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THE INTERACTION OF COMBUSTION PRESSURE OSCILLATIONS AND LINER VIBRATIONS

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Abstract

Gas turbine combustors have at industrial scale a thermal power released by combustion of 1 to 400 MW. As the flames in these combustors are very turbulent, the combustion generates high levels of thermo acoustic noise. Of crucial importance for the operation of the engine is not the noise emitted, but its structural integrity. This may be at hazard when the combustor liner starts to vibrate in a mode linked to the thermo acoustic noise. This is even more likely when the combustion noise changes to an unstable closed loop feed back system. Another dangerous situation may arise when there is a two way interaction between the combustion oscillations and the liner vibration. For these reasons the understanding of transient combustion and its coupling with wall vibration in a typical gas turbine combustion chamber is of prime interest. This phenomenon is investigated in the project FLUISTCOM in both experimental and numerical work.

In the project a liner was designed with a thin, flexible section with a significant amplitude response on changes in the pressure field caused by the combustion oscillations. Numerical calculations of eigenfrequencies and eigenmodes were performed, followed by transient numerical calculations of the transient combusting flow within the combustion chamber with the use of CFX-ANSYS. The flame investigated was a 1.5 bar, 150 kW premixed natural gas flame.

Solutions for the pressure field obtained during numerical computations of the combustor flow were collected and implemented in the structural code (Ansys) as surface loads on the liner side. Results show the one way response of the liner structure as a result of the transient pressure generated by the combustion of the gas flow.

The paper will present the predicted results on the combustion field, the accompanying oscillating pressure field, and the induced structural vibration of the combustor liner as predicted by the finite element structural code.

INTRODUCTION

Gas turbine technology moved to decreased burning temperatures for natural gas lean premixed combustion. However, flames are more sensitive to intrinsic instabilities in case of lean premixed combustion [4]. The instabilities have a source in interaction between heat and sound [5]. This behaviour can lead to self-excited oscillations of such high amplitude that fatigue damage of the structural parts is done. Understanding of transient combustion and its coupling with the wall vibration in a typical gas turbine is the prime interest of the EU sponsored FLUISTCOM project. Experimental and numerical work concerning the interaction between fluid flow behaviour and a liner wall structure vibration is performed.

To investigate fluid-structure interaction a laboratory scale liner with well controlled acoustic and structural boundary conditions and maximized flexibility was designed. The main part of the liner is a thin, flexible section which has a significant amplitude response on changes in the pressure field caused by the combustion oscillations (fig. 1). Analytical and numerical calculations of eigenfrequencies and eigenmodes were performed to provide information about the structural dynamics of the liner. Subsequently transient numerical calculations of the transient combusting flow within the explored combustion chamber were performed with the use of the CFX-Ansys CFD code. Solutions for the mechanical load field obtained during numerical computations were collected and implemented in the Ansys structural code as a surface load on the liner side. Thereafter two-way computations with direct exchange information between two solvers and with the introduction of moving walls during the fluid dynamic analysis were done. Results obtained show the one- and two-way response of the liner structure as a result of the transient pressure field generated by the combustion of the gas flow.

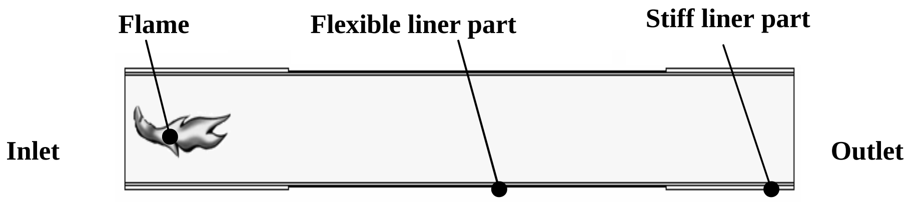

Figure 1: Combustion chamber geometry

EIGENFREQUENCIES AND EIGENMODES INVESTIGATION

Analytical model

To validate the results for the liner wall dynamics, as obtained from numerical calculations, the combustion chamber wall model was investigated with use of analytical data. In the analytical analysis the plate was supported by four side clamped boundary conditions. The width/length ratio of the plate was 0.4 what corresponds to data in table 1; isotropic material properties for stainless steel are presented in table 2. The plate eigenfrequencies for clamped degrees of freedom are given by Blevins [2].

$$f_{ij} = \frac{\lambda_{ij}^2}{2\pi a^2}\sqrt{\frac{Eh^3}{12\gamma(1-\nu^2)}} \qquad \text{[Hz]} \tag{1}$$

In addition to that, a finite element model with equally distributed Shell type 63 elements mesh with dimensions, material properties and boundary conditions like the analytical result, was set up.

Mode	λ_{ij}^2
1	*23.65*
2	*27.82*
3	*35.45*
4	*46.70*

Table 1. Value of λ_{ij}^2 for a clamped plate

Symbol	*Description*	*Value*
E	*Young's modulus*	*210 [GPa]*
h	*Plate thickness*	*0.001 [m]*
a	*Plate width*	*0.15 [m]*
γ	*Mass per unit area*	*7.8 [kg/m²]*
ν	*Poisson's ratio*	*0.3 [-]*
ρ	*Density*	*7800 [kg/m³]*

Table 2. Material properties and geometry dimensions

Numerical and analytical results are in good agreement (tab. 3). Based on that fact, it was assumed that the results obtained from the numerical calculations for the liner eigenfrequencies are correct.

Analytical calculations	*Ansys calculations for liner structural model*
262.68	*262.30*
308.99	*308.19*
393.74	*392.18*
518.69	*516.49*

Table 3. Analytical and numerical comparison of eigenfrequencies

Numerical investigation

To investigate the fluid-structure interaction a liner with well controlled acoustic and structural boundary conditions and maximized flexibility is needed. To fulfil these requirements several liners with different shape, thickness and length of the flexible section were considered. The influence of the combustion chamber and cooling passage cavities at elevated temperature was tested as well. Properties of stainless steel and air were adequate to work at room temperature (20 ^oC) and during combustion process (air and stainless steel temperatures are 1530 ^oC and 760 ^oC, respectively). Pressure degrees of freedom from the combustion chamber and from the cooling passage were coupled directly to the structural nodes. To prevent junction nodes from the air cavities, the structural part was divided into two equal segments connected but with displacement degrees of freedom [3]. Both ends of the air cavities were modelled as acoustically hard walls. As the dynamic liner behaviour depends mainly on the flexible part, only this section was modelled in the Ansys code.

Results obtained during numerical investigation show that significant decrease of the liner eigenfrequencies can be obtained by modification of the liner shape or geometrical walls dimensions (fig. 2a, 2b). The observed system behaviour is caused by variations in the second moment of area and mass of the solid body. Another source of the diminishing eigenfrequencies is the elevated temperature (fig. 2d), which changes substantially the material properties. The influence of the surrounding air cavities is not as significant as the geometrical dimensions and the material properties but it also affects eigenfrequencies (fig. 2c). The vibrating liner body induces vibrations of the air in the combustion chamber and the cooling passage, which are a source of additional inertia forces due to the mass of air.

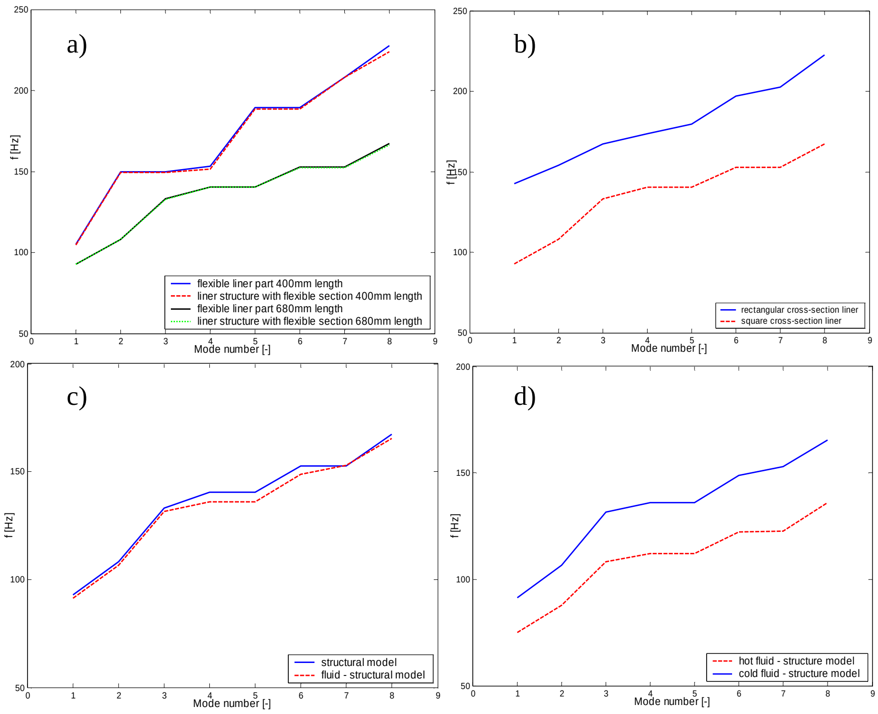

Figure 2. Eigenfrequency investigation: a) the total liner structure and flexible section only; also lengths comparison, b) rectangular and square cross-section shapes, c) structural and fluid-structural model, d) hot and cold calculations of fluid-structural model

The eigenmodes pattern obtained during the modal analysis of the most flexible liner (fig. 3) presents a strongly 'one dimensional' mode distribution caused by the small width/length ratio. Analytical and numerical investigation of eigenmodes and eigenfrequencies of the solid structure were performed to provide information about the structural dynamics of the liner and to find one with the highest flexibility to perform further experimental and numerical analysis.

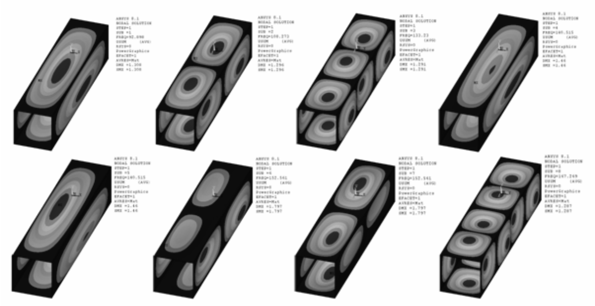

Figure 3. Eigenmodes pattern

INTERACTION ANALYSIS

One- and two-way interaction is a sequential or simultaneously process of combined fluid and solid dynamics analysis. The surface forces from the CFD calculation are exported to the structural code with automatic support for the independent mesh. This allows the fluid and solid domain to be meshed independently with various element shape, size and distribution. The structural body shape should be simplified in order to obtain efficient computational coupling with the corresponding fluid region. Also both models must be coincident in space to predict well the amplitude of deformations and stresses. During one-way analysis the solutions for the normal (pressure) and tangential (shear) components of the mechanical load obtained during transient numerical simulation of the combusting flow inside the combustion chamber are input to the structural code as a surface load on the liner side. Two-way interaction is based on the dynamically exchange of data concerning mechanical forces (fluid solver) and mesh displacement (structural solver). In this case any changes in the wall geometry caused by pressure and shear influence are immediately transferred to the fluid solver which calculates the next step with the new, changed geometry and sends a new load field to the solid solver [1].

For the interaction analysis, transient numerical calculations of the transient combusting flow within the explored chamber were performed with the use of the CFD code CFX-Ansys. In order to save computational time and to increase the number of elements within the calculated domain, the model domain was reduced to a quarter section of the real combustion chamber, with periodic boundary conditions. Most of the elements were placed near the burner mouth region to monitor phenomena that occur during the combustion process. The investigated flame was a premixed natural gas flame with conditions presented in table 4. The combustion was described by the standard CFX one step Eddy Dissipation and Finite Rate Chemistry model; turbulences by k-ε model. Transient calculations were done with 5% perturbation of the equivalence ratio with 100 Hz frequency. A constant time step of 0.5 ms for both analyses was chosen. Results obtained from the RANS calculation of the whole combustion system served as the inlet boundary conditions. Moreover adiabatic walls were assumed and the influence of the pressure from the cooling passage neglected.

Power [kW]	*Absolute pressure [bar]*	*Air factor [-]*	*Total mass flow [g/s]*	*Air preheating temperature [K]*
150	*1.5*	*1.8*	*90.64*	*593*

Table 4. Operating conditions

Associated with the CFD model, a structural dynamics model of the wall was prepared in the FEM code Ansys. The model consists of 7 500 equally distributed elements of type Solid 92. All degrees of freedom of the wall lateral surfaces are taken away (fig. 4). The liner has a modular structure and because of the slide connection between its segments it can expand freely without significant thermal stresses and without change in the total length (fig. 5). As thermal stresses and elongation of the liner structure has not a significant effect on the dynamic liner behaviour but increase substantially the computation time by sending additional thermal data to the structural code, properties of stainless steel are taken at a temperature of 760 ^{o}C. Every time step the mechanical load of the CFX transient analysis is sent to the Ansys code (one-way) and in case of two way interaction the structural code also sends back information about the wall deformation.

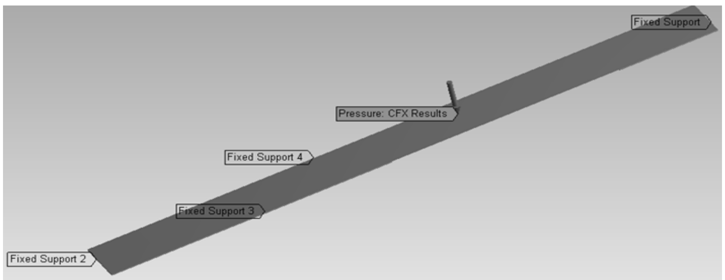

Figure 4. Boundary conditions in solid model

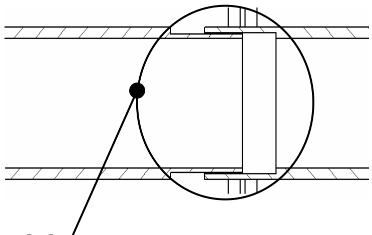

Figure 5. Liner modular structure

Due to the slender design the pressure field inside a typical combustion chamber is often assumed to be one-dimensional and depending on the axial direction only (but in fact some variations can be observed). During numerical analysis the pressure field in the region near the wall was non-uniform, especially in the flame zone, where maximal and minimal pressure amplitudes for one-way interaction were observed. This behaviour was even promoted during two-way interactions in such a scale that maximal and minimal pressure were noticed on the flexible liner wall (fig. 6). Because the thickness of investigated liner in the flame zone is high (4 mm) pressure changes in this area do not affect substantially the liner vibration pattern. The opposite situation was noticed near the flexible wall, where significant fluctuations in the pressure field induced vibration of the liner structure. The variation in the pressure amplitude near the wall region differed significantly for the one- and two-way interaction. Minimal and maximal values observed at the point located in the middle of the liner face are approximately 600-770 Pa for one-way investigation and 540-840 Pa for two-way interaction (fig. 7). This is caused by the fact that during one-way interaction changes in the liner geometry do not disturb the flow pattern. It means that structural vibrations do not induce any vibration in the fluid. The pressure sound field is caused only by the fluctuation in equivalence ratio and therefore looks like a sinus function. In the case of two-way analysis, where geometry/mesh changes are transported to the CFX code, the vibration plate enforces also vibrations of the air inside the combustion chamber. The differences in amplitude of the pressure fluctuation near the wall region during both analyses do not affect significantly the deformation pattern. Maximal deformations for one- and two-way interactions are 0.37 mm and 0.38 mm, respectively. The influence of the air mass excited by the mesh deformation in the CFX code with comparison to the vibrating liner mass is too small to substantially change the wall deformations amplitude but it can affect shape changes (fig. 8). The deformation pattern in both cases shows not only the first mode but also higher modes (fig. 9).

During both analyses, maximal stresses (equal approximately 20 MPa) remain below the yield point, which for this kind of steel at temperature of 760 ^{o}C is approximately 135 MPa. It means that the liner operates in the elasticity range and that plastic deformations of the flexible part are not a risk.

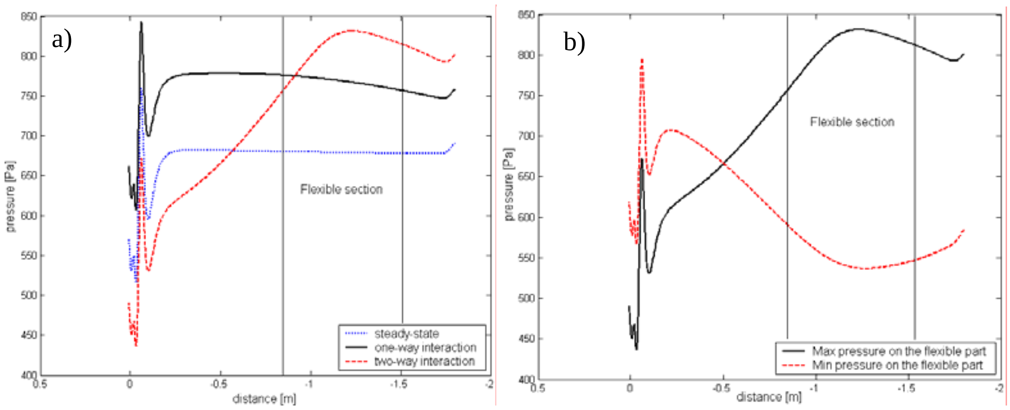

Figure 6. Pressure changes along the liner a) steady-state and maximal values in case of interaction analyses b) maximal and minimal value in case of two-way interaction

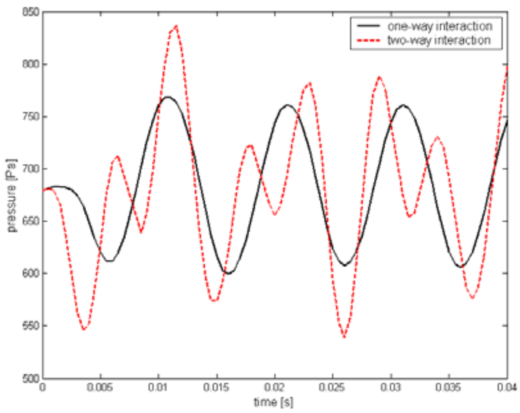

Figure 7. Pressure changes at the point located on the flexible liner face

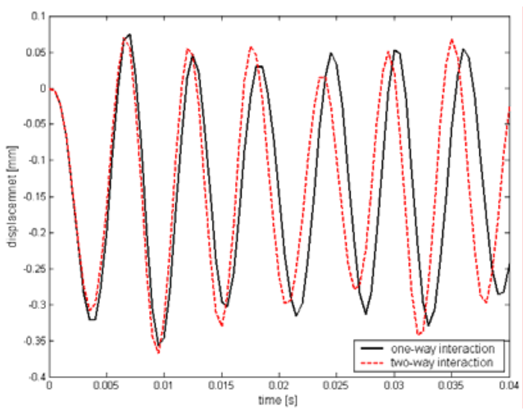

Figure 8. Structural response on pressure changes

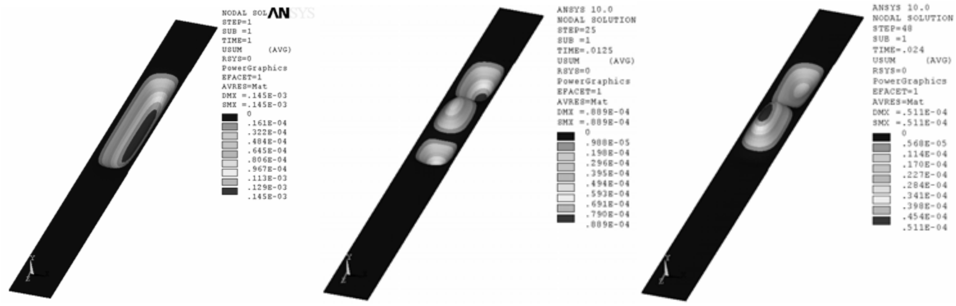

Figure 9. Deformation shape

CONCLUSIONS

Analytical and numerical calculations were done to investigate eigenfrequencies and eigenmodes present inside the combustion chamber due to noise generated by the combustion process. The liner stiffness plays an important role in the interaction between the fluid and structure behaviour. Thus for better insight in this phenomenon a very flexible liner was designed with a first eigenfrequency below 100 Hz. Significant eigenfrequency dependence on changes in geometrical dimensions and material properties was predicted. The influence of the combustion chamber and cooling passage cavities on the eigenfrequencies was calculated. Subsequently, an one- and two-way interaction analysis with a fluctuation of the equivalence ratio during the combustion process was done. The investigations show a significant influence of the moving walls on the pressure behaviour inside the combustion chamber. Also the influence of mechanical loads obtained during flow analysis on liner deformation was investigated. Both coupled analyses show similar deformation amplitude. The investigations confirmed the presence of small elastic deformation in the liner structure as the result of oscillations in the pressure field during combustion.

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