2010 Gas Turbine Industrial Fellowship Report

Thermo-acoustic Network Software Validation

Solar Turbines Incorporated

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Introduction:

Solar Turbines Incorporated is one of the world's leading manufacturers of industrial gas turbines, with more than 13,400 units and over 1.4 billion operating hours in 96 countries. Solar Turbines provides industrial gas turbines ranging from 1-22 MW for power generation, natural gas compression, and pumping systems. Their products include gas turbine engines, gas compressors, and gas turbine-powered compressor sets, mechanical-drive packages, and generator sets.

During my summer internship at Solar Turbines Incorporated I worked in the Turbomachinery Production division for the combustion group. I was responsible for validating oscillation predictions made by the Thermo-acoustic network, which is currently being developed. The program is capable of predicting natural frequencies that could be present within a combustion chamber during operation. Several models varying in complexity were created to determine the capabilities of the software. Once the models were created, tests were performed on a single injector rig to gather information for comparison against the model predictions. An illustration of how a test rig was modeled in the software can be seen in Figure 1.

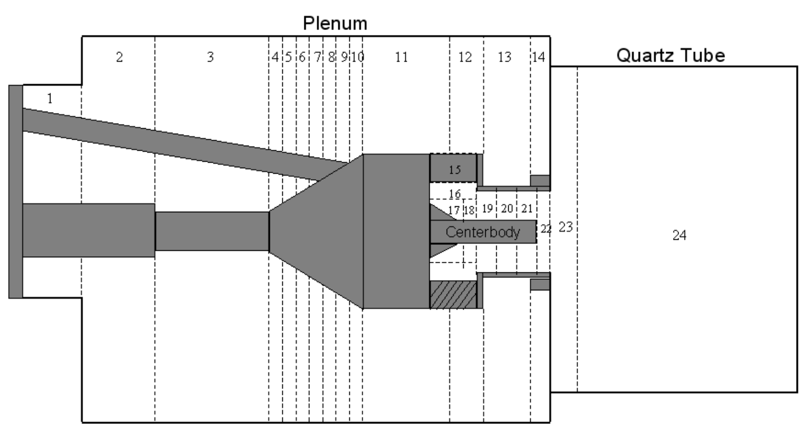

Figure 1: Model illustration with each duct separated by dashed lines.

Acoustic instability studies are extremely important for the design of gas turbines. The overall goal is to eliminate these instabilities as they can cause large-amplitude structural vibrations, contribute to the formation of NO_x, and create flashback or blowout. All of these are adverse conditions that gas turbine designers want to minimize. Predicting what frequencies a gas turbine will oscillate at is the first step to designing a way to eliminate the oscillations. This is why the acoustic network is being developed, to predict acoustic oscillations in current gas turbines as well as during the design phase of new gas turbines.

Oscillations Validation Testing:

Tests were conducted in order to validate the frequency predictions given by the acoustic network software. Data points were collected in a single injector rig operating at atmospheric pressure. The rig and injector were modeled from the choke point of all the fuel and air lines to the end of the combustion liner section. In order to capture the widest range of oscillations the flame temperature (TPZ), inlet air temperature (T2), percent pilot fuel flow, and percent pressure drop were varied during each test. This was also done to see if the model could accurately respond to the change in any one of these variables. Table 1 below presents the data collected during these tests including the operating condition settings and the 1st and 2nd harmonic frequency recorded.

Table 1: Test data.

TPZ (°F)	T2 (°F)	% Pilot	% PD	1st Harmonic (Hz)	2nd Harmonic (Hz)
3114	767	3.98	3.94	339	641.4
3107	774	5.97	4.03	311.2	629
3019	774	4.04	3.8	316.1	603.2
3000	798	5.90	3.75	359.1	631
2996	717	5.44	3.49	362.7	623.9
2962	739	5.87	3.25	312.2	652.7
2936	830	6.00	2.57	328	640.2
2916	788	4.05	3.04	330.8	642.2

Once the test data was collected the operating conditions were entered into the acoustic network model. Figure 2 presents the natural frequency prediction given by the model for TPZ = 2936 °F, % pilot = 6.00, T2 = 830 °F for a combustion liner with a variable length between 0.4m and 0.6m. This figure is provided to illustrate the output of the oscillation software.

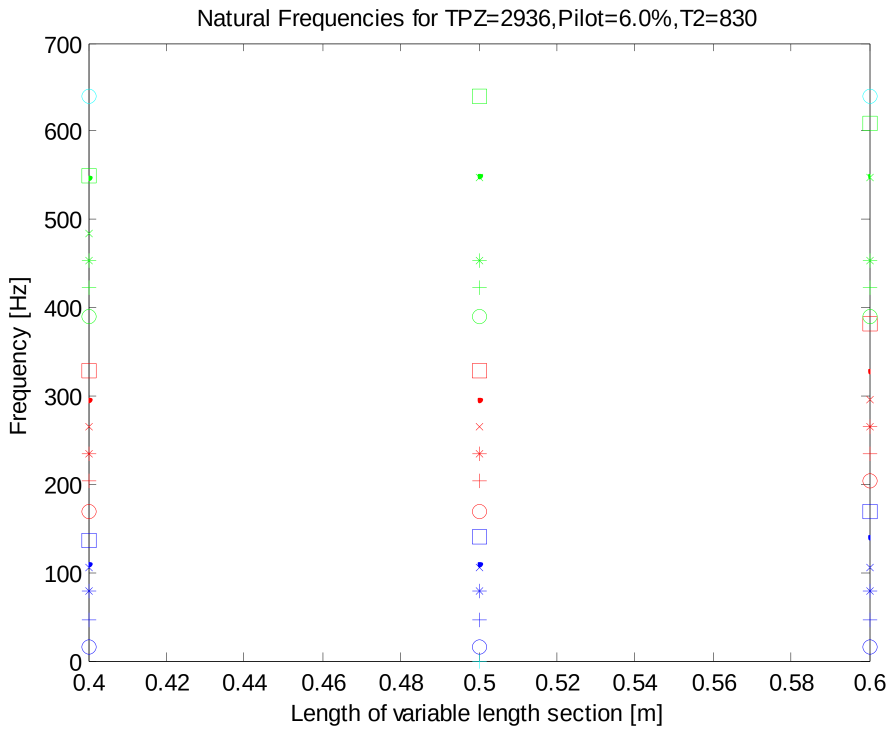

Figure 2: Thermo-acoustic network natural frequency prediction.

Table 2 below provides the results produced by the model for each condition collected during testing. It should be noted that the software also predicted several more frequencies than what is listed in Table 2. These are just the frequencies that are similar to what was measured. Once the software is further developed it will be able to predict which frequencies will actually resonate and complete validation can be performed. As of now it just predicts the natural frequencies that could be present based on the model geometry and operating conditions.

Table 2: Model results.

TPZ (°F)	T2 (°F)	% Pilot	% PD	1st Harmonic (Hz)	2nd Harmonic (Hz)
3114	767	3.98	3.94	339	641.4
3107	774	5.97	4.03	311.2	629
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When comparing the model results to the test results it can be seen that the minimum error between the 1st harmonic was 1 Hz while the maximum error was 36.7 Hz. The average error for the 1st harmonic was found to be 12.3 Hz. The minimum error between the 2nd harmonic was 8.8 Hz while the maximum error was 57.8 Hz. The average error was found to be 30 Hz. This data has also been provided in Table 3.

Table 3: Statistical analysis.

Smallest 1st Harm Error	**Largest 1st Harm Error**	**Average 1st Harm Error**	**1st Harm σ**
1 Hz	36.7 Hz	15.4 Hz	12.3
Smallest 2nd Harm Error	**Largest 2nd Harm Error**	**Average 2nd Harm Error**	**2nd Harm σ**
8.8 Hz	57.8 Hz	30.0 Hz	17.1

The results given above by the acoustic network were considered a success because of many factors that could have led to a disagreement between the collected test data and the model data. The main factor that skewed the data was that oscillations recorded during testing most likely affected the other operating condition measurements such as the percent pressure drop, which was an input to the model. Once again it should be noted that once the software is further developed it will be able to predict which natural frequencies will resonate based on the phase angle of the heat release and pressure wave.

Rig Sensitivity Study:

A sensitivity analysis was performed to determine the acoustic effects of solid fuel supply piping compared to braided fuel supply piping on the single injector rig. To do so, the testing conditions recorded above were duplicated with braided fuel lines instead of solid lines. Once the data was collected it was compared to the solid fuel line data to discover any effects on the oscillation frequencies and amplitudes. Table 4 presents the sensitivity analysis that was performed.

Table 4: Solid vs. braided fuel line sensitivity analysis.

	First Harmonic			
Type	**Average Amp (psi)**	**Max Frequency (Hz)**	**Min Frequency (Hz)**	**Range (Hz)**
Solid lines	**0.260**	**337**	**325**	**12**
Braided lines	**0.361**	**339**	**298**	**41**
	Second Harmonic			
	Average Amp (psi)	**Max Frequency (Hz)**	**Min Frequency (Hz)**	**Range (Hz)**
Solid lines	**0.0175**	**674**	**641**	**33**
Braided lines	**0.02**	**678**	**596**	**82**

From this data it can be seen that the average oscillation amplitude was higher when the braided lines were attached for both the first and second harmonic. Secondly, it can be concluded that the range in frequency measured was higher for the braided line tests. Both of these conclusions are valuable when conducting oscillation experiments. Solid lines reduce the variability that can come with using braided lines. Solid lines are also important when designing against oscillations since they create a more consistent oscillation frequency.

Summary of Accomplishments:

Along with the frequency prediction validation and rig sensitivity analysis I was able to help make improvements to the software by building complex models. Initially the software could not handle the complexity of these models. This led to discovering the issues behind the problem. I also was able to create a document that includes suggestions on how to make the software more user friendly and easier to use for employees who aren't acoustics experts. Lastly, I was able to give some insight on how this new software could be incorporated into the existing in-house software.

Conclusion:

Overall, the UTSR Gas Turbine Industrial Fellowship provided me with a great opportunity to experience what its like to work in the gas turbine industry. Solar Turbines Incorporated was also a great place to work. Everyone was friendly and helpful and there was a team-oriented atmosphere not only between the engineers but between everyone who worked there. I would recommend this fellowship and this company to anyone who is interested in the gas turbine industry.

Acknowledgements:

I would like to express appreciation to everyone in the combustion group who provided guidance and information that helped me accomplish my summer objectives, especially my mentor James Blust. James was extremely knowledgeable in this area of research while very down to earth at the same time. James made my time at Solar Turbines Incorporated educational as well as enjoyable.   I would also like to thank Arnold Martinez for his assistance with the oscillations testing. Lastly, I would like to thank Solar Turbines Incorporated and all the people who were involved in giving me this opportunity to contribute and gain knowledge in the field that I am passionate about.