Utilizing Modal Testing for Monitoring the Structural Health of Wind Tunnel Facility Hardware

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ABSTRACT

The 10- by 10-Foot Abe Silverstein Supersonic Wind Tunnel (10×10) is the largest and fastest wind tunnel facility at NASA's Glenn Research Center(GRC) and is specifically designed to test supersonic propulsion components from inlets and nozzles to full-scale jet and rocket engines[1]. Recently, a critical part of the wind tunnel failed and required a redesign before reintegrating into the facility. The design requirements of this new component required that clearances between large metallic components exist, which have the potential for undesirable nonlinear dynamics to occur, in particular rattling. Rattling is feared to occur when the wind tunnel is being operated in certain flow regimes that induce cyclic aero loads on the new component near its natural frequencies. This paper describes the approach taken to better understand and resolve this vibration problem using modal testing. A modal test was developed and executed by GRC's Structural Dynamics Lab to quantify the modal parameters of the structure, namely which specific excitation frequencies caused the structure to rattle. These results were shared with facility operators as frequency ranges that should be avoided to ensure maximum lifespan of the new structure. Additional means of structural health monitoring (SHM) as well as Vortex shedding are briefly discussed in this paper.

Keywords: non-linear dynamics, rattle, structural health monitoring, modal test, aerospace

INTRODUCTION

Modal testing and analysis has been and continues to be used extensively in practice as a means to check the structural health of a system. Sources such as Hsieh(2006)[1] and Kim(1993)[2] provide excellent literature reviews as well as get into the history and methodology of structural health monitoring utilizing modal data.

The motivation for this project came when the 10- by 10-Foot Abe Silverstein Supersonic Wind Tunnel (10×10) at NASA Glenn Research Center began redesigning a cooling unit with the hopes of increasing its lifespan. The cooler is used to reduce the temperature of post combustion gases coming from various engines running in the wind tunnel. It is comprised of an array of thin walled tubes supported at various axial locations and can be seen in better detail below in Figure 1. In the previous designs, these tube supports were press fit between the tube and a bore through a piece of sheet metal. However, the new design would have a small clearance between the tubes and the bores to allow thermal growth of the tube to not be impeded by the supports or vice versa. A simplified schematic of one of these tube and bore supports can be seen below in figure 2. Although these clearances alleviated a potential thermal expansion issue, it introduced a new failure mode. The clearances between the tubes and their bores now allowed for rattling to occur within the support which could lead to cracks within the support structure, damage to individual tubes, and contribute to accelerated fatigue of critical components.

This paper serves predominately to describe a modal test done on this new cooler design to characterize the structure and predict what types of excitations induced rattling between the tubes and their bores. The analysis portion of this paper describes how select structural health monitoring techniques such as harmonic distortion are used in conjunction with Campbell diagrams to identify nonlinear behavior in the test data. Lastly, the conclusions section provides a summary of the guidance given to the wind tunnel operators in light of the results from the analysis section and includes some future work topics to increase the effectiveness of this study.

Failure Mode

Rattling is a well-documented phenomena in modal and vibration testing and analysis. The non-linear nature of rattle and how it can be applied to structural health monitoring is discussed in detail in Worden (2007) [3]. This article describes nonstationary and nonlinear behavior such as rattling as a failure mode in itself. This cooler is still operable when the tubes rattle, but the concern is this rattle will lead to a severe failure as described above. Nonlinear system identification methods are described in detail such as Harmonic distortion where a structure is evaluated by applying a constant frequency sine wave and the response is measured for higher harmonics. This methodology is applied in the analysis portion of this paper. Worden mentions that the primary usage of structural health monitoring in practice is with rotating machinery so many of the techniques that are describe require slight modification to be applied to modal testing and aero-structures in general.

During operation, fluid flow over these tubes will cause vortices to be shed around each tube in a phenomena known as vortex shedding. Vortex shedding is a well-studied phenomena and background can be found in a multitude of fluid mechanics textbooks. In 1984 P.W. Bearman wrote a literature review called “Vortex Shedding From Oscillating Bluff Bodies”[4] which is an excellent overview of many studies on vortex induced oscillations similar to the structure being tested in this paper. Bearman describes how a flexible body enduring vortex shedding will begin to oscillate due to the fluctuating pressure fields and can have an amplitude as large as 1.5x to 2x the body’s diameter. Bearman also mentions the oscillations induced by vortex shedding routinely are more severe than those induced by turbulent boundary layers. For a further and more complete discussion on vortex-induced oscillations, a 1977 book by Blevins titled “Flow-Induced Vibration” is a good reference.

MODAL TEST

A modal characterization of the structure was proposed to identify what frequencies would induce rattling. These frequencies in which major tube rattling was induced would better inform the fluid dynamics team and allow them the ability to identify what tunnel parameters could potentially induce rattling so they could be avoided.

The cooler being tested is shown in figure 1.

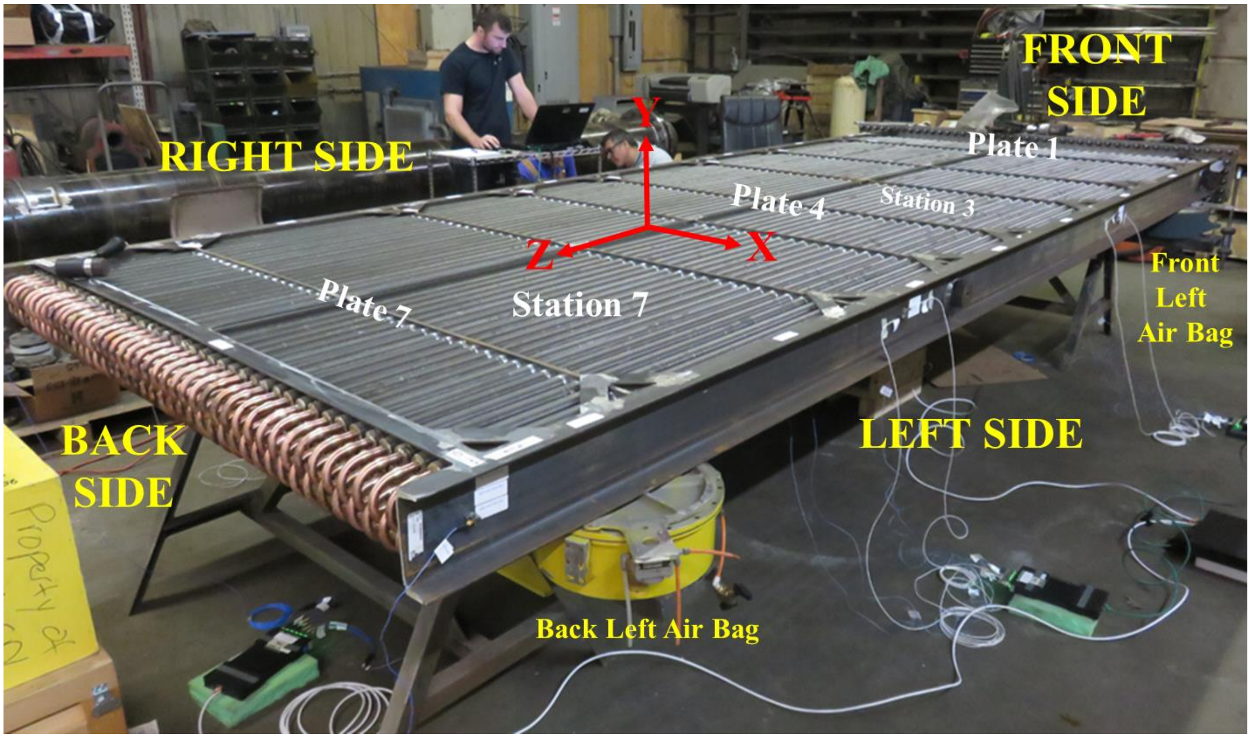

Figure 1. Test Article Setup

The test article is comprised of 168 tubes running from the “front side” to the “back side” and a rack that supports the beams at various axial locations. The rack consists of an outer box with intermediary “plates” that are normal to the tubes. The plates are metal sheets with bored out clearance holes for each tube and a three of the seven plates are labeled in the photo as

“Plate 1, Plate 4, and Plate 7”. “Stations” are used to describe the region between individual plates. The outer sides of the cooler are defined in the above picture as “FRONT”, “BACK”, “LEFT”, and “RIGHT”. The basic operation of the cooler involves cold water flowing through the tubes along the Z-direction as a means to cool down hot post-combustion gases flowing through the structure in the Y-direction.

A challenge in this test, as in most modal tests, is that replicating the “in operation” boundary conditions of the test article would be nearly impossible to replicate in this modal test. In this test, mimicking the boundary conditions was deemed unfeasible To remedy this, it was important that the boundary conditions were simple and well understood to aid in future analytical work. To accomplish this, air bags were placed at each of the four corners of the structure. These isolate the structure from the ground induced vibration as well as ensure the rigid body modes are low enough in frequency as to not couple with the flexible body modes that were relevant to the test.

Figure 2 below shows a breakout schematic of one of the tube in bore supports. This is one example of the “tube and bore” support of which there are 1176 of throughout the cooler split evenly between the 7 plates. The clearance gap is exaggerated and the tube, bore, and plate thickness dimensions are not to scale.

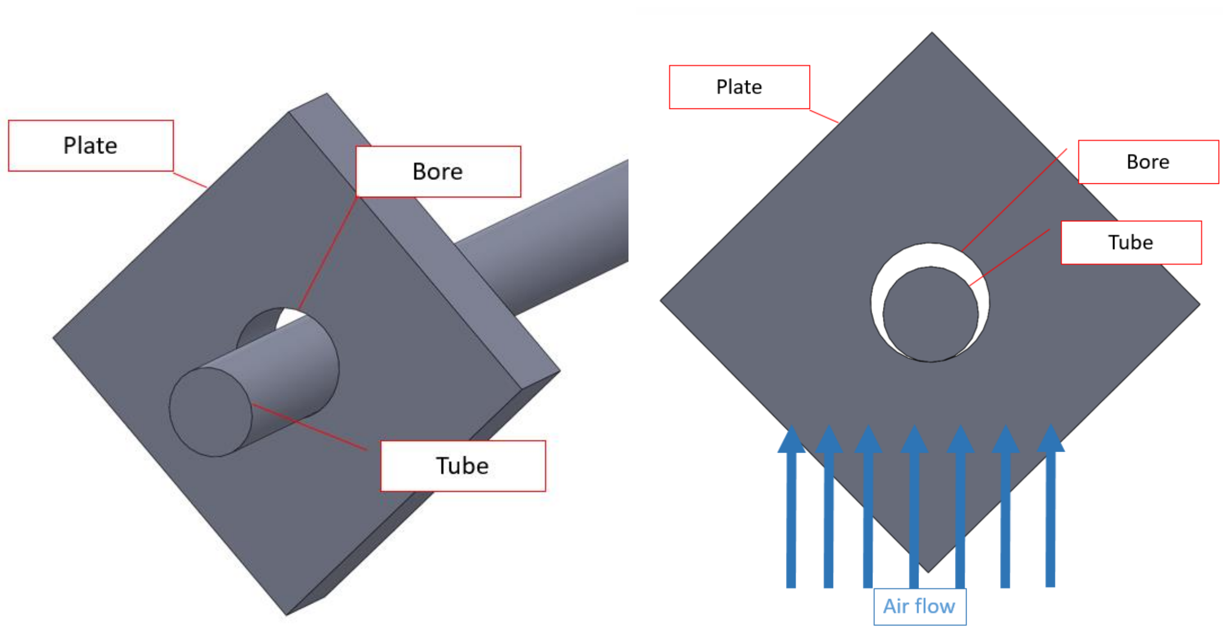

Figure 2. Tube in Bore Schematic

The test included measuring the force input to the structure through load cells in line with the modal hammers and modal shakers while measuring the response with 35 accelerometers and two microphones. Response Accelerometers were placed around the structure using engineering judgement to capture the global modes of the rack. In addition, select supports were instrumented to capture local rattling of the tube within the bore. An example of this type of accelerometer placement is shown below in Figure 3.

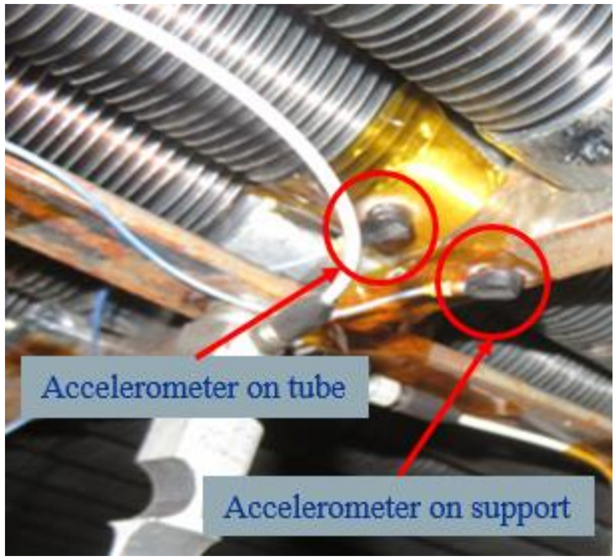

Figure 3. Select Supports Instrumented Both on and Adjacent to a Single tube

Two modal shakers were used to excite the structure and can be seen below in figure 4. The shakers were placed on pedestals to position them as close as possible to minimize the length of the shaker stinger. The stingers were attached to custom aluminum flexures that reduce any potential moments due to shaker misalignment to be input into the force sensors.

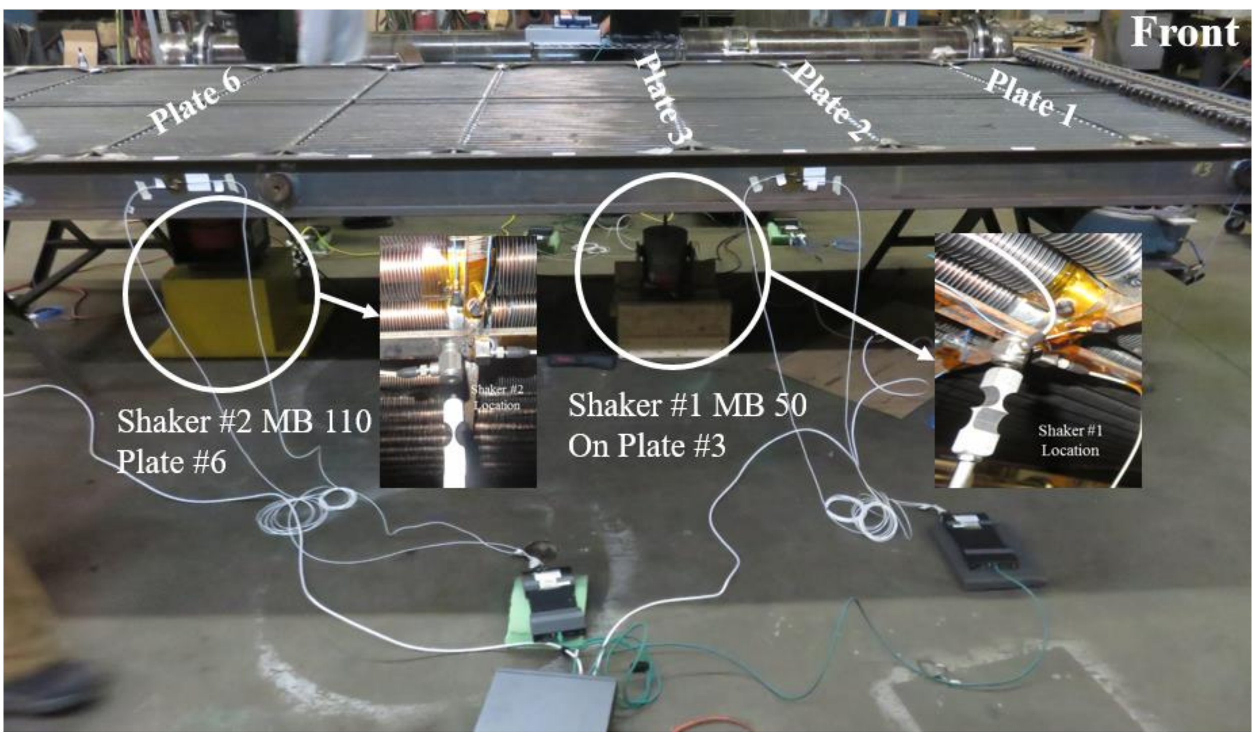

Figure 4. Modal Shakers Positioned on the Test Article

A multitude of excitation techniques were used to characterize the structure including impact with modal hammers and random, burst random, and sine sweeps using the modal shakers. The impact and random data was found to be effective at extracting global modes of the racks. The coherence of the random data was very poor due to the rattling and for this reason was not effective at identifying rattling. As will be discussed in more detail in the analysis portion the sine sweeps response data exhibited the rattling clearly.

ANALYSIS AND RESULTS

As vortices are shed around the tube, the fluctuating pressure fields will cause the tubes to oscillate at a specific frequency. This frequency can be estimated from the fluid properties and flow parameters using the Strouhal number. The Strouhal number is proportional to the vortex shedding frequency and the characteristic length of the body, and is inversely proportional to the fluid velocity. In this case, the characteristic length of the body is the diameter of the tube. The Strouhal number is a function of the Reynolds number; however, can be assumed to be about .22 for many flow regimes. Calculating vortex shedding frequencies from Strouhal numbers has been thoroughly studied for a vast array of flow regimes and is not trivial for as complex as flow regimes as this cooler will see. For this reason, a more detailed discussion is not included in this paper. An expansive literature review of these methods can be found in an article written in 1990 by H Sakamoto titled *"A Study on Vortex Shedding From Spheres in a Uniform Flow"* [5]. The problem presented by this cooler is significantly more complex and challenging that a simple cylinder in a fluid field. Compounding the complexity of the free-stream flow parameters of this cooler is the fact that many of the tubes will not see the uniform free-stream flow. Most closed form calculations assume a steady uniform flow field impacting a cylinder, however due to the closely packed nature of these tubes there will be flow interactions between the tubes increasing the complexity of the vortices. In addition, the tubes that are not on the intake face of the cooler will see a non-uniform flow distribution comprised of the vortices being shed by the tubes in front of them. This paper does not get into how these more complex fluid regimes will affect the problem.

In a very simplistic view of this problem the wind tunnel operators can use the vortex shedding analysis in conjunction with the modal test results and identify which flow regimes will cause rattling to occur.

As the tubes begin to oscillate, they will begin to rock within the bore. The amplitude of the rocking will be a function of two main parameters, excitation frequency and amplitude. As the vortex shedding frequency approaches the structures natural frequencies this rocking will couple with the tube's natural modes and be amplified by the resonance. The excitation amplitude will also directly increase the amplitude of the rocking. This phenomena behaves similar to an airplane wing undergoing flutter where a bending mode frequency lies near the frequency of vortices being shed around it. When the amplitude of the rocking increases past a tipping point the tube actually becomes detached from the bore and it will begin to rattle.

The most promising data came from the sine sweeps. These sine sweep rates were set slow enough to fully develop modes and acquire sufficient data in relevant frequency bands to accurately extract modal parameters. The figures below show results from sine sweep tests from 1500 Hz to 50 Hz at 1 octave per minute. Campbell diagrams were chosen to plot the data below due to their keen ability to identify nonlinear system dynamics. The first plot is of an accelerometer on an actual tube and the second plot is an accelerometer on the support immediately adjacent to the tube as shown above in Figure 3. These accelerometers were chosen due to their proximity to the rattling events. Harmonic distortion is easily identified in these diagrams as lines of high g-levels parallel to the input excitation shifted an exact frequency multiple of the excitation frequency to the right or left.

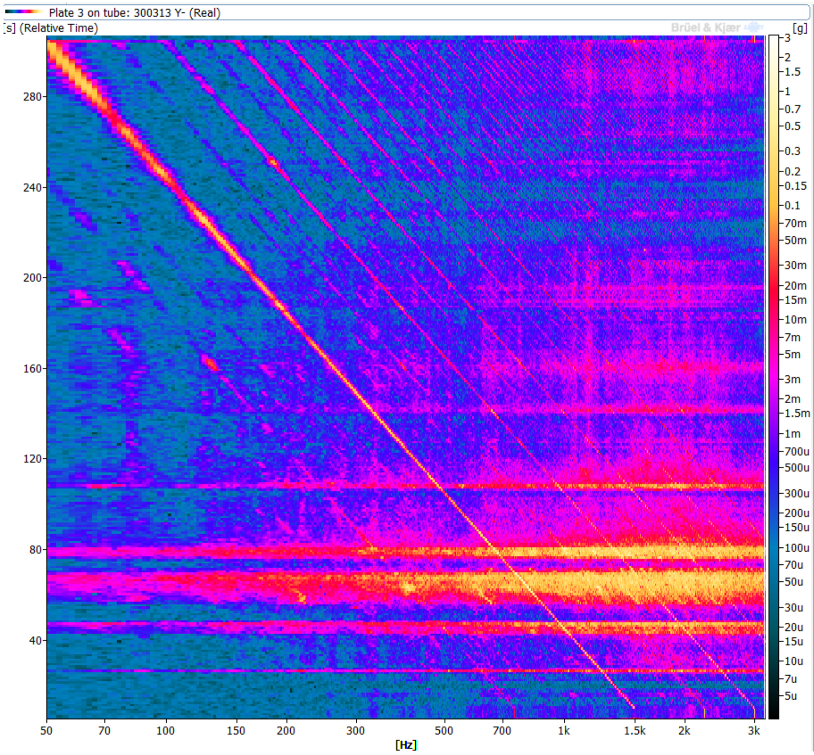

Figure 5. Campbell Diagram of Accelerometer on Tube

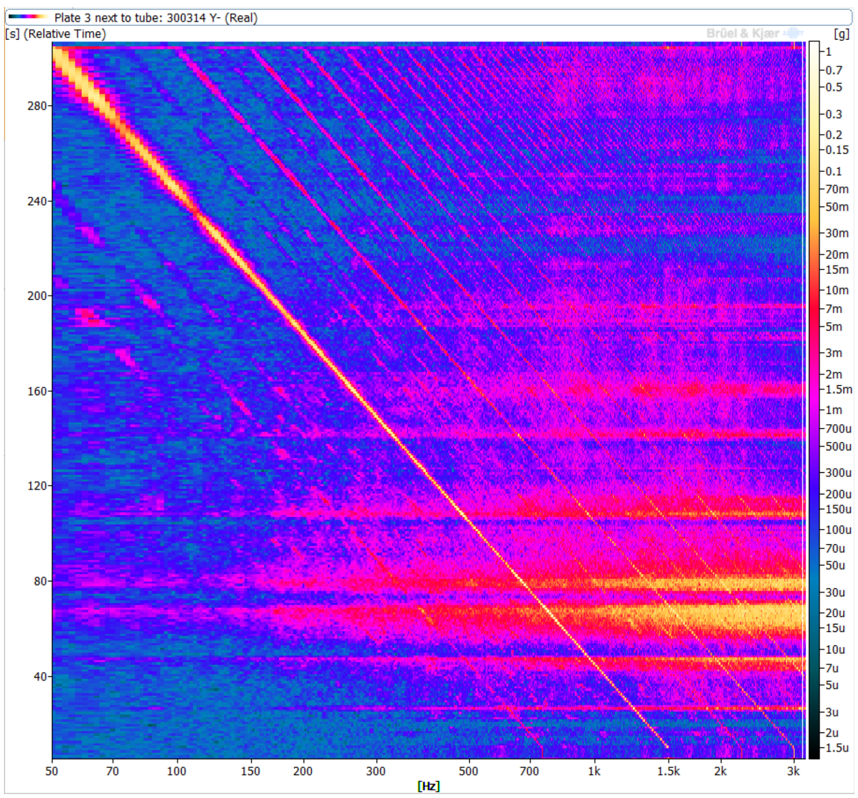

Figure 6. Campbell Diagram of Accelerometer on Support

The vertical axis is time in the sweep, the horizontal axis is response frequency, and the color code is normalized g levels of response. There are two distinct features on these plots, the diagonal line of high amplitude from top left to bottom right and the horizontal lines of varying thickness. The diagonal line of high amplitude is due to the frequency of the shaker and the lines parallel to it are its accompanying sub and super harmonics. At the beginning of the sweep when time is zero the shaker excitation line is at a frequency value equal to 1500 Hz and at the end of the sweep, about 300 seconds, the line is at a frequency value of 50 Hz. The horizontal lines with high amplitude indicate a broadband response at a specific excitation frequency and are an indication that rattling has occurred. The larger the amplitude of these broadband responses are the more severe the rattling and higher potential for damage. The intersection of the horizontal and diagonal lines represent the frequencies in which rattling is induced. Figure 6 is reshown below in Figure 7 with these intersections identified. The accompanying frequencies of each intersection are listed in Table 1 and are frequencies to be avoided when operating the wind tunnel.

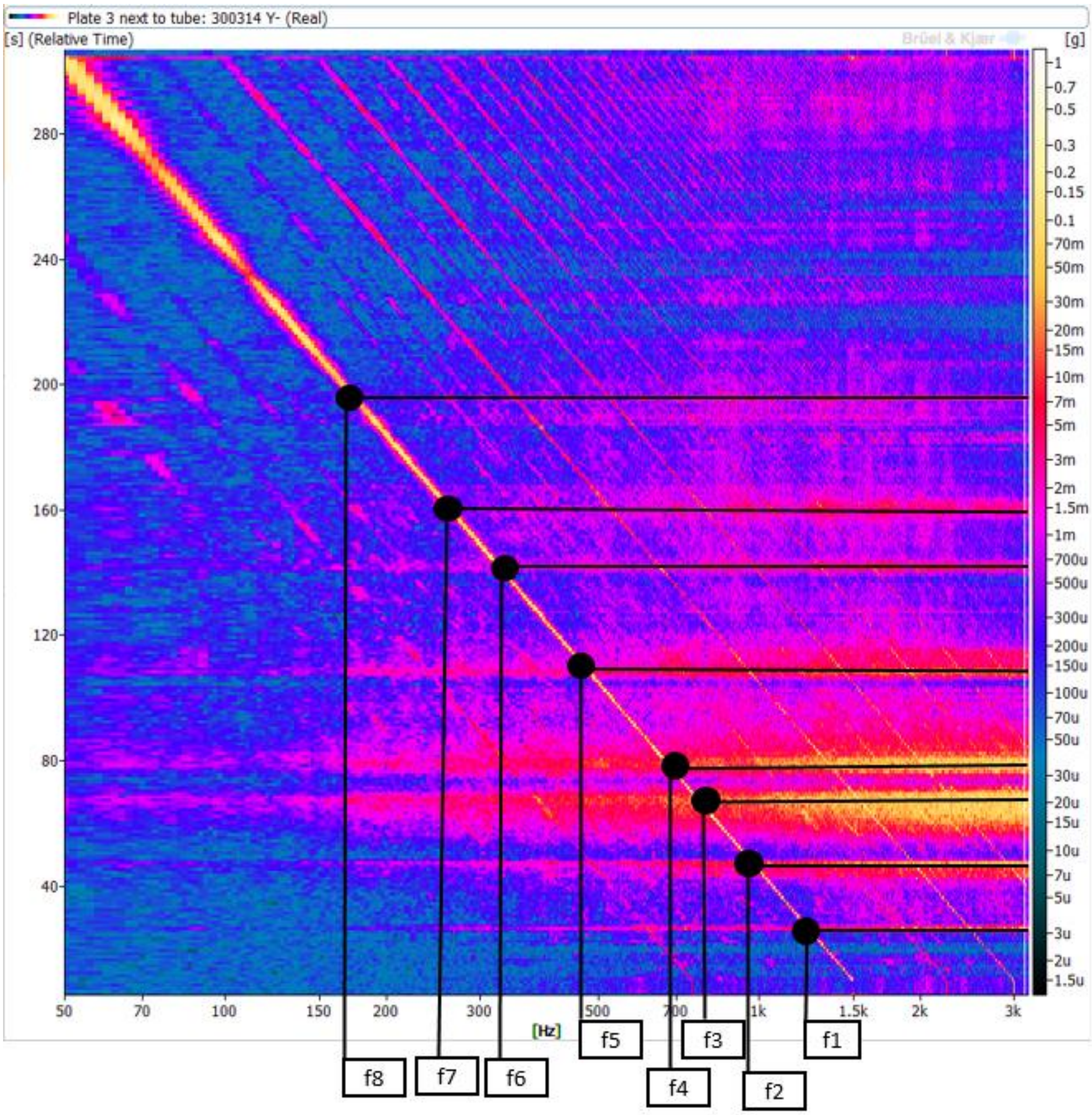

Figure 7. Rattling frequencies

Table 1. Rattling Frequencies as noted in Figure 7

Label	Frequencies
F1	1217.465206
F2	949.728238
F3	759.5086677
F4	670.7794989
F5	473.7961395
F6	328.0537758
F7	259.7556309
F8	174.5776203

CONCLUSION

Accelerometers on the tubes as well as on the supports directly adjacent to the tubes exhibited instantaneous broadband response over about 150 Hz – 3 kHz at single shaker excitation frequencies. A linear structure would only exhibit a single frequency response at the same frequency of the excitation. It is possible for structures to exhibit non-linear phenomena such as super and sub harmonics of the input excitation without directly causing rattle. This broadband response, in addition to test engineers being able to audibly pick up high pitched rattling during the sine sweeps, confirms that rattling will occur in this cooler design at specific excitation frequencies. The frequencies listed in Table 1 should be used in conjunction with the vortex shedding analysis suggested in the analysis portion of this paper to advise wind tunnel operators on what flow regimes should be avoided during tunnel operation.

This work also demonstrated a potential means of in operation structural health monitoring for this cooler system. The acceleration response of the structure proved to be an excellent indicator of rattling and could be transitioned from a modal test environment to a wind tunnel environment. This would require ruggedized accelerometers capable of resisting high temperatures and drag loads. Future work could be performed in developing a real time data acquisition approach to acquire vibration data from the cooler during operation. Microphones were used to collect response data during the modal to allow wind tunnel operators to install microphones during operation and have pre-test baseline data to compare to. This would allow facility operators to perform in-situ modal parameter extractions and identify if rattling is occurring during tunnel operation. It would also allow for significant changes in the natural frequencies of the cooler to be detected over time, which could infer structural degradation.

REFERENCES

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