Vibration Analysis of a Compressor Blade at High Temperature

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Abstract

This paper summarizes the vibration analysis of a stage two T56 compressor blade at high temperature. First, an implicit thermal analysis was performed to elevate the blade's temperature to 700°C. The output parameters of this analysis were then used as a "pre-stress" condition of the blade prior to starting the vibration analysis. Velocity results obtained using numerical simulations were compared to experimental results. The simulation was able to capture the peak velocity within 10% of the experimental result. This analysis was also used to estimate the peak equivalent stress location under combined vibration and high temperature loading. Increased stress was found around the base of the blade where the physical geometry changed abruptly and where the loading was applied.

Introduction

Military and aerospace customers require that component specifications be verified by test over their full range of environmental conditions. For most components, vibration and temperature testing can be performed independently because there is little coupling between the ambient temperature and the components vibration response. However, the effect of temperature on the compressor engine blade vibration response due to dynamic loading can be significant, making simultaneous vibration and temperature testing essential to demonstrate compliance.

This work is concerned with the numerical simulation of vibration analysis of a compressor blade at an elevated temperature. The finite element analysis (FEA) program LS-DYNA® [1] was used to perform this simulation. The thermal analysis was first performed using the implicit solver to elevate the blade's temperature (from room temperature 21°C to 700°C) to capture the resulting physical parameters (i.e. displacement and strains). The results from the thermal analysis were then imported into an explicit analysis for the vibration simulation. The vibration analysis was performed using the "Frequency Random Vibration Fatigue" keyword to compute the velocity profile for a base excitation at different power spectral density (PSD) inputs.

Experimental Testing

The main purpose of the experimental test was to obtain the velocity on the blade at room temperature (21°C) and at 700°C as documented in [2]. Three PSD levels at 2g, 3g and 4g across a bandwidth of 400Hz to 600Hz was used to excite the blade. Note here "g" represents acceleration due to gravity or 9.81m/s.

A variety of equipment was used to conduct the experimental test. The primary equipment is listed below and shown in Figures 1 & 2.

- Stage two T56 Compressor Blade
- Test Fixture used to attach the Blade to the Shaker Table
- Shaker System
- Thermal Chamber in house constructed thermal chamber
- Water Cooling System

- Laser Vibrometer Recorder System (Figure 2) coupled with the LMS [3] data acquisition software

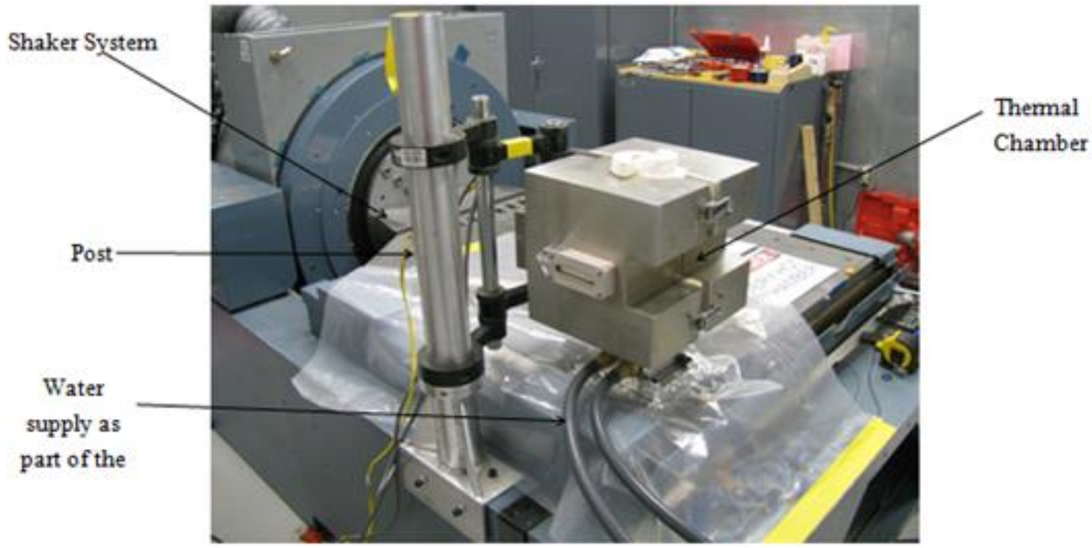

Figure 2: Thermal chamber supporting posts

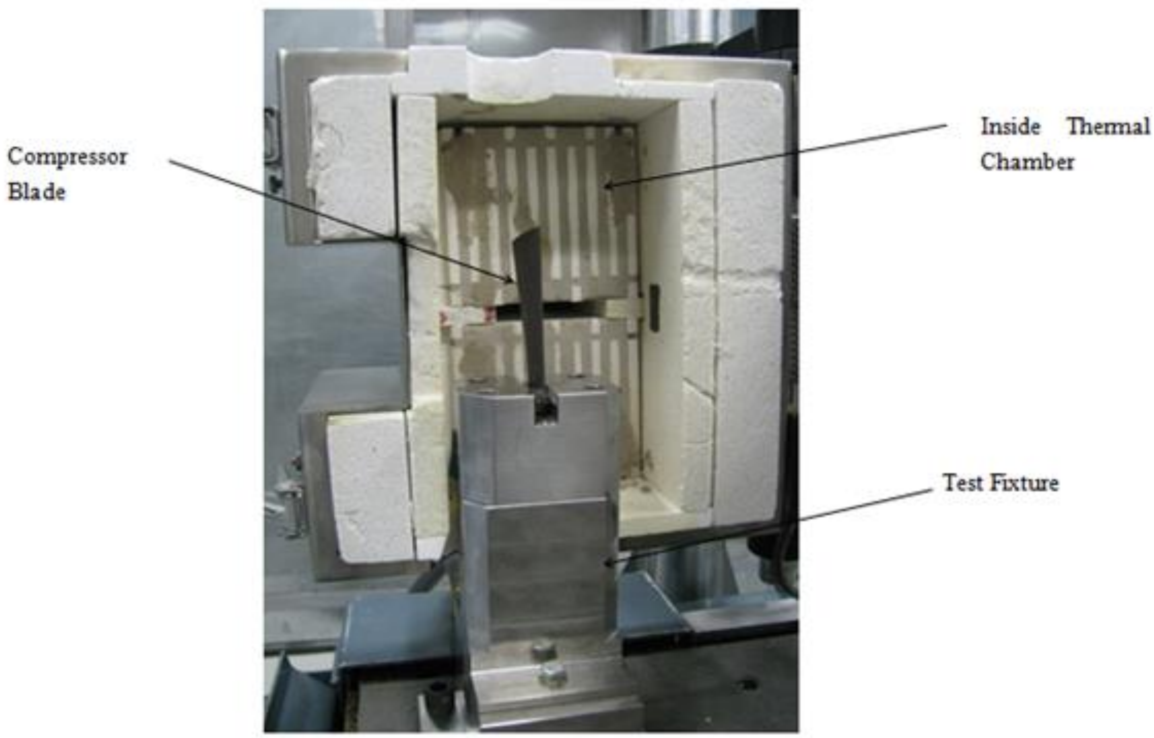

Figure 1: Experimental Setup

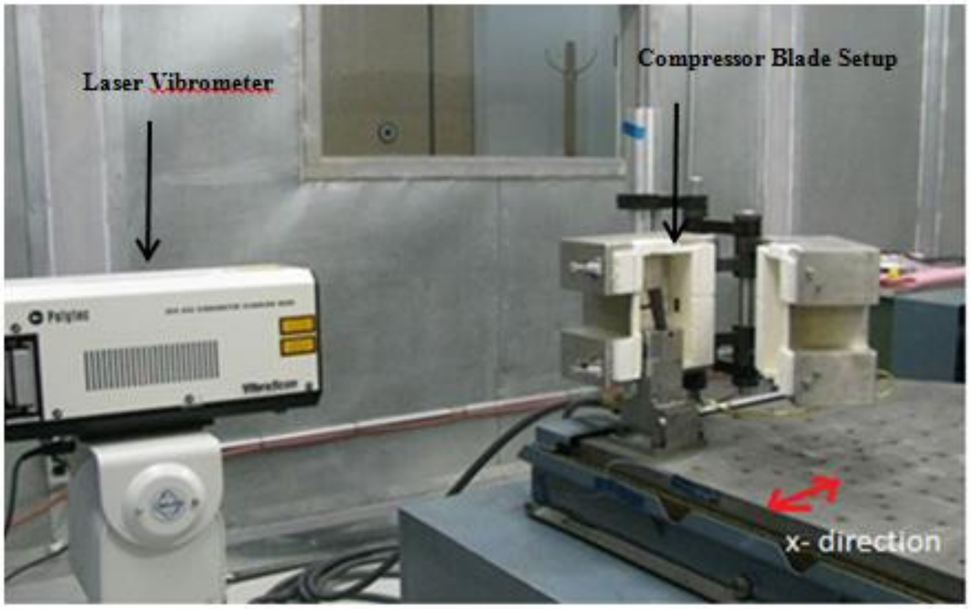

Figure 2: Experimental Setup: Laser Vibrometer System

Modal Test: Sinusoidal Frequency Sweep

A sine sweep (frequency scanning) at low amplitude was used in order to excite and characterize the blade's natural frequencies at room temperature (21°C) and at the elevated temperature of 700°C. This technique involved using a low level input (0.1g PSD level) to excite the compressor blade and to measure its velocity using the laser vibrometer. At the natural frequency a peak can be seen where the blade starts to resonate (551Hz) relative to the other frequencies nearby (see Figure 3).

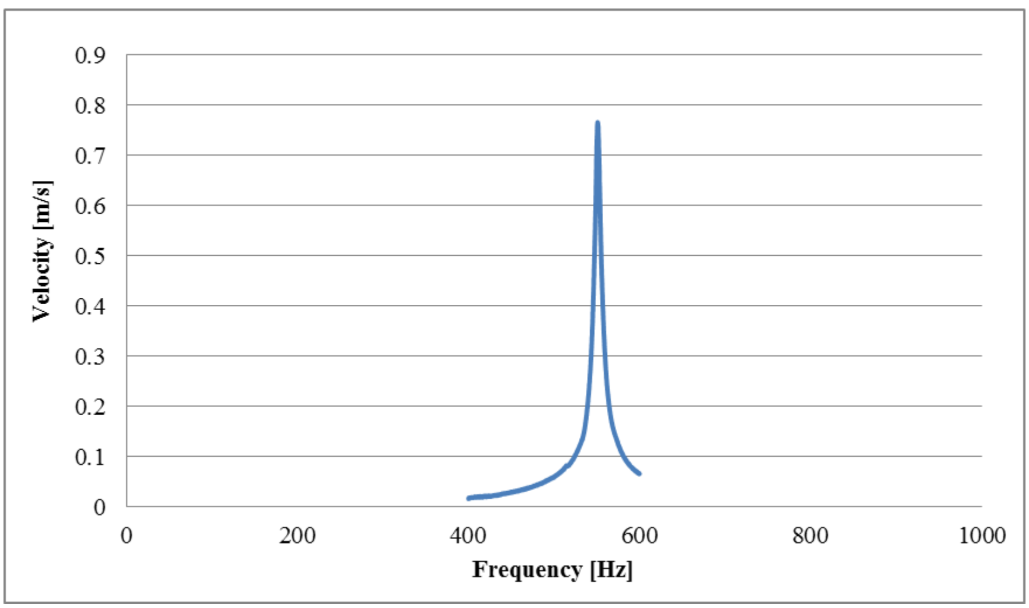

Figure 3: Sinusoidal Frequency Sweep of the Blade at 0.1g PSD level

Experimental Vibration Test at Room Temperature (21°C)

The blade was fixed on the shaker table by a rigid fixture, whose first natural mode was well above that of the blade. The blade was then subjected to a base excitation (sinusoidal frequency sweep) in a plane perpendicular to the surface of the blade at 3 excitation levels (2g, 3g and 4g) between 400Hz and 600Hz frequency. A small opening in the thermal chamber, as shown in Figure 4A, allowed for the velocity to be measured by the laser vibrometer at two different locations (Location 1 and 2), Figure 4B.

Experimental Vibration Test at Elevated Temperature (700°C)

A similar process for the high temperature process was undertaken with the additional step of heating up the blade in the thermal chamber to 700ºC. When the temperature inside the chamber was stable at 700ºC, the blade was exposed to the same excitation levels and bandwidth frequency as the room temperature test.

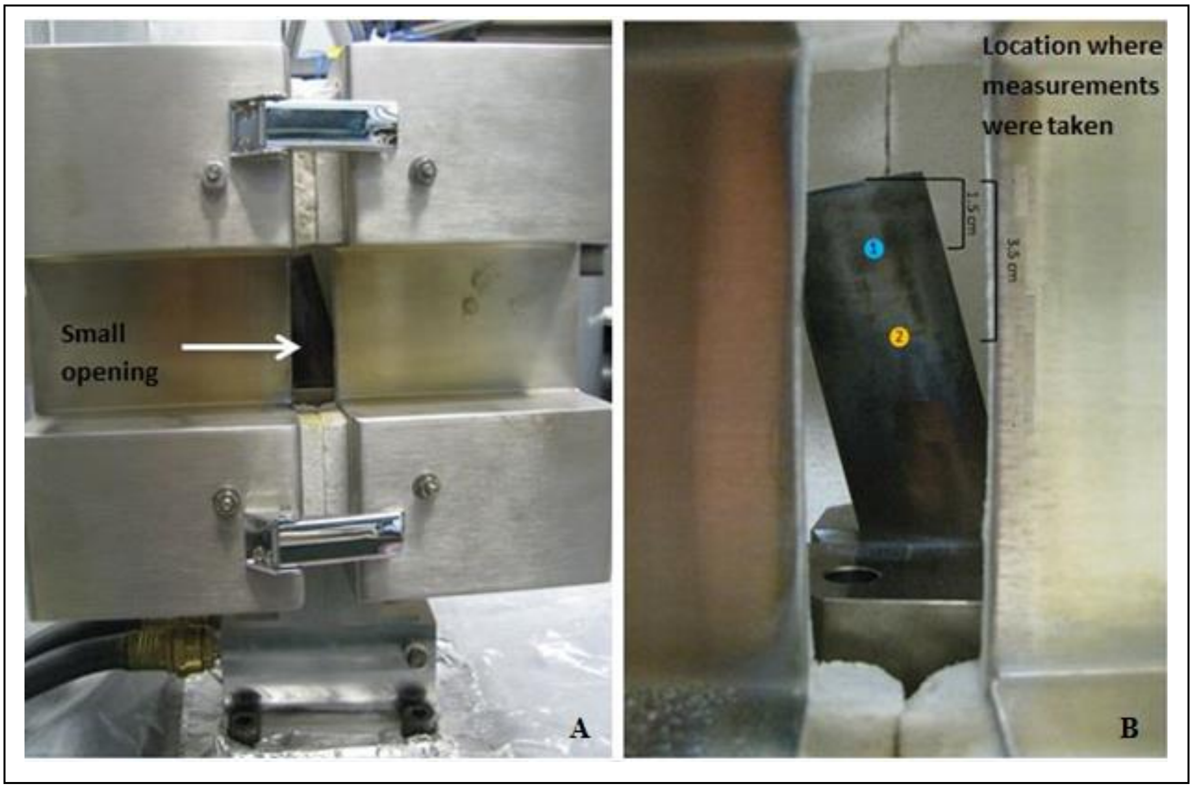

Figure 4: (A) Thermal Chamber and (B) Locations 1 & 2 where measurements were taken

Numerical Simulation

The geometry of the compressor blade was generated by using a HandyScan 3D Handheld 3D Scanner [4] to accurately (within 1%) capture the geometry of the turbine blade. The blade was meshed with tetrahedron elements using Hypermesh [5]. The finite element model contains approximately 206,000 elements. Finite element analysis of the T56 stage two compressor blade was performed to determine the peak velocity location when the blade was subjected to resonant excitation. The finite element mesh used in the modal and harmonic analyses is shown in Figure 5. For the finite element analysis, a rigid boundary condition is applied to all nodes between the platform and the base of the blade consistent with the loading imparted by the test fixture to the blade.

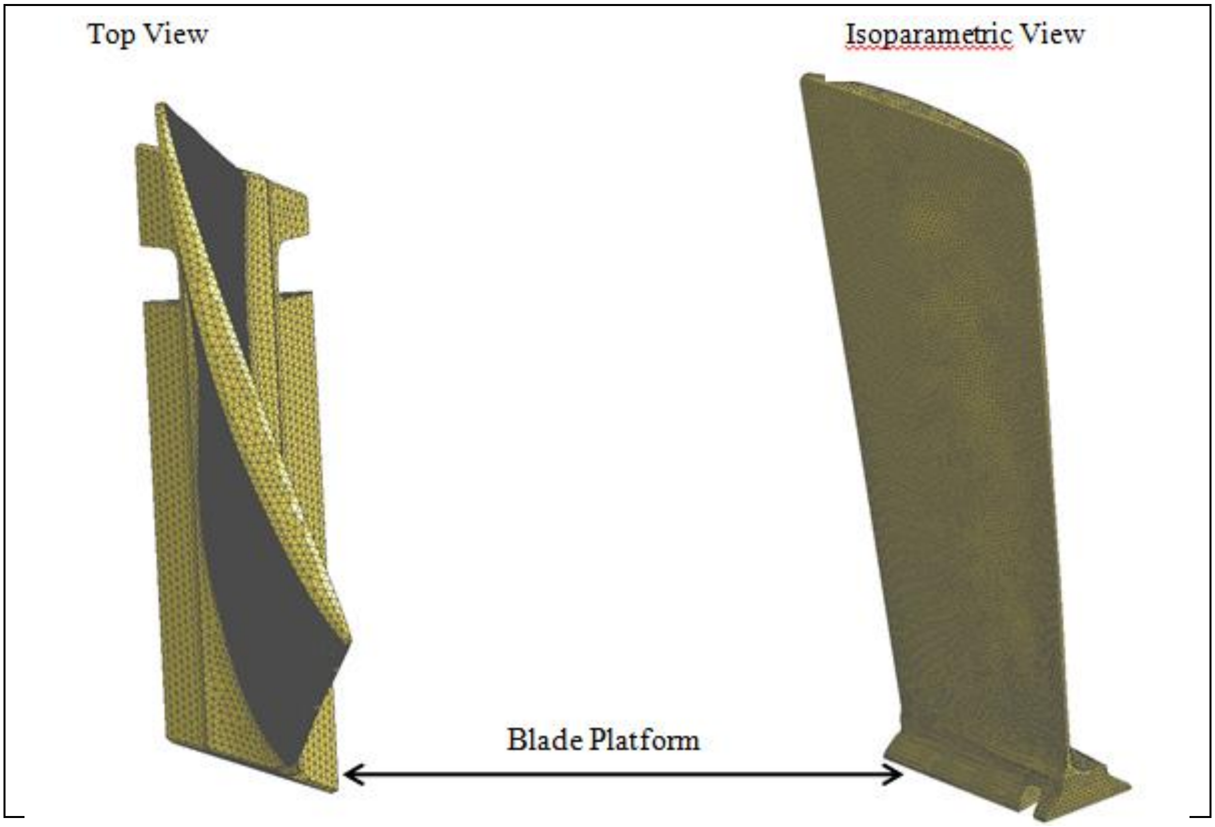

Figure 5: Developed Finite Element Model

Material Property

The compressor blade was made with Inconel 718. It is a super alloy composed primarily of nickel, cobalt and chromium which gives it high-strength and an increased resistance to corrosion. This alloy is primarily used in turbine blades to withstand the high heat environment. The material properties used for the compressor blade in the simulation are listed in Table 1 although the properties at 700°C were not directly provided and a linear interpolation was undertaken based on the information provided in [6]. The interpolation was specifically related to the Young's Modulus, it was expected that as the temperature of the blade increased the modulus became lower and thus had a softer stiffness.

Table 1: Material Properties of Blade (Inconel 718)

Parameters	Units	21°C	700°C
Young's Modulus	Pa	199.9×10^{9}	158.7×10^{9}
Density	kg/m^3	8193.3	8193.3
Poisson's Ratio	-	0.3	0.3

Frequency Random Vibration Keyword

In LS DYNA, the "Frequency Random Vibration" keyword allows for a random vibration analysis of the blade. This keyword includes an identified application region for the input and a frequency range. The keyword also incorporates a damping parameter which was used in this simulation based on the input level listed in Table 2. The damping coefficient remained the same for both the room temperature (21°C) analysis and the elevated temperature at each input level presented in [7].

Table 2: Damping Coefficient at 21°C and 700°C

Input [g^2/Hz]	Damping Coefficient
0.02	0.019
0.045	0.0145
0.08	0.0125

Simulations Sequence

Four steps were carried out in order to validate the numerical model against the experimental tests.

1) A modal analysis was undertaken at room temperature (21°C) and at 700°C to validate the geometry and material properties used in the numerical model.
2) A random vibration analysis at 21°C was carried out to evaluate the velocity at room temperature.
3) A thermal analysis was then completed using the implicit solver which characterized the internal stress and displacement of the blade at 700°C.
4) The displacement and strains from step 3 were used as a starting pre-condition for the blade at the elevated temperature. This pre-condition along with the lower Young's Modulus was required to perform the vibration analysis at the elevated temperature. The velocity was evaluated at the same location as the room temperature analysis.

Modal Analysis - Step 1

The results of the two modal analysis at room temperature (21°C) and 700°C are listed in Table 3. Overall the result for the first mode compares well with the experimental results with a maximum frequency deviation of 2.9% at the elevated temperature. This low deviation between the experimental and numerical results confirms not only the correct material properties were used in the model but also that the geometry of the blade was modeled accurately.

Table 3: First Natural Frequency at Room Temperature and Elevated Temperature

	Simulation	Experimental	Deviation %
Mode 1 [Hz] - 21°C	554.1	551.3	0.5%
Mode 1 [Hz] - 700°C	493.6	508.4	2.9%

Vibration Analysis at 21°C - Step 2

The vibration analysis was carried out using the "Random Vibration Analysis" keyword. This keyword works by computing the dynamic response to a harmonic excitation spectrum, by modal superposition. The natural frequencies are calculated and then the specimen is excited at those natural frequencies based on the loading input. The velocity of the blade at room temperature was extracted from two different locations (1 and 2 in Figure 4). In the simulation 5 nodes were associated with each location and averaged to yield numerical results at that particular location.

Thermal Analysis - Step 3

The thermal analysis of the blade was performed as a means of pre-stressing the blade prior to the vibration analysis. The temperature of the blade was increased from 21°C to 700°C for the first 50s and then held at a constant 700°C for the next 150s. This was sufficient time for the blade to stabilize in terms of displacement and strains caused by the elevated temperature. The "Interface Springback LSDYNA Thickness" keyword allowed for the displacement and strains to be stored in a separate output file which would then be called on at the start of the vibration analysis.

Vibration Analysis at 700°C - Step 4

The vibration at the 700°C was done similar to that in step 2, with the addition that the compressor blade was pre-stressed with the displacement and strain from elevated temperature discussed in step 3.

Results

Velocity profile

The velocity profiles for the 3g input at room temperature (21°C) and 700°C shown in Figures 6 and 7, respectively. The simulation results at room temperature are within 10% of the experimental results and within 5% for 700°C case. Along with a natural frequency shift, 700°C case caused a higher peak velocity of 2.98m/s compared with 2.50m/s at room temperature. Figure 8 shows the velocity contours of the blade at 21°C and 700°C, the highest velocity experienced by the blade was at the tip location and turned to rigid body motion at the root of the blade.

A comparison of the velocity results at the different input levels is shown in Table 4. The 4g input level yielded the highest velocity as expected, with the elevated temperature slightly higher than the room temperature for all input levels. Overall the simulated results were within 10% of the experimental. A number of factors contributed to this difference; the most likely cause was the camber of the blade inducing motion in two orthogonal directions, the X and Y. However due to the nature of the laser vibrometer only the X direction was captured.

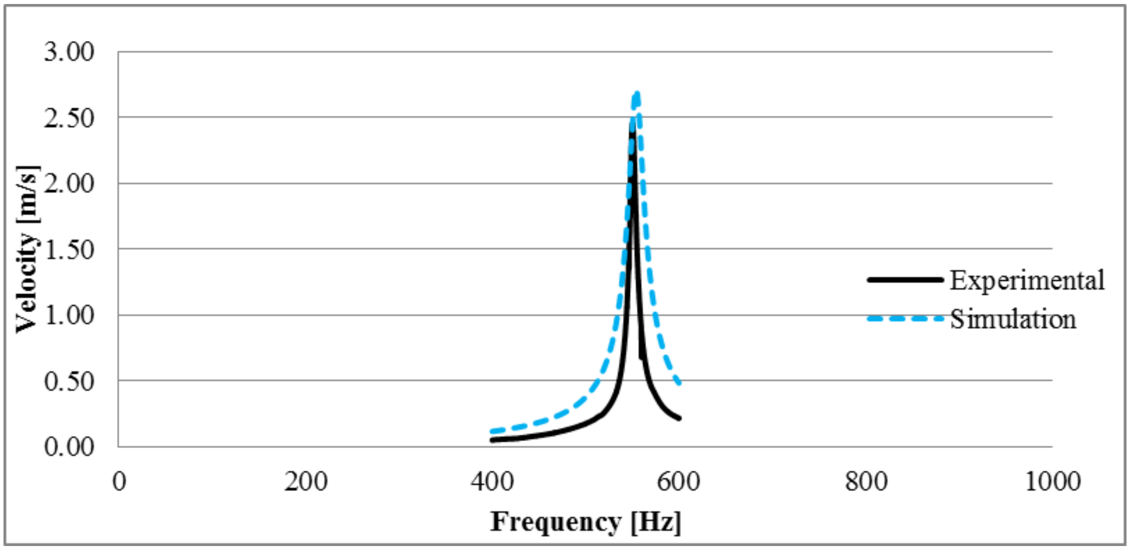

Figure 6: Velocity Curve at 21°Cat Location 1 for 3g input level

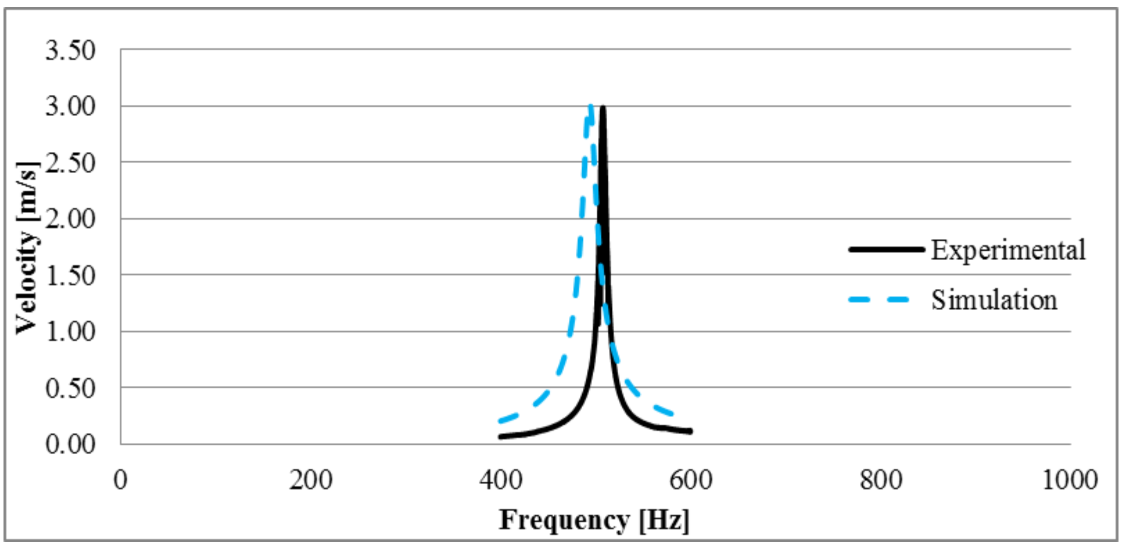

Figure 7: Velocity Curve at 700°Cat Location 1 for 3g input level

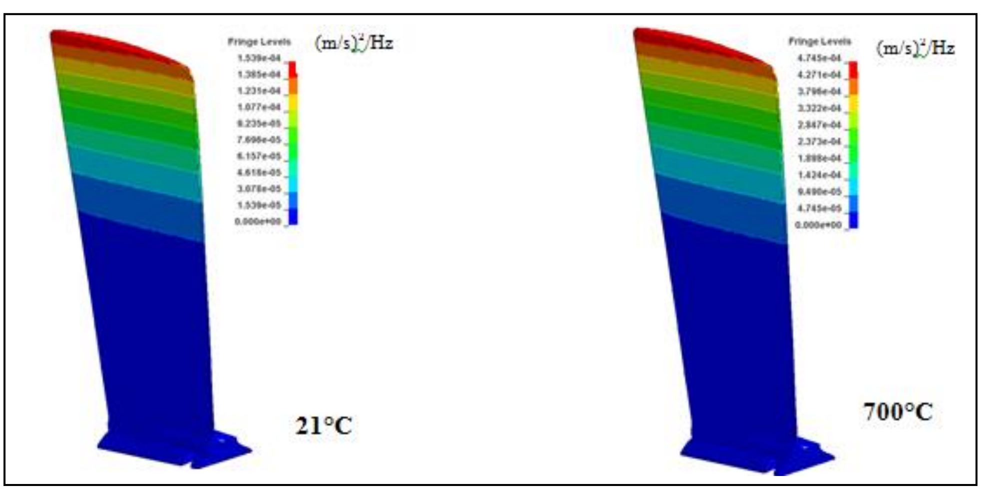

Figure 8: Contours of Velocity at 21°C (left) and 700°C (right)

Table 4: Velocity Results

Velocity (m/s) Value at 21°C				Velocity (m/s) Value at 700°C		
Location/Input Level	**Test**	**Sim.**	**Deviation**	**Test**	**Sim.**	**Deviation**
Location1/ 2g	1.60	1.7	7.3%	1.98	1.89	4.8%
Location2/ 2g	0.80	0.79	4.6%	0.94	0.89	5.4%
Location1/ 3g	2.50	**2.7**	9.4%	2.98	**3.04**	1.8%
Location2/ 3g	1.20	1.23	7.8%	1.4	1.40	0.7%
Location1/ 4g	3.30	3.6	9.7%	3.99	4.07	2.2%
Location2/ 4g	1.60	1.7	7.6%	1.90	1.90	1.0%

Effective Stress

The effective stress (Von-Mises stress) profile for the blade is shown in Figure 9 at room temperature (21°C) and at the elevated temperature (700°C). The stress profile is shown at the natural frequency at each temperature tested. The results indicate a maximum Von Mises stress of 0.83MPa at 700°C while the room temperature peak was 0.34MPa.The effective stress contours at 700°C for the sinusoidal base motion at the first bending mode frequency is shown in Figure 10. The maximum stress contours are centered on the base and edges of the blade. The abrupt change in geometry at the base caused the elevated stress levels along with the thin edges of the blade.

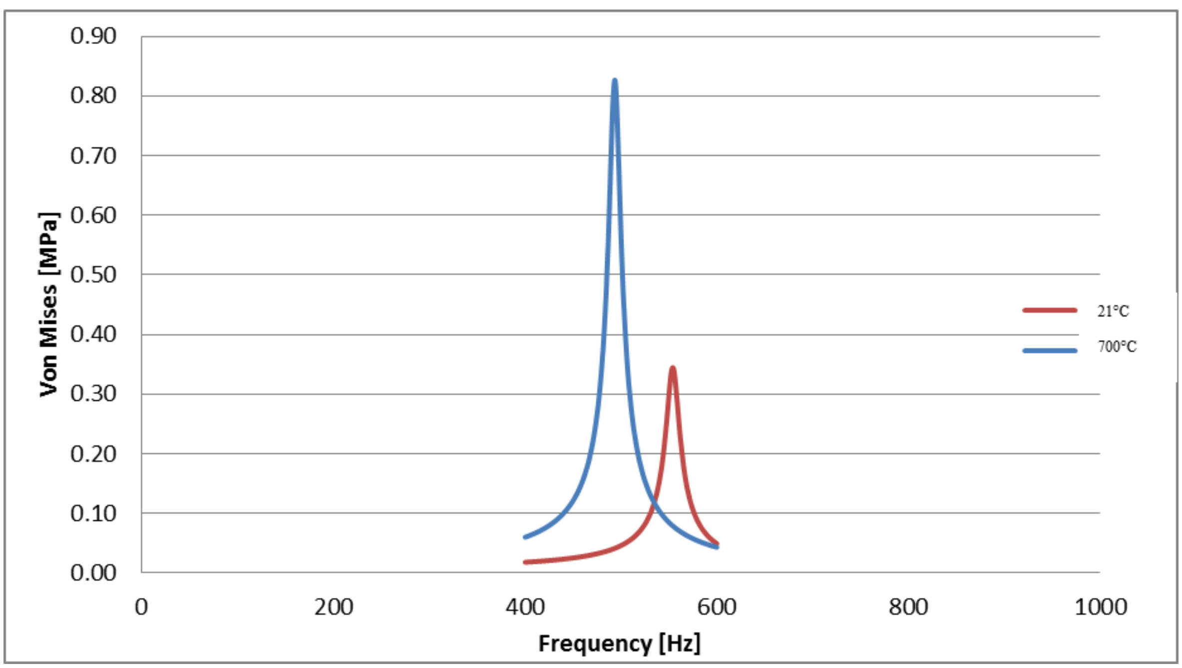

Figure 9: Effective Stress (Von-Mises) Profiles at 4g input Level

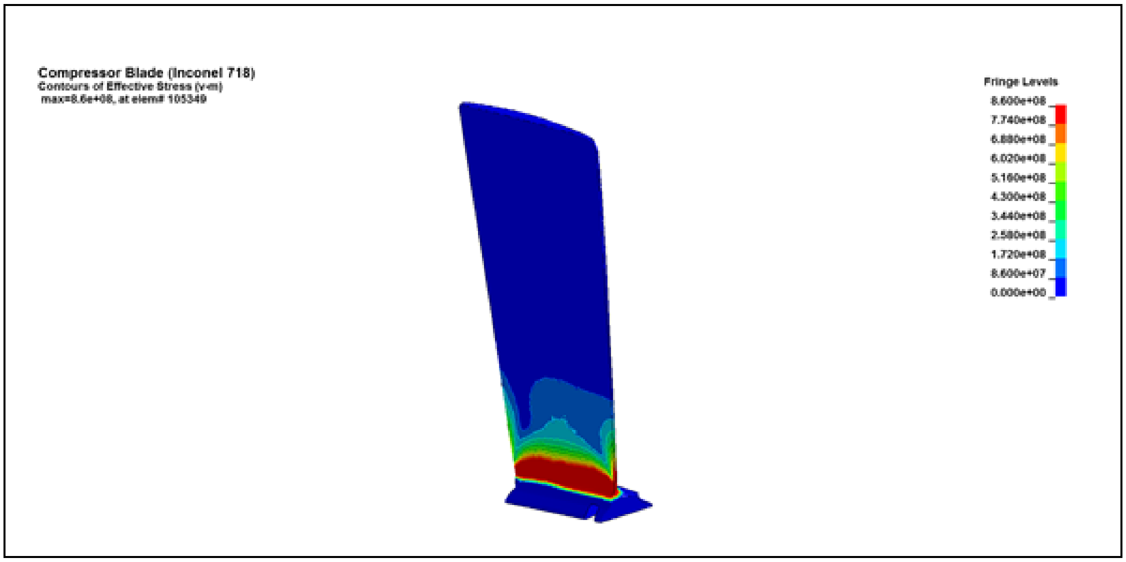

Figure 10: Effective Stress (Von-Mises) Contours at 4g input level

Conclusion

A numerical model was developed to demonstrate the effectiveness of the vibration analysis of a stage two T56 compressor blade at high temperature (700°C). The simulation used a pre stress condition created from a thermal analysis as the starting point of the vibration analysis. The numerical prediction agrees reasonably well with the experimental results being within 10% accuracy. There was good correlation between simulation and experimental peak velocity values and in velocity profile trend. It was noted that there was a 0.49MPa increase in effective stress value due to the increase in temperature prior to the vibration analysis.

References

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