Combustion Instability Modelling Using Different Flame Models

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Abstract

Using the Low Nox systems in gas turbines in order to produce the minimum amount of Nox has been done to reduce environmental pollution. Combustion instabilities are important problems occurred in industrial and aerial gas turbines If the heat release fluctuations and acoustic pressure are in the same phases, the amplitude of the fluctuations will increase. To study the dominant low frequency acoustic modes of an industrial silo gas turbine combustor, in a certain range of operating conditions, theoretical models was used in this study. This method leads to predictions for the frequencies of oscillations and the susceptibility to instabilities in which linear disturbances grow exponentially in time. The main components of the combustor model are assumed to be a plenum, burner, flame sheet, combustion chamber. This simplification is conceptually convenient since low frequency acoustic waves are not influenced by bends and some elements in the combustor are smaller than the wavelength of propagated acoustic perturbations. For the flame model the fuel is assumed to be injected in the burner (which is considered as a premix duct) at a steady rate. A convection time is assumed to characterize the required time for the acoustic velocity fluctuations to travel from the point of injection to the location of flame front in the combustion chamber. By applying proper boundary conditions between the components of combustor model, along with the combustor inlet and outlet boundary conditions, a system of equations can be obtained. This system of equations has a related eigenvalue equation which has complex roots. The sign of imaginary part of these roots determines whether disturbances grow or decay, and the real part of these roots gives the frequency of the modes. Acoustic mode shapes of the combustor are also studied by using COMSOL software. The results of calculated dominant acoustic frequencies which are obtained from theoretical model, simulation with COMSOL and measurements on operational gas turbines, show reasonable agreement.

Introduction

Today’s industrial gas turbines are designed to be more energy efficient and more reliable while they have to produce the minimum amount of NOx emission. For this purpose and to reduce the amount of NOx, low emission natural gas systems have been used. In order to decrease the amount of NOx emission a leaner fuel–air mixture should be used and this will lead to a lower flame temperature which consequently may result in heat release fluctuations. These heat release perturbations also may lead to combustion instability which is a major concern in the design process of industrial and aerial gas turbines.

In certain circumstances, the coupling between the generated heat release oscillations and acoustic pressure perturbations will result in specific low frequency instabilities, which is called Humming. Humming emerges in high levels of dynamic pressure in the combustion chamber and it can prevent the system to reach to its full load operating condition. Also it can result in dangerous damage to the internal component of combustion chamber. As a consequence, it can lead to decrease in the lifetime of the chamber or even failure of the whole structure. This phenomenon is a great barrier in development of gas turbines with pre-mixture combustion capability using natural gas.

Hobson et al. [1], in a study conducted on a silo combustor, developed a theoretical model which has been used to derive some generic characteristics of combustion instability in terms of damping ratio.

Richards et al. [2-3] proposed a model for instability of a simple combustor based on the passive control method. In their study, the range of frequency of stability and the improvement in stability of combustor was investigated.

Schuermans et al. [4] studied a combustion system as a network of acoustic elements and based on their model the frequency of instability was obtained. They noted that it is necessary to include flame translation in the analytical model of the flame response. Schuermans et al. [5] also investigated the limit cycle characteristics of combustion instabilities in annular combustion chambers.

Andreini et al. [6] developed a modular and mono-dimensional code (TA-1D), considering the linear acoustics analysis, to predict longitudinal resonance frequencies. They also performed a proper stability analysis for each obtained frequency and demonstrated the modal shapes of combustion chambers. Furthermore, several heat release models, such as a thin planar flame sheet or a conical flame shape, have been studied in their work. In their study [7], it has been reported that the capabilities of the code could lead to extensions of the analysis to the actual gas turbines.

Compa [7] also studied the thermoacoustic combustion instability, considering RANS simulations for modeling of the flame. His analysis was carried out by using commercial software, called COMSOL Multi-physics, based on the finite element methods. For the study of the nonlinear flame models, an acoustic network code (LOTAN) was also used. It has been

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reported [6] that the research was carried out through collaboration with Ansaldo Energia, which provided the geometry of the combustion chamber of the V94.3 machine.

According to the Rayleigh criterion [8], if the heat release fluctuations and acoustic pressure are in the same phases, this might boost the growth of oscillation's amplitude and could result in unpredicted behavior of the flame. Actually, the combustion instability is the result of a feedback mechanism . It should be noted that the onset of instability is only a part of the problem of combustion instability. Accurate and complete understanding of the phenomenon requires the realization of mechanisms that are associated with the initiation and saturation of oscillations. Also according to studies of Lieuwen [9], some factors that might lead to occurrence of combustion instability are: (1) fuel feed line-acoustic coupling; (2) equivalence-ratio oscillation; (3) oscillatory atomization, vaporization and mixing. A significant amount of research in this area has been done. In spite of all these researches, yet little is known about the exact mechanisms and their sequences which may lead to occurrence of combustion instability. It has also been reported that equivalence ratio oscillation may result in perturbation of heat release through both direct and indirect mechanisms [10].

However, in this study we focus on prediction of unstable modes which could lead to the initiation of instabilities. The models that are used in this investigation could be applied to small linear oscillations, not to the large amplitude limit cycles. However, such linear models can provide useful information. This is because; if a mode is linearly stable it will not grow to form limit cycle. Furthermore, the frequency of linear modes usually provides a good approximation of the resulting limit cycle.

In this paper the thermo-acoustic instability of a silo type combustor is investigated. For this purpose the main components of the combustor model are assumed to be a plenum, burner, flame sheet and combustion chamber. Acoustic matrices of all these subsystems are evaluated by means of thermodynamic conditions and flow speed. For instance, to model the acoustic behavior of the flame in terms of a transfer matrix, it is assumed that the acoustic and heat-release fluctuations at the flame front are coupled with fluctuations in the fuel–air mixture that are associated with acoustic disturbances at the fuel injectors. In other words, a convection time is considered to characterize the required time for the acoustic velocity fluctuations to travel from the point of injection to the location of flame front in the combustion chamber. By assembling the acoustic matrices of all subsystems, a model is generated which can predict the unstable frequency modes of the combustor. On the other hand, acoustic mode shapes of the combustor are also investigated by the COMSOL software.

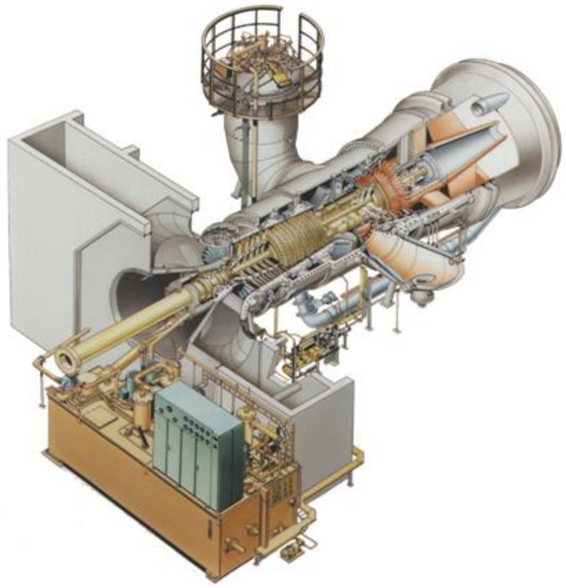

Figure 1: Silo-Type gas turbine combustor

Silo Combustor Modelling

Figure 2 shows a silo gas turbine combustor schematically. Plenum receives the combustion air which is conveyed from the compressor (not shown) and feeds it to a combustion chamber by passing the air through the outer surface of both the mixing chamber and flame tube. In some simplifications of the geometry, it has been assumed that there are two large chambers, representing the plenum and combustion chambers, which are connected by short premix ducts in which fuel is added to the air.

In this work the main subsystems of combustor are assumed to be: plenum, burner, flame sheet and combustion chamber. Using the upstream and downstream properties of mean flow, the transfer matrix of each subsystem can be determined.

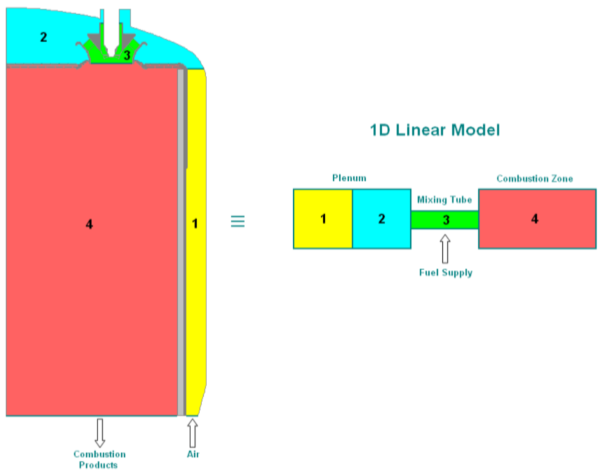

Figure 2: Schematic of flame tube in silo combustor and 1D Linear Model

Plenum Model

We consider inviscid flow plenum transfer matrix between the mixing chamber and flame tube. In this case the coefficients C1, C2, K are displayed. K represents the energy loss. This index is based on data considered in the mixing chamber. C1 and C2 = -1 are considered in [11].

Elements of plenum matrix :

$$A=\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \tag{1}$$

$$A_{11}=1-\frac{KM_1^2}{1-M_1^2}$$

$$A_{12}=\frac{KM_1Y_1}{1-M_1^2}$$

$$A_{21}=\frac{-S_3\left(1-\frac{KM_1^2}{1-M_1^2}\right)-C_1S_1\left(1-\frac{(\gamma-1)M_1^4}{1-M_1^2}\right)+\frac{C_2S_2Z_2(\gamma-1)KM_1^3}{(1-M_1^2)Y_1}}{C_2S_2Z_2+S_3M_3Y_3}$$

$$A_{22}=\frac{-\frac{S_3KM_1Y_1}{1-M_1^2}-C_1S_1M_1Y_1\left(1-\frac{(\gamma-1)M_1^2}{1-M_1^2}\right)+C_2S_2Z_2\left(1-\frac{(\gamma-1)KM_1^2}{1-M_1^2}\right)}{C_2S_2Z_2+S_3M_3Y_3}$$

Transformation matrices for different geometries are defined in [11]. Subtitle 0 and 1 to state before and after passing through cylinder is concerned.

$$\begin{bmatrix} p_0 \\ u_0 \end{bmatrix}=e^{-jMK_cl}\begin{bmatrix} \cos K_cl & jY\sin K_cl \\ (j/Y)\sin K_cl & \cos K_cl \end{bmatrix}\begin{bmatrix} p_1 \\ u_1 \end{bmatrix} \tag{2}$$

C: sound velocity
M: mean flow mach number
Z:specific acoustic impedeance
$K_c=2\pi fL/c, Y=c/S$
S: area of cross section

Burner Model

The flow in the burner element is described by the unsteady, incompressible Bernoulli equation. In this model, the effect of unsteady fluctuations is associated with inertia work. Losses caused by the complex three-dimensional flow inside the burner are taken into account by using an integral loss coefficient and as a consequence the burner transfer matrix can be written as[5]:

$$\begin{pmatrix} p_2 \\ u_2 \end{pmatrix}=\begin{bmatrix} 1 & \rho_1c_1\left[M_1(1-\varsigma-(\frac{A_1}{A_2})^2)-i\frac{\omega}{c_1}L_{red}\right] \\ 0 & \frac{A_1}{A_2} \end{bmatrix}\begin{pmatrix} p_1 \\ u_1 \end{pmatrix}, \tag{3}$$

where:

$$L_{red}=\int_0^1\frac{A_0}{A(s)}ds=\int_0^1\frac{u(s)}{u_0}ds, \tag{4}$$

ς = loss coeficient

The derivation of Eq.(3) is based on the assumption of compactness, that is, no physical length of the burner element would be considered in this study [5]. Actually for acoustic wavelengths that are much larger than burner dimensions the burner could be assumed as a compact element.

Flame Model

In order to model the acoustic behavior of the flame, it is considered that the acoustic and heat-release fluctuations at the flame front are coupled with fluctuations in the fuel–air mixture that are attributable to acoustic disturbances at the fuel injectors. This implies the existence of a characteristic time lag τ after which the fuel particles reach the flame location in the other hand this model is based on a time delay. For fuel–air mixture φ and its fluctuation in time, the following relation can be written:

$$\frac{\varphi_1'(t)}{\varphi_1}=\frac{\varphi_i'(t-\tau)}{\varphi_i} \tag{5}$$

Whereas the heat release Q in the flame can be written as:

$$Q=\varphi_1\rho_1S_fh_{fuel} \tag{6}$$

In this work, the S_f is not assumed to be constant but is considered to be affected linearly by the fuel supply which is reasonable for lean $\varphi\prec 1$ flames. $S_f\approx\varphi$ Consequently the fluctuations of heat release might be written as:

$$\frac{Q'}{Q}=2\frac{\varphi_1'}{\varphi}+\frac{\rho_1'}{\rho_1} \tag{7}$$

By using the Rankine–Hugoniot jump conditions across the flame, the flame model can be formulated as[4], [5]:

$$\begin{bmatrix} 1 & \rho_1c_1(\frac{T_2}{T_1}-1)M_1(1-e^{-i\omega\tau}) \\ 0 & (\frac{T_2}{T_1}-1)(-e^{-i\omega\tau}) \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} 1 & \rho_1c_1(\frac{T_2}{T_1}-1)M_1(1-2e^{-i\omega\tau}) \\ 0 & 1-(\frac{T_2}{T_1}-1)(2e^{-i\omega\tau}) \end{bmatrix} \tag{9}$$

With Two different flame models reached the same result in the predicted frequency of instability

Acoustic Transfer Matrix for a Step Expansion

A step expansion (in the form of sudden area change) is placed at the interface between the burner exit and the combustor inlet. The heat release region is treated as a thin flame sheet located just downstream of this step expansion. The acoustic transfer matrix for step expansion is:

$$
\begin{bmatrix} 1 & M_2 Y_{02} \\ M_2/Y_{02} & 1 \end{bmatrix}
\begin{bmatrix} P_2 \\ V_2 \end{bmatrix} =
$$

$$
\begin{bmatrix} 1-\dfrac{KM_1Y_1}{1-M_1^2} & \dfrac{KM_1Y_1}{1-M_1^2} \\ \dfrac{(\gamma-1)KM_1^3}{(1-M_1^2)Y_1} & 1-\dfrac{(\gamma-1)kM_1^2}{1-M_1^2} \end{bmatrix}
\begin{bmatrix} 1 & M_1 Y_{01} \\ M_1/Y_{01} & 1 \end{bmatrix}
\begin{bmatrix} P_1 \\ V_1 \end{bmatrix}
$$

(10)

Boundary Conditions

To study the effect of boundary conditions on thermoacoustic modes of combustor, various inlet and outlet boundary conditions, as shown in Table 1, were considered in this analysis.

Table 1 Combustion chamber boundary conditions[6].

Type	**Boundary Condition**	**Acoustic Impedance**
Open	$P' = 0$	$Z = 0$
Closed	$u' = 0$	$Z = \infty$
Non-reflective		$Z = \pm 1$
Choked outlet	m' = Constant	$2u'/u + p'/p - p'/p = 0$
Choked Inlet	m' = Constant	$u'/u + p'/p = 0$

Method of Analysis

All the transfer matrices can be combined into one system of equations, as shown in Eq.(8). The left-hand side of this equation consists of a large matrix that contains the transfer matrices of each subsystem and of a vector that contains the unknown pressures and velocities. The right-hand side of this equation contains the source terms.

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M = [m_1_1,m_1_2,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
    TM_TUBEA(1,1),TM_TUBEA(1,2),-1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
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    0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,TM_TUBEE(2,1),TM_TUBEE(2,2)
    0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,m_16_15,m_16_16];
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The stability of the system can be assessed by analyzing the system's eigenvalues. The eigenvalues are frequencies for which the determinant of the large matrix (that contains the transfer matrices) vanishes. This determinant of large matrix can be solved by using a numerical root-finding procedure. If the imaginary parts of all roots are larger than zero, then the system is stable. If one or more roots have negative imaginary parts, then the system would be unstable. In addition, stability borders of the system as a function of the operation parameters, such as flame temperature, can also be determined.

A numerical-graphical method for solving the system of equations is used. The stability of the system can be assessed by analyzing the system's complex-valued eigenvalues. The eigenvalues are frequencies of instability for which the determinant of the matrix vanishes. Real and imaginary parts of determinant of marix in the ranges of 0-100 Hz for frequency and 0-0.1 second for time lag are shown in Fig. 3-6. The frequency of instability in this ranges is 80Hz.

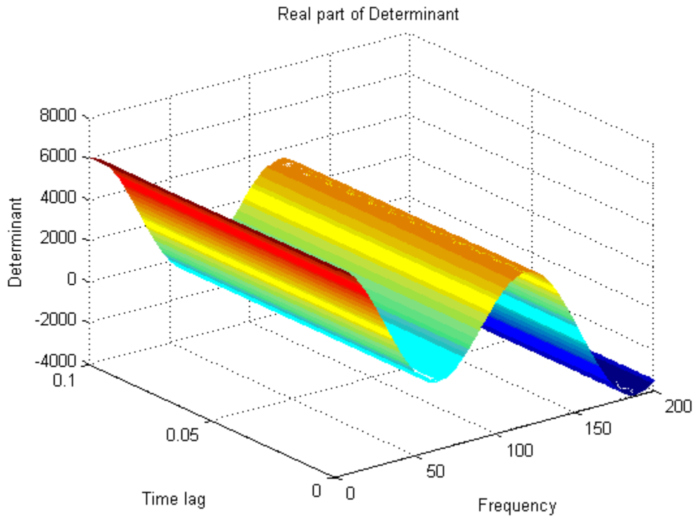

Figure 3: Real part of determinant of matrix vs frequency and time lag

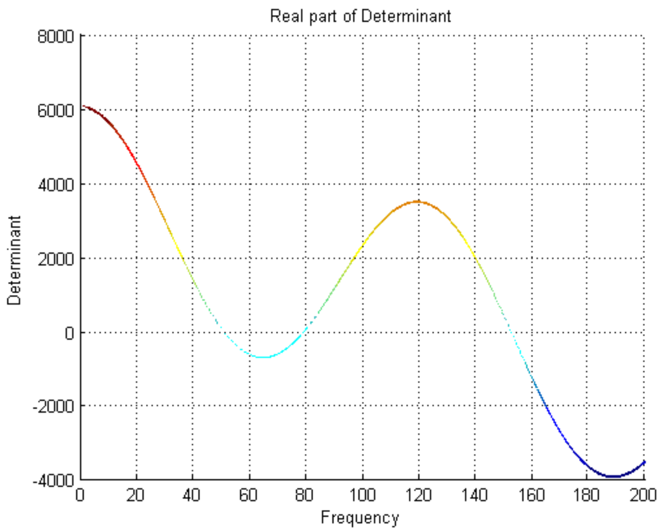

Figure 4: Real part of determinant vs frequency

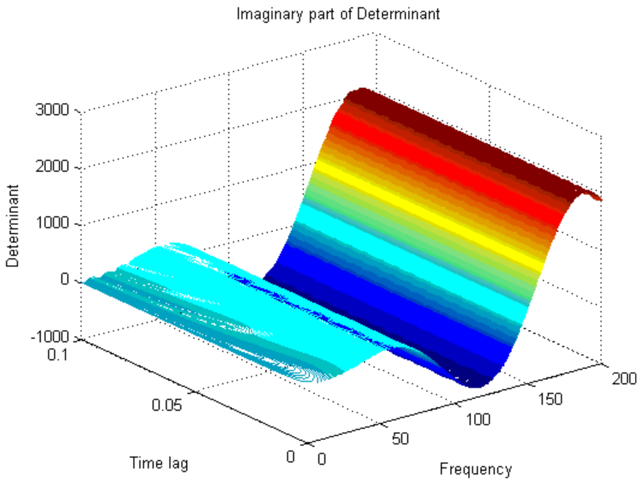

Figure 5: Imaginary part of determinant of matrix vs frequency and time lag

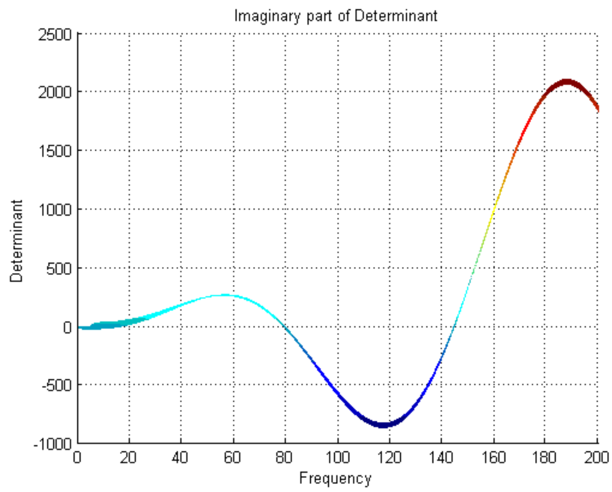

Figure 6: Imaginary part of determinant vs frequency

Combustion instability is the result of an interaction between acoustic pressure fluctuation and heat-release perturbation. The feedback element (H) represet the conversion of heat-release variations into a pressure disturbance. The output signal from block H would represent the pressure produced in the flame region. [2]

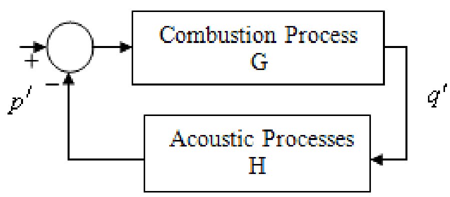

Figure 7: Block diagram of a dynamic thermoacoustic system

Fig.7 shows the variation of amplitude and phase of the system transfer function. This analysis indicates that the dominant modes of the system are around 80, 231 and 384 Hz.

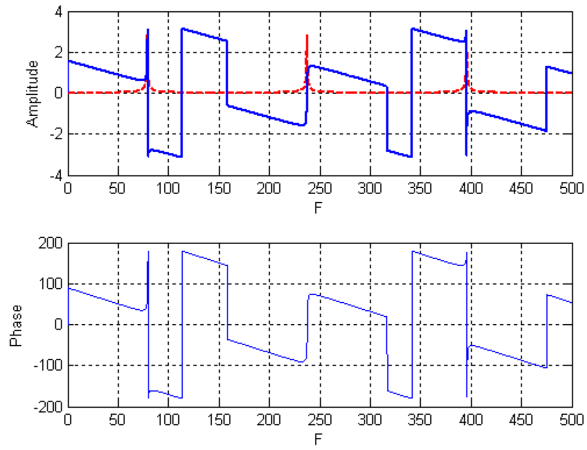

Figure 8: Amplitude and phase of the system transfer function versus frequency.

Results

The geometry of the silo combustion chamber is created from real data. The geometry created at this stage is simplified compared to the main drawing. Some detailed parts are cut off, since their influence to the acoustical analysis is negligible. These simplifications are allowable because the dimensions of these elements are smaller than the dominant acoustic wavelength. Using COMSOL software the modeshapes of silo combustor were obtained and based on these results the dominant frequencies of system is studied. Results show that the dominant longitudinal mode are 80 Hz. The first longitudinal acoustic mode of 80 Hz is shown in Figure 8. In Figure 9, the results of the data collected during the humming occurred shown.

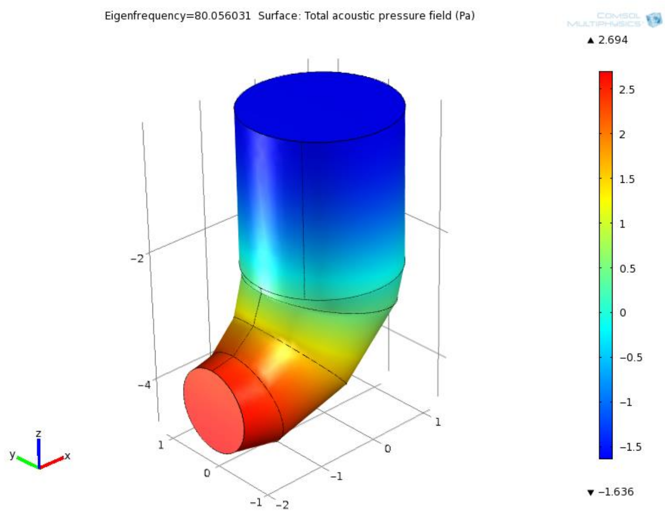

Figure 9. Acoustic modeshape of the combustor for frequency of 80 Hz

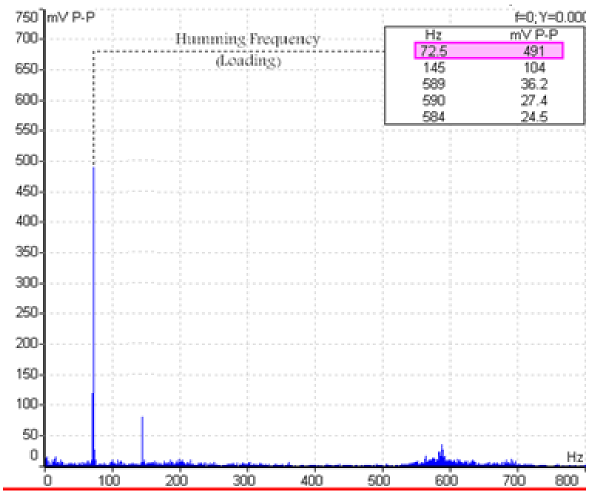

Figure 10: Frequency of humming by measurements

Table 2: Results of predicted frequency

Method	Frequency(Hz)
Hobson et al. [1]	78
Analytical [2-3]	80
Analytical [4-5]	79
COMSOl	80
Measurements	72.5

Conclusions

In this study, thermoacoustic modes of a silo combustor (MGT-70 heavy-duty gas turbine) were investigated using theoretical models together with COMSOL software. The frequencies associated with dominant acoustic modes of this combustor which are obtained from analytical models and simulation show a reasonable agreement. These frequencies are in the range of results which has been reported in previous studies [1] and is shown in table 2.

Acknowledgments

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