Thermoacoustic Modeling of Gas Turbine Injector Geometry and Performance

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Solar Turbines
A Caterpillar Company

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I. INTRODUCTION

For the average industrial gas turbine engine, reliability is of highest importance, as products accumulate thousands of hours of run time at variable loading conditions. This large timescale requires designers and engineers to take into consideration advanced phenomena such as geometry-based acoustics, wear, creep, and cyclic loading. One of the most surprising factors that can affect longevity of gas turbine combustors is called thermoacoustic oscillation. The complex, highly non-linear relationship between fuel flow, flame dynamics, and combustor geometry can cause high-cycle fatigue failure of liners and injectors well before the mature component lifetime. Figure 1 shows an oscillations-based catastrophic failure of a combustor liner assembly on a popular Solar Turbines engine package. Without engineering foresight, these flame-induced vibrations can cost the end customer hundreds of thousands of dollars in equipment replacement and downtime.

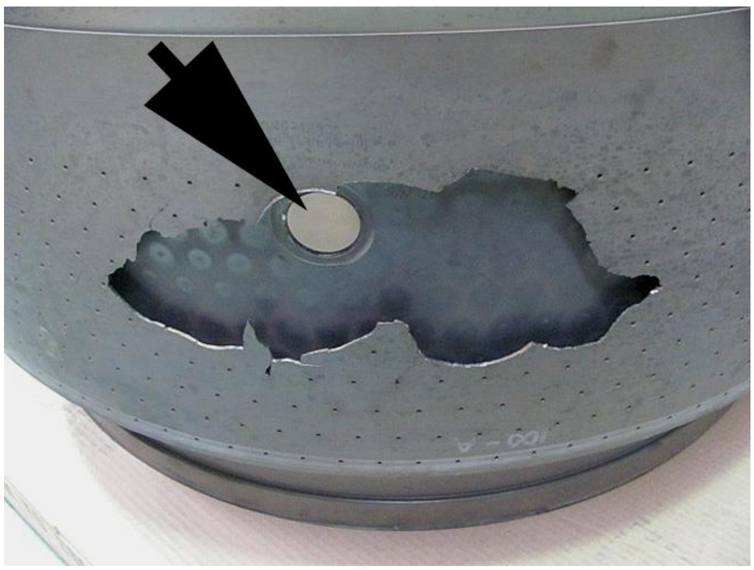
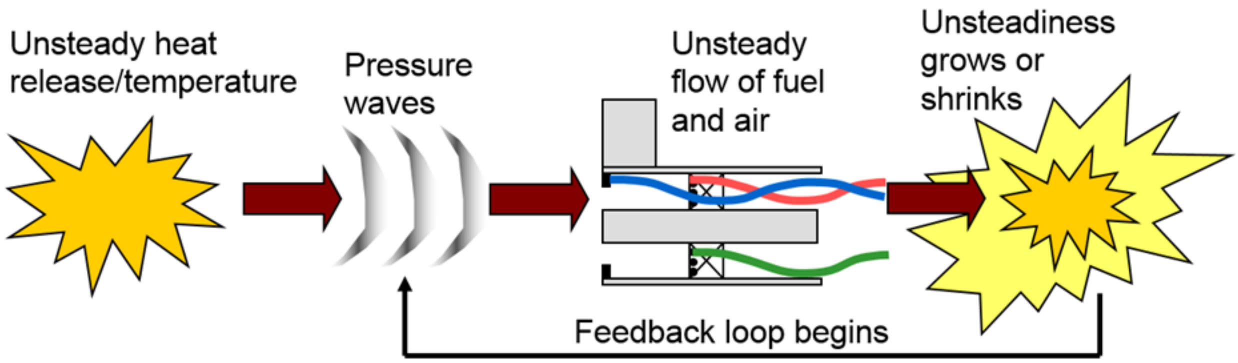


Figure 1: *Combustion Liner Damage Caused by Combustion-Induced Oscillations*

From a basic perspective, thermoacoustic oscillations become a problem when there is a positive feedback loop between the flame region in the combustor and flow of reactants being supplied to the primary zone. Figure 2 shows a pictographic diagram of the phenomenon described below. As the turbulent air and fuel reacts in an annular combustor, a somewhat uniform broadband white noise is created. Just as air blowing over a glass bottle can resonate with the bottle geometry, so too can this white noise cause natural resonances within the complex geometry and numerous passageways of the engine. For example, there commonly exists a natural frequency on the order of 300-500 Hz that corresponds almost exactly to the circumferential length of the annular combustor. These natural frequencies can be mitigated through intelligent physical design, but it is impossible to eliminate them completely. They are normally not problematic, unless they grow to the point where they start to affect the reactant flow, causing the instantaneous equivalence ratio to oscillate at a similar frequency. If conditions are correct, this can exacerbate the acoustic oscillations at the flame, causing a positive feedback loop where the oscillation magnitude grows rapidly and puts greater-than-expected stress on physical components. This thermoacoustic phenomenon is very similar to how a microphone in a public setting that is located to close to a connected speaker can cause a random environmental noise to grow until it becomes unbearably loud. By using the geometry-based natural frequencies and the known flame transfer function for a specified production engine,



these problematic modes can be modeled, identified, and mitigated through physical design modifications.

Figure 2: *Illustration of Thermoacoustic Feedback Loop (Courtesy of Jim Blust, Solar Turbines Inc.)*

II. PROJECT SCOPE

Since the advent of commercial scale metal additive manufacturing, gas turbine injectors have stood out as an ideal specimen for manufacturing process conversion from conventional cast and subtractive techniques. The high-temperature materials and hundreds of intricate passageways are not a problem for today's printers, and manufacturers, including Solar Turbines, are moving towards widespread implementation of additive manufacturing at a production level. However, some additional design work must be completed in order to optimize the geometry for the new manufacturing technique. The additive technique allows the mechanical designer even more freedom to create an ideal aerodynamic design without having to worry about how fuel passages will be drilled or accessed for assembly. As part of this push towards additive manufacturing, a popular low-NOx injector was selected by the industrial sponsor to go through the conversion process to additive manufacturing. A test "print" of the injector heads is shown in Figure 3. Designers adjusted several aspects, such as injector length, fillet radius on some holes, and eliminated a large aerodynamic blockage by rerouting fuel passageways. All these changes had a minimal impact on the visual appearance of the injector and would theoretically improve performance. However, even "small" design changes can cause dramatic changes in the acoustic performance of the combustor. In-depth analysis was needed to ensure that well-functioning engines would not experience thermoacoustic issues once fitted with the new AM injectors.

Figure 3: Preliminary Injector Head Results from Additive Manufacturing Process

III. MODELING

The main two tools for thermoacoustic oscillations modeling are Flownex, a widely available flow solver software, and another in-house custom software used to solve acoustic networks. Flownex is used to input geometry, fluid properties, and boundary conditions. This information is then exported to the acoustics solver to find frequencies of interest.

a. Geometric Modeling

To begin, geometric data was derived from CAD models and input into the one-dimensional flow solver. This included basic information such as passage length and diameter, as well as surface roughness and any sort of taper or sudden flow restriction. Large, sudden changes in diameter were modeled as two pipes connected by a restrictor to simulate the flow separation and momentum characteristics of a jet penetrating a larger volume. It is important to note that only one slice of the engine was modeled, corresponding to a single injector and its associated section of the annular combustor.

b. One Dimensional Flow Model

By systematically connecting each of the tiny “pipes” in the injector body, a comprehensive flow network was created from the exit of the axial compressor to the entrance of the first turbine stage. Boundary conditions were also added to the entrance and exit, along with the heat addition in the primary zone. From this information, the one-dimensional flow solver calculates the pressure, temperature, and composition of every node in the network using fundamental continuity and conservation laws. The network solver also iteratively calculates the mass flow splits and corresponding velocity in the different circuits of the network. The boundary conditions of the model were based upon production engine test data, and the inputs were set up to be easily and iteratively changed to simulate different engine loading scenarios.

c. **Flow Calibration**

In order to ensure the model matched real world engine conditions as closely as possible, the output of the flow model was compared to real world engine performance metrics. Parameters such as the coefficient of discharge on small cooling and fuel holes were then individually tweaked in order to calibrate meta-parameters such as mass ratios between airstreams and pressure drop across different fuel circuits. This was a non-linear optimization process that required prioritizing the importance of different data sets such as simulated engine performance, real engine performance, CFD simulations, and aerodynamic manufacturing specifications. The calibration process, although tedious, is essential to ensuring later calculations will yield meaningful results.

d. **Exporting into Acoustic Network Solver**

Following the creation of the comprehensive flow network, the parameters were exported into the custom acoustic network solver program. This process was fairly user-friendly, but required some tweaking and troubleshooting to ensure that all values had been transferred correctly. During this stage, the flame transfer function was also input into the model to be used for thermoacoustic analysis.

e. **Solving Using Forced Excitation**

To begin the process of finding thermoacoustic frequencies of interest, the entire frequency domain was swept to find the system's forced response. This process, although less accurate than eigenvalue-based solution methods, is very useful in determining frequency ranges of interest to focus on with methods of higher computational cost. First, the frequency range was discretized into intervals of 0.1 Hz. These test values were then plugged into the acoustic solver without the inclusion of the flame transfer function. Instead of having flame induced oscillations, the solver would analytically force the system to vibrate at a certain test frequency. The resultant magnitude of response was recorded and used to compile an FFT-style plot across the entire frequency domain. An example of the forced output is shown in Figure 4. Moving forward, one would focus on the regions surrounding 360 Hz and 513 Hz**,** as these have high likelihoods of yielding problematic frequencies when coupled with flame dynamics.

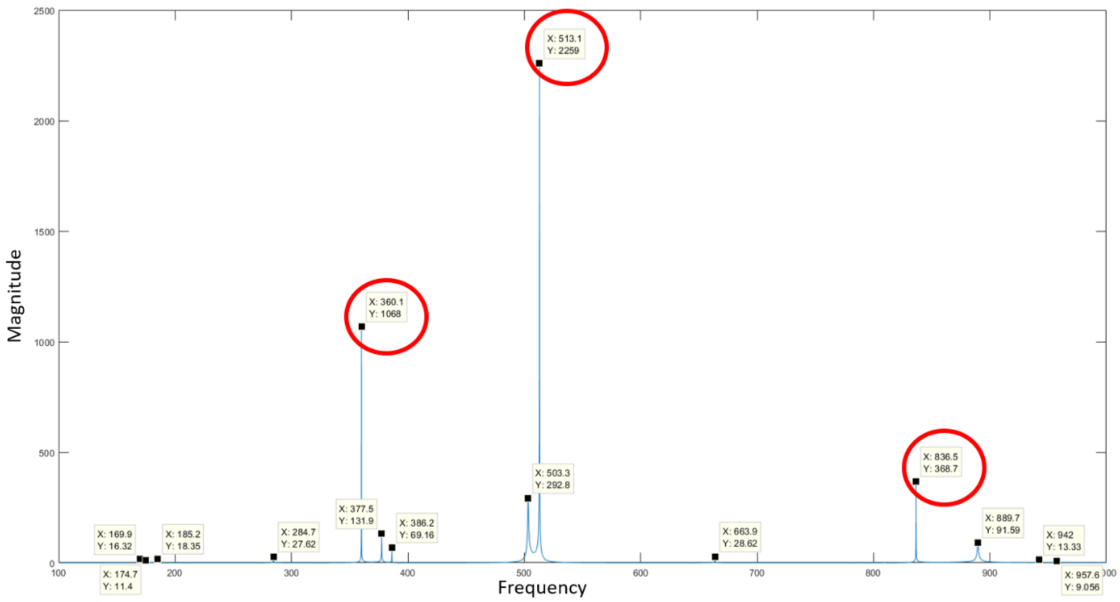


Figure 4: *Forced Response Output Example*

f. Solving Self-Excited Frequencies

Once areas of interest were identified, the next step was to introduce the Flame Transfer Function and determine the system response with a full thermoacoustic model. In order to efficiently run the acoustic solver, the calculations were initialized with discretized "guesses", based on the results of the forced response output. For example, if the area of interest was around 700 Hz, the solver would be set to run with 10 frequency guesses evenly distributed between 675 and 725 Hz. The solver, once finished, yields a set of complex-valued solutions that correspond to possible modes of thermoacoustic resonance. Each solution has both a real term, corresponding to the frequency, and an imaginary term that relates to the growth or attenuation rate with respect to time. Solutions with positive imaginary terms are more problematic and therefore of special interest because the oscillation will tend to grow until it becomes destructive. However, solutions with negative imaginary terms are not ignored, because it only takes a slight discrepancy in the flame transfer function to dramatically affect the solution. The amount of change required to make the imaginary gain positive is well within the range of statistical error on the model of flame dynamics. Once a set of solutions is obtained, it will then be subsequently filtered to determine which values correspond to plausible, real world mode shapes throughout the geometry of the engine.

g. Mode Shape Plotting

In order to further determine the validity of these solutions, the pressure and volume velocity fields for each were calculated and plotted against a one-dimensional representation of geometric engine passages. To make this to be possible, flow "paths" through the network needed to be selected as possible routes for standing waves to form. For example, one possible selection could be a path that starts at the exit of the compressor, routes though the main air passage of the injector, past the main swirler, through the primary zone flame, and azimuthally around the annular combustor. Modes that loop back on themselves, like the one in the stated example, must have pressure and velocity endpoint values that make sense, and form a continuous wave structure all the way around the annulus. Figure 5 shows a valid mode shape, along with the corresponding path through the engine. This plot is essentially the absolute value of simulated pressure and velocity with respect to position along a predefined geometric path through the engine. In order to facilitate depiction, the absolute value function means that sinusoidal wave shapes show up as 2 or more large, positive humps that either touch the x axis or reach a local maximum before changing the sign of its slope. As predicted by transverse wave theory, the fluid velocity is 90 degrees out of phase with the pressure. The velocity (blue dashed) plot can have point discontinuities due to continuity across ducts of varying cross-sectional areas. However, as shown in the valid mode shape plot, the red pressure line should have no discontinuities.

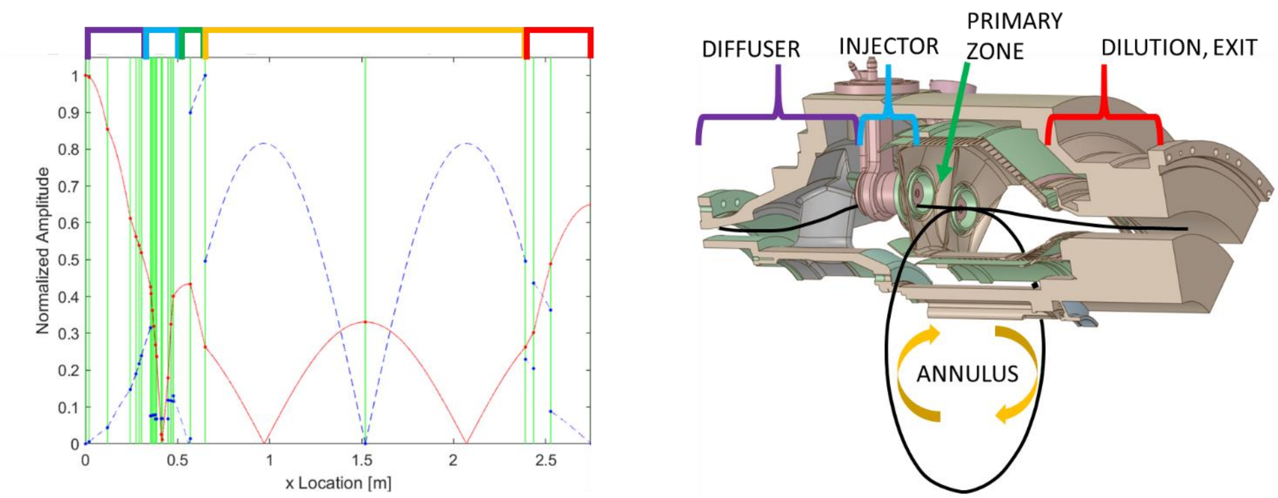


Figure 5: *Valid Self-Excited Mode Shape (Red: Pressure, Blue: Volume Velocity)*

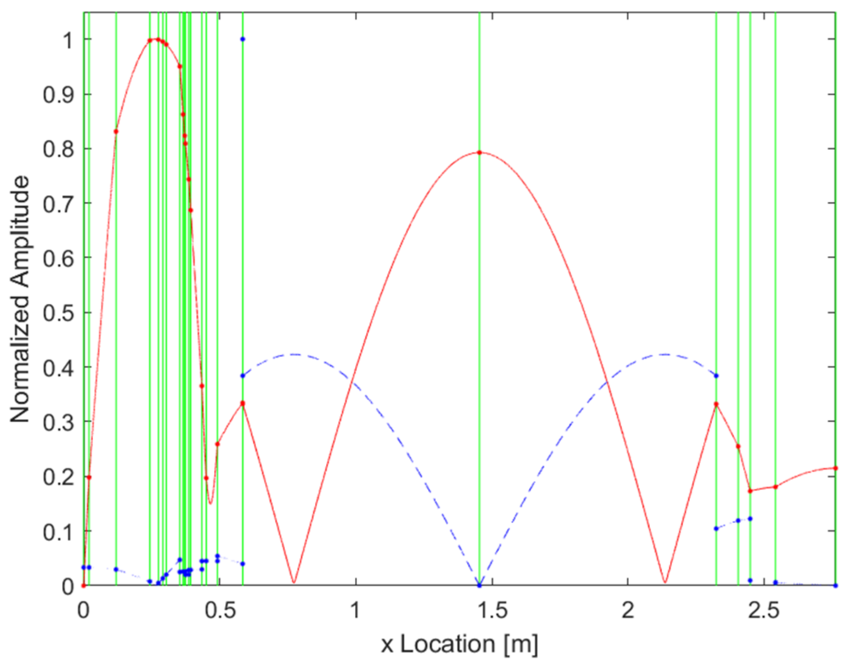


Figure 6: *Invalid Self-Excited Mode Shape*

Figure 6 shows an invalid mode shape. It is invalid because there are several locations where the plot does not make sense as a representation of a multiple of half wavelengths. Around x=0.4, the pressure trace does not reach zero before changing from decreasing to increasing. This also occurs for the blue velocity line around x=0.6. It should be restated that for volume velocity, continuity does not matter, as velocity is assumed to change instantaneously as the gas flows through passages of different cross-sectional areas. These same invalidities are seen further along the flow path, such as at x=2.3 for velocity and x=2.45 for pressure.

Therefore, the model indicates that there is not actually a valid physical wave corresponding to this particular solution, and the frequency is not likely to be a problem. Although the frequency is mathematically a solution for the acoustic network, there is not a major path through the engine that geometrically corresponds to an oscillation with the correct wavelength.

Once the mode shapes are systematically plotted and analyzed for validity, a final subset of possible problem modes can be compiled. These than then be compared to real world oscillations measurements or sent to engineers to optimize their combustor geometry early in the design process. Since the mode shapes are plotted with respect to a real path through the engine, node and anti-node locations can be used to intelligently place vibration mitigation devices or tweak certain dimensions.

IV. RESULTS

Over the course of a summer, the modeling procedure was completed on two injector setups. Data from the additive manufactured model was compared to the conventionally manufactured model and real-world test data to determine model validity and generate conclusions about future performance. To begin, the conventionally manufactured model was run through the acoustic solver to yield a set of four problem frequencies, shown on the left side of Table 1**.** As previously noted, each of these solutions is a complex number with a real term corresponding to frequency (in Hz) and an imaginary response corresponding to growth or attenuation over time.

Table 1: *Tabulated Results of Self-Excited Frequencies for Both Models*

Conventional Manufacturing	Additive Manufacturing
186.7271 + 0.6329i	394.2119 - 0.1742i
285.4323 - 1.8012i	672.2059 + 0.0001i
324.91 - 0.0065i	783.6439 - -0.024i
390.374 + 0.6149i	

Figure 7 shows a selection of oscillations test data from a real engine under matching load conditions. The spectral data shows major peaks around 187Hz, 285Hz, and 390 Hz. These closely correspond to the frequencies on the left side of the above chart generated by the engine thermoacoustic simulation. This adds validity to the model setup and indicates that the results are a relatively good predictor of real-world engine behavior.

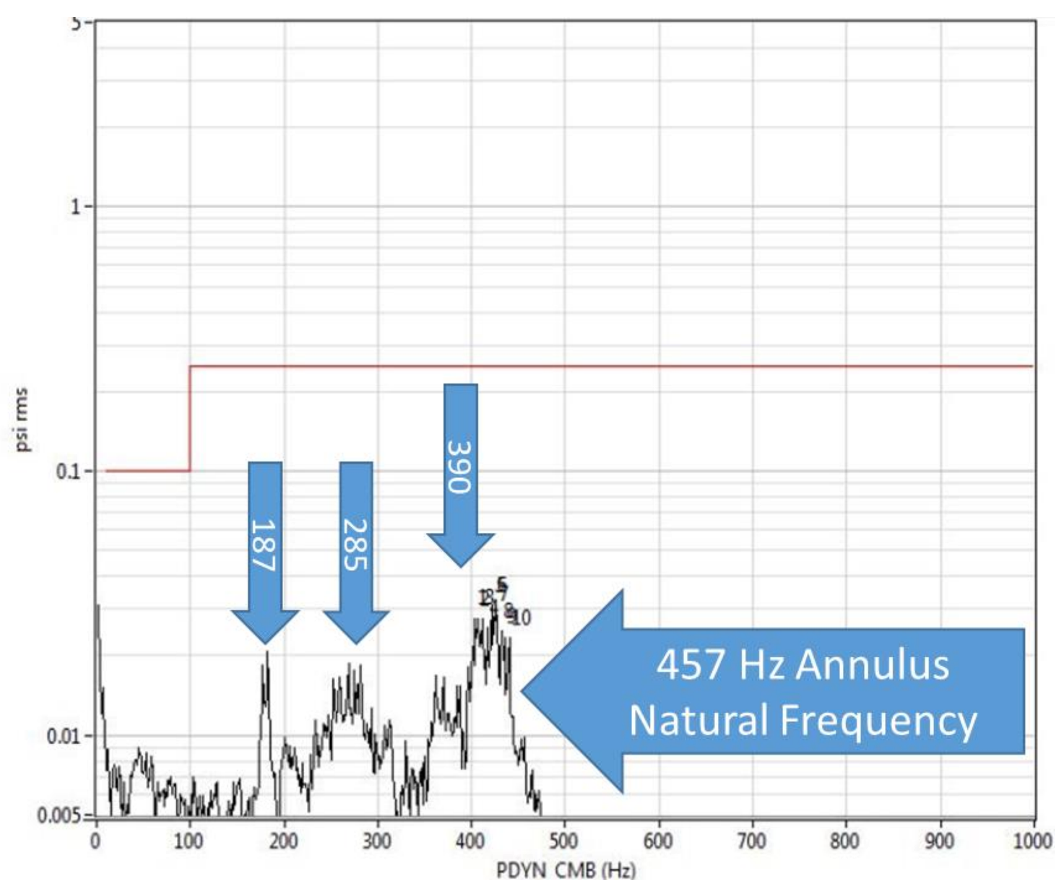


Figure 7: *Spectral Test Results for Model Validationd*

Once the model was validated, a model for the additively manufactured injector was created and run in the exact same procedure. The valid mode shape solutions for this model are tabulated on the right side of Table 1.

It is evident that most of the solutions for the conventionally manufactured model have additively manufactured analogs with very similar mode shapes. In fact, the additive solutions tend to have lesser imaginary gains than the conventionally manufactured ones. In addition, one of the solutions becomes invalid in the additive model, indicating that a small geometric change in the design modification caused it to be impossible for a wave to form through the engine at that frequency. This comparison is shown in Figure 8. Other solutions pairs seem to have identical plotted mode shapes, indicating that they are in fact the same phenomenon occurring in the two different injector models.

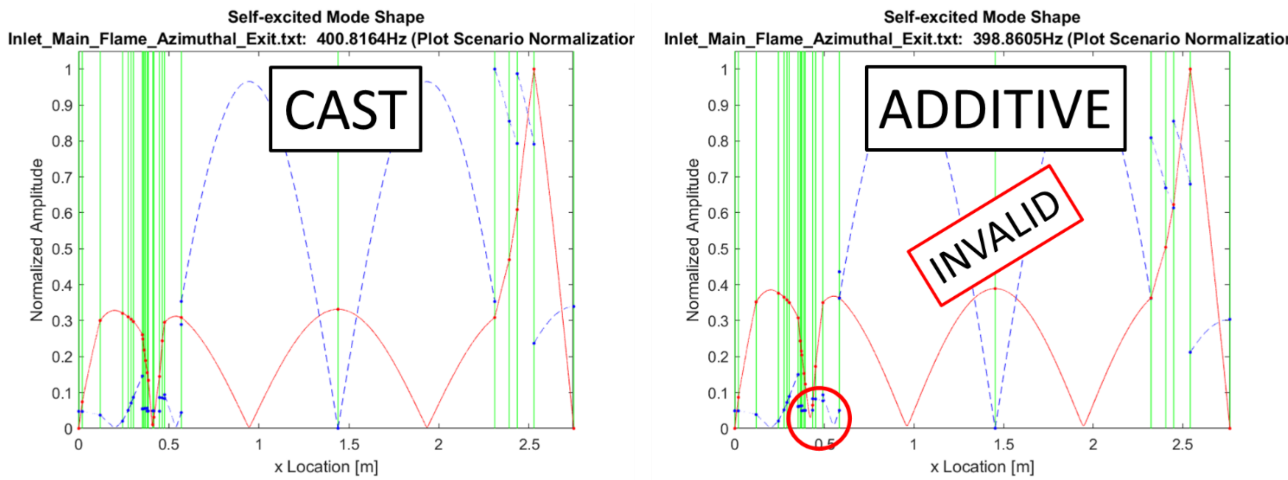


Figure 8*: 400 Hz Mode Shapes on Cast and Additive Models*

Overall, the tabulated solutions and mode shape plots seem to indicate that there are no initially apparent thermoacoustic risks with the design changes made in preparation for additive manufacturing. In fact, the modified physical injector model seems to actually perform slightly better, with some of the modes being more attenuated over time or becoming completely invalid.

V. CONCLUSIONS

Thermoacoustic oscillations are a big problem in the industrial gas turbine industry, and engineering time and costs must be spent on analysis and mitigation in order to avoid large customer costs associated with premature component failure. By using an analytical acoustics solver on a flow network representing an engine diffuser, injector, and combustor, meaningful results can be generated that have real world significance. As manufacturers move increasingly towards production-level additive manufacturing techniques, the changes in engine thermoacoustic response caused by small design changes required by the new manufacturing method must not be overlooked. In this specific case, a popular low NOx injector model was modeled in order to mitigate oscillations concerns early in the design process. The analysis procedure was comprehensive and included importing geometry, calibrating geometry, inputting the flame transfer function, generating solutions, and filtering those solutions to find valid mode shapes. The final set of solutions for the conventionally manufactured injector was compared to production test data to validate the model as a whole, while the additively manufactured injector results will be compiled and sent back to design engineers to assist in further optimization of the geometry and aerodynamic performance. There seem to be no additional problem frequencies for the new model, and some of the frequencies attenuate or become completely invalid. Overall, the results suggest development of the current AM injector iteration can continue with minimal thermoacoustic concerns.

VI. AKNOWLEDGEMENTS

I would like to thank my Solar Turbines mentors, Michel Akiki and Jim Blust, for their patience and expertise answering endless questions as I worked through the modeling and simulation process. Thank you to my manager, Shaun Ho, and the rest of the Methods and Analysis group at Solar for supporting me throughout the summer. My experience at the company was an invaluable learning experience that exposed me to the real-world application of thermodynamic, aerodynamic, combustion, and acoustic concepts to gas turbine engines.