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Investigation of the Effects of Dimensional Variations and Manufacturing Tolerances on the Modal Behavior of the IGT25 Combustion Chamber

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Abstract

The dynamic behavior of a gas turbine combustion chamber is governed by two main external excitation sources: the dynamic pressure fluctuations generated by combustion instabilities and the unbalanced forces transmitted from the rotor. The vibrations induced in the combustion chamber structure by these excitations may cause structural resonances, which play a crucial role in the analysis and design of the chamber. Such resonant conditions can lead to failure, particularly through the activation of high-cycle fatigue and wear mechanisms, thereby directly or indirectly reducing the structural lifespan of the combustion chamber. Achieving an accurate and reliable dynamic analysis is essential for determining the chamber's modal characteristics, including its natural frequencies and mode shapes, which enable precise identification of the frequency ranges where excitation and structural responses may interact. Various factors—including boundary conditions, geometric configuration, and finite element modeling parameters—significantly influence the predicted modal properties. The IGT25 gas turbine, one of the products of OTC Company, incorporates an annular combustion chamber with complex geometry and multiple assembled components. During the manufacturing and assembly stages, dimensional tolerances are defined within standard acceptable limits; therefore, individual chambers may exhibit slight geometric variations in accordance with these tolerances. In this study, the experimentally obtained natural frequencies, extracted through impact testing, are compared with the numerical modal analysis results. The effects of dimensional variations and manufacturing tolerances of the IGT25 combustion chamber on the modal properties—specifically the natural frequencies and mode shapes—are then investigated. Determining the variation range of the structural natural frequencies due to manufacturing tolerances and assembly-induced dimensional deviations is essential for assessing their potential interaction with excitation frequencies.

Keywords: Modal Analysis; Impact Hammer Test; Combustion Chamber; Gas Turbine.

1. Introduction

The external excitation sources acting on the combustion chamber of a gas turbine primarily include combustion instabilities caused by dynamic pressure fluctuations in the hot gas flow and rotor unbalance, which induces vibration through the combustion casing. The interaction between the natural frequencies of the combustion chamber and the excitation frequencies arising from combustion oscillations and rotor unbalance may lead to structural resonance, which can directly cause failure in critical components. Moreover, these oscillations can activate wear and high-cycle fatigue mechanisms, resulting in damage to vital parts and consequently affecting the structural lifetime [1]. In some cases, such vibrations may cause operational disturbances within only a few hours of turbine operation. However, due to the inherently non-axisymmetric nature of the combustion chamber, this issue has received limited attention in the existing literature. Previous research has primarily focused on the dynamic behaviour of rotors and casings, while the detailed vibration characteristics of the combustion chamber structure itself have been comparatively less investigated [2].

Modal analysis is a fundamental approach for identifying the inherent dynamic characteristics of a system, including its natural frequencies, damping ratios, and mode shapes. A mode shape represents the characteristic deformation pattern of a structure when excited at one of its natural frequencies. This analysis provides the foundation for understanding and predicting the vibrational behaviour of complex structures such as gas turbine combustion chambers [3]. In the design of a combustion chamber structure, accurately determining the natural frequencies and mode shapes is crucial for mitigating the potentially damaging effects of excitation frequencies on the structure [4]. The dynamic behaviour of combustion chambers is influenced by factors such as joint and contact conditions, material properties, geometric details, and finite element modelling parameters of the assembly. Despite the importance of these factors, industrial studies on combustion chamber dynamics—based on numerical and experimental modal analyses—remain limited. In particular, detailed investigations into how these factors affect natural frequencies and mode shapes are scarce. Previous work at Turbotec indicates that for large and complex assemblies like the IGT25 combustion chamber, accurate determination of modal properties requires both experimental and numerical analyses, as well as systematic evaluation of the independent effects of key parameters [5].

Manufacturing tolerances in the dimensions of combustion chamber components, as well as dimensional variations arising during assembly, can result in chambers with slightly different geometries, all within acceptable standards and manufacturing limits. In this study, the effects of these manufacturing tolerances and dimensional variations on the modal analysis results of the complete IGT25 combustion chamber assembly are investigated, enabling the determination of the range of natural frequency shifts and mode shape changes. The interaction between the chamber's natural frequencies and its excitation sources is then examined to support more precise structural design. To achieve this, a numerical modal analysis is first performed on the finite element model, followed by a systematic evaluation of the independent effects of tolerances and dimensional variations on simpler subassemblies and individual components, with results compared against experimental and numerical data.

2. Modal Analysis

The modal behaviour of a structure can be investigated through both numerical and experimental approaches. In this study, numerical modal analysis is performed using finite element software, such as ANSYS Workbench, to obtain the structural mode shapes and their corresponding natural frequencies. Experimental modal analysis is conducted via impact hammer testing, where the structure is excited and frequency responses are measured at a grid of points [5,6]. Impact heads with different stiffnesses can be employed to cover specific frequency ranges. As shown in Figure 1, the IGT25 combustion chamber exhibits significant geometric and manufacturing complexity. To evaluate the independent effects of manufacturing tolerances and dimensional variations, both the liner segments and the complete combustion chamber subassemblies are analysed separately, providing insight into how these factors influence the modal characteristics [7].

Figure 1. 3D schematic of the combustion chamber (right side) and the FE Model of the inner liner (left Side) of the IGT25 gas turbine

As shown in Figure 2, modal impact testing was performed on the complete assembly and on individual segments of the inner liner under free boundary conditions, achieved by suspending the structure with soft straps at ambient temperature.

Figure 2. Impact hammer testing on combustion chamber components and assembly under free boundary conditions.

The combustion chamber finite element model was developed using second-order tetrahedral elements. To verify mesh independence, models with maximum element sizes of 25, 16, 10, 6, and 4 mm were analyzed, and the first three natural frequencies were compared relative to the mesh volume (Figure 3). The model with a 6 mm maximum element size was selected as the converged solution.

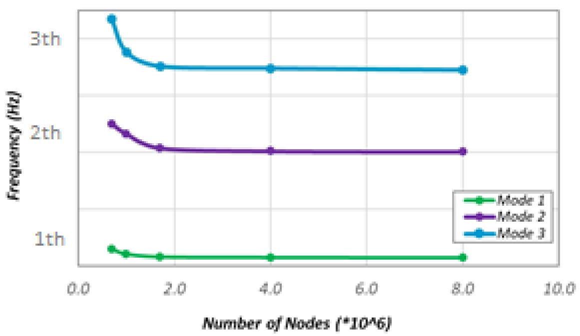

Figure 3. Variation of the first three natural frequencies with the mesh volume

3. Parameter Study

The liner segments, free of contact surfaces, joints, or geometric complexities, provide an ideal case for independently assessing the effects of manufacturing tolerances. According to the IGT25 fabrication drawings, each segment has specific tolerances for thickness and length, allowing production within the allowable range. Dimensional variations, particularly in thickness, affect structural stiffness and mass, thereby altering the natural frequencies, which are inversely proportional to mass and directly proportional to stiffness [8]. To systematically investigate these effects, models representing the minimum and maximum allowable dimensions and corresponding mass variations were generated. The natural frequencies of these models were then compared with those of the nominal-dimension model. Table 1 summarizes the first five natural frequencies under identical boundary conditions, temperature, and material properties.

Table 1. Effect of segment dimensional tolerances on numerical natural frequencies

Mode Number	Frequency [Hz]	Δf (with Max Weight) [%]	Δf (with Max Thickness) [%]
1	22.266	4.90	5.17
2	37.546	5.69	6.06
3	62.751	4.94	5.21
4	119.520	5.02	5.29
5	126.390	5.60	6.05

The modal analysis results in Table 1 indicate that thickness variations within the specified manufacturing tolerances can change the natural frequencies of a segment by an average of 5.5%. Simultaneous variations in thickness and length, resulting in minimum segment mass, produce an average 5% difference compared to the nominal-dimension model. Thickness variations have a greater impact than length, as they directly affect structural stiffness, whereas length primarily influences mass. The first five experimental and numerical natural frequencies of the liner segment are summarized in Table 2. The mode frequencies differ by a nearly constant 4%, suggesting the influence of a single dominant factor. With material properties confirmed, these discrepancies are attributed to the effects of manufacturing tolerances.

Table 2. Comparison of numerical and experimental natural frequencies of the segment

Mode Number	FEM Frequency [Normalized]	Experimental Frequency [Normalized]	Frequency Deviation Δf [%]
1	0.17	0.166	-4.76
2	0.293	0.301	2.63
3	0.492	0.468	-5.08
4	0.944	0.888	-6.25
5	1	0.984	-1.61

Investigation of manufacturing tolerances in IGT25 combustion chamber components shows that their effects, with an average influence of around 5%, are a significant factor in modal analysis and a critical consideration in structural dynamic assessment.

During assembly, the joining between liner segments forms the main liner assembly, which is then positioned onto the burner assembly to complete the combustion chamber. When components from different subassemblies are assembled, contacting parts are machined according to fabrication instructions. Specifically, the end components and the first liner segment are machined following standard procedures (Figure 4). Dimensional variations of these machined parts, within acceptable tolerance limits, represent an additional source of variation in component dimensions and can influence the natural frequencies and mode shapes of the combustion chamber structure.

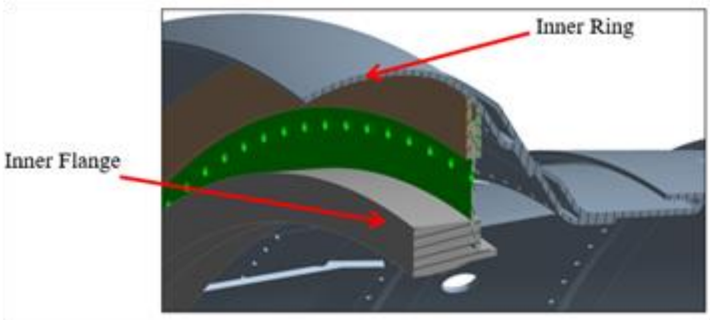

Figure 4. End components of the inner liner of the IGT25 combustion chamber.

To investigate the effect of dimensional changes in the liner assembly due to machining, two finite element models were generated, representing the minimum and maximum allowable dimensions according to the machining guidelines. The first five natural frequencies of the liner assembly obtained from the numerical modal analysis of these models are summarized in Table 3. Frequency differences across the first five modes vary.

As shown in Figures 1 and 2, the liner assembly consists of multiple contacting and connected components. The degrees of freedom at the segment connections in the main section and at the liner end can give rise to diverse mode shapes, depending on which parts are involved in each mode. To better understand the variable frequency differences, the first five mode shapes were analyzed to identify the sources of these variations.

According to Table 3, the largest frequency differences, 7% and 6%, occur in the second and fifth modes, respectively. Examination of these mode shapes shows that the maximum vibration amplitudes occur at the flange and ring components at the liner end. Therefore, dimensional changes—particularly in thickness—of these machined parts alter structural stiffness, resulting in larger shifts in the corresponding natural frequencies. The second mode shape of the liner assembly is shown as an example in Figure 5, illustrating the maximum vibration amplitude at the inner flange.

Table 3. Comparison of the liner's natural frequencies at maximum and minimum machining dimensions

Mode Number	$f_{min\ size}$ (Normalized)	$f_{max\ size}$ (Normalized)	Δf [%]
1	0.18	0.17	3.78
2	0.39	0.36	**6.95**
3	0.47	0.47	0.17
4	0.87	0.88	-0.81
5	1	0.94	**6.03**

The third and fourth modes exhibit frequency differences of less than 1% between the minimum and maximum machined liner dimensions. These modes have their maximum vibration amplitudes on the central segments, which are unaffected by machining. Consequently, dimensional changes due to machining do not influence the natural frequencies associated with these modes. Overall, dimensional variations of machined components affect the natural frequencies of modes with maximum amplitudes on the machined parts by an average of 6.5%, which is a significant impact.

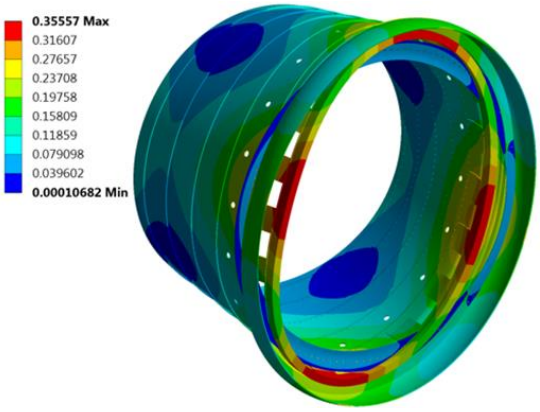

Figure 5. Second mode shape of the inner liner of the IGT25 combustion chamber

4. Conclusion

This study provides a detailed investigation of the dynamic behavior of the IGT25 gas turbine combustion chamber through combined numerical and experimental modal analyses to examine the effects of component dimensional variations. Understanding the chamber's dynamic characteristics is crucial for accurately determining its natural frequencies and mode shapes, predicting potential structural damage from interactions with excitation frequencies caused by combustion instabilities and rotor unbalance, and assessing the service life with respect to vibration-induced damage mechanisms such as high-cycle fatigue and wear.

To systematically evaluate the effects of manufacturing and assembly parameters, components and subassemblies of the combustion chamber were analyzed sequentially, allowing the independent impact of each factor to be observed. Modal impact tests and numerical analyses were performed on both the liner segments and the complete inner liner assembly to investigate the effects of dimensional variations on the modal characteristics. Dimensional variations arising from manufacturing tolerances and machining procedures were found to influence the chamber's modal properties significantly. Thickness variations in liner segments can alter natural frequencies by up to 5.5%, while combined thickness and length variations produce differences of approximately 5%. In assembled components, machining-induced changes in critical parts such as flanges and rings can shift natural frequencies by an average of 6.5%, with modes exhibiting maximum amplitudes on machined parts being most affected.

These shifts in natural frequencies due to tolerances and machining are particularly important when comparing structural natural frequencies with excitation frequencies to identify potential resonances or critical frequency bands that could cause damage. The agreement between numerical and experimental results confirms the sensitivity of the combustion chamber's modal response to component tolerances and assembly variations. Overall, these findings emphasize the need to account for manufacturing and assembly-induced variations in the design and analysis of gas turbine combustion chambers to ensure structural integrity and extend operational life.

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