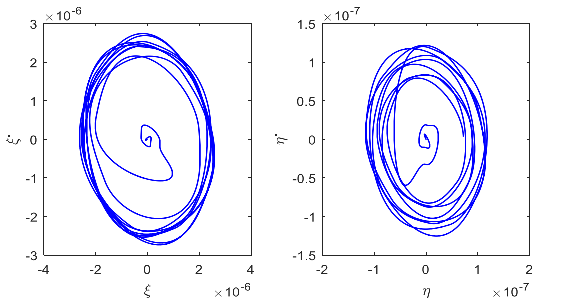


(b)

Figure 4: (a) Time responses of pressure and velocity and (b) phase diagram of acoustic pressure and velocity. (For q=0.4 and d=0.3).

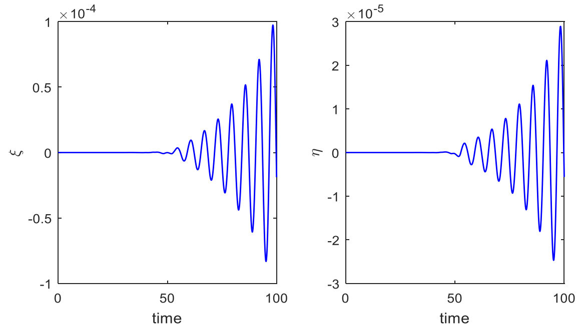


(a)

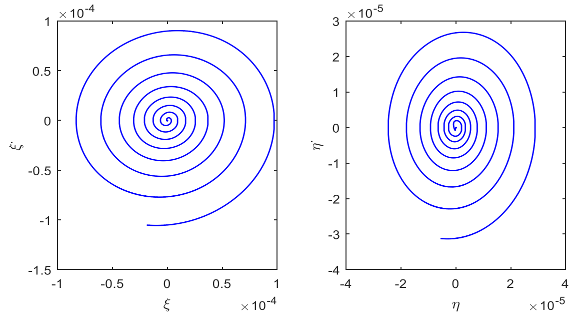


(b)

Figure 5: (a) Time responses of pressure and velocity and (b) phase diagram of acoustic pressure and velocity. (For q=0.2 and d=0.2).



(a)



(b)

Figure 6: (a) Time responses of pressure and velocity and (b) phase diagram of acoustic pressure and velocity. (For q=-0.1 and d=0.2).

In order to classify the stable and unstable states from the coupled parameter d and q, a neural network model is employed.

3.2 Neural network modelling

In order to identify the stable and unstable conditions, a neural network model is trained with a three-layer perceptron neural network with two inputs (d and q) and two output classes (stable and unstable). The classification problem is not a linearly separable one. Therefore, back propagation algorithm is employed for training. So it consists of three layers namely input, hidden and output layer. By varying d and q over a range of values, stability of the system is identifying from time domain response. Accordingly, it is classified either as stable or unstable. If it is stable, the first output node fires otherwise the second one fires. Figure 7 shows the training trend of the neural network and the classification hyper plane. Figure 8 shows the training pattern supplied to the neural network with classes considered (red circle indicate stable and blue circle indicate unstable states).

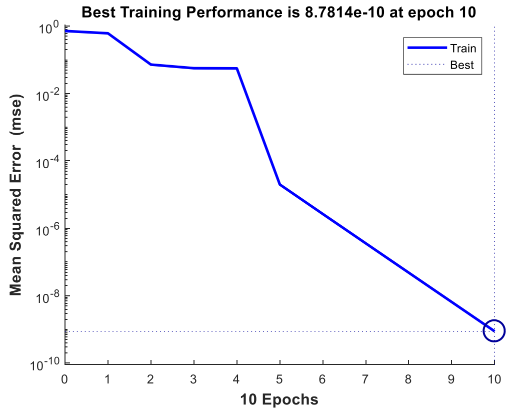


Figure 7: Training trend

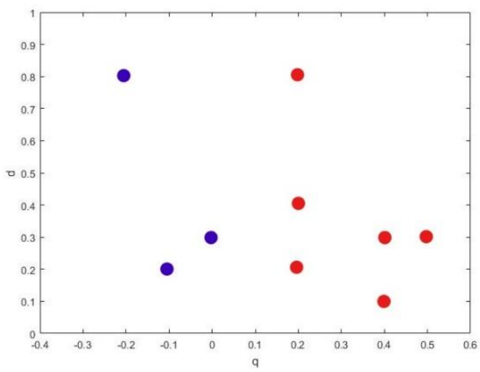


Figure 8: Classification domain

4.CONCLUSION

The combustion instabilities with coupling between the pressure oscillation and unsteady heat release were studied by introducing the Helmholtz resonator. There are some factors like dimension, fluid property and placement of resonator is also important for the efficient damping. Since, there is a variation seen in the phase diagram and pressure and velocity distribution by changing the values of d and q, by solving with nine different value, result has been discussed. For the negative value of $k_0(q)$, the constructive interaction is larger than energy dissipation which leads to thermosacoustic instabilities. Further acoustic simulation has to be done in Ansys so that acoustic pressure distribution and sound level across the combustor can be found with and without resonator. That pressure distribution and sound level can be check experimentally by passing hot flue gases in the combustor and intensity of sound can be detected with the mic and compare with analytical result.

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