Mechanical Engineering Division
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VIA E-MAIL

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Subject: Revised Final Test Report: Tests of Orbital/Daily VE Helical Strake Thermowells
Southwest Research Institute® (SwRI®) Project Number 18031.17.021

Dear Tom and Ian:

I am pleased to present this revised final report on the tests of the Orbital VE helical strake thermowell performed at SwRI's Metering Research Facility (MRF) on May 1, 2017. The primary test objective was to experimentally demonstrate the differences in vibration behavior between the Orbital VE helical strake thermowell design and a standard ASME straight-shank thermowell design. A secondary objective was to assess the thermal response of the helical strake and ASME thermowell designs to temperature transients. The report describes the thermowell designs under test, the MRF test facilities, the SwRI data acquisition system used for the vibration measurements, the measured flow conditions, and the measurements of thermowell vibrations and transient temperature response.

MRF Test Facilities

The thermowells were tested in high-pressure flows in the MRF High Pressure Loop (HPL). The HPL is a recirculating test loop used to simulate flowing conditions in natural gas transmission pipelines using distribution-quality natural gas as the flowing medium. The HPL is typically used to test and calibrate meters in line sizes from two inches to 16 inches at volumetric flow rates from 3,600 actual cubic feet per hour (acfh) to 107,000 acfh, and at line pressures from approximately 190 psia to 1,000 psia. Flow in the HPL is driven by a centrifugal compressor, allowing continuous flows at the desired flow rate and pressure for long-term testing.

Volumetric flow rates in the HPL are determined using critical flow Venturi nozzles traceable to National Institute of Standards and Technology (NIST) standards for mass and time. The critical flow nozzles are individually calibrated relative to the MRF Weigh Tank System, which serves as the primary NIST-traceable mass flow reference for the facility. During the calibration process, flow passes through an individual nozzle into a weigh tank. The total mass collected over a known time is measured and used to compute the critical mass flow rate through the nozzle, which provides the nozzle discharge coefficient at critical conditions.

Pressure and temperature measurements at the MRF are also traceable to NIST. The MRF reference pressure transmitter is calibrated directly against a deadweight reference by the SwRI Calibration Laboratory. This laboratory provides traceability to NIST and is accredited by the American Association for Laboratory Accreditation (A2LA). MRF temperatures are measured with a combination of temperature transmitters and resistance temperature detectors (RTDs). Each RTD is calibrated against a standard platinum resistance thermometer that is also traceable to NIST through the SwRI Calibration Laboratory. Differential pressure transducers are calibrated relative to a digital quartz transmitter, also calibrated traceable to NIST. Finally, an online gas chromatograph (GC) determines the gas composition in the loop. Uncertainties in the gas composition are determined through the repeatability of the GC analyses and the uncertainty in the certified composition of the GC calibration gas. The MRF requires that the certified compositions of its GC calibration gases be determined through a NIST-traceable, gravimetric blending procedure.

Turbine meters and ultrasonic meters in the HPL serve as secondary flow references. These secondary meters are calibrated against the critical flow nozzles, maintaining a traceability chain to NIST. The nozzles can only be "choked" at specific, discrete flow conditions, and it was known that the target flow conditions for resonant thermowell vibrations might not correspond to these discrete flow rates. For the thermowell tests, the nozzles were bypassed, the speed of the centrifugal compressor was used to control the flow rate, and a secondary reference meter (a 12-inch-diameter Daniel turbine meter) provided the traceable measurements of the HPL flow rate.

Thermowell Test Articles

Orbital Gas Systems (Orbital) and Daily Thermetrics (Daily) provided six thermowells for use in three flow tests.

- In the first test, the temperature responses of a helical strake thermowell and a straight-shank thermowell were compared during a startup transient from zero flow to a bulk flow velocity of approximately 6 ft/s in a nominal 12-inch-diameter pipe.
- In the other two tests, a helical strake thermowell and an ASME straight-shank thermowell were monitored at a series of flow rates where vortex shedding was expected to cause resonance vibrations for the ASME thermowell. One test was performed on thermowells mounted in a 12-inch-diameter pipe, and the other on thermowells in a six-inch-diameter pipe.

Table 1 identifies the six thermowells used in the tests and lists the dimensions provided by Orbital and Daily. The straight-shank thermowell lengths were chosen so that their natural frequencies coincided with vortex shedding frequencies at specific HPL flow rates. Figure 1 illustrates the locations of the dimensions listed in Table 1. Figures 2 and 3 are photographs of the helical strake thermowells and ASME thermowells evaluated in two of the tests.

Table 1. Dimensions of the Thermowell Test Articles

Each pair of thermowells tested together had identical overall lengths, bore diameters, and tip thicknesses, but the helical strake thermowells had smaller shaft diameters to accommodate the strakes. The table lists the symbols used by Daily for the thermowell dimensions, which may not correspond to the symbols used in the ASME thermowell standard.[1] *All dimensions are in inches.*

Thermowell type	Serial number	Overall length, *OAL*	Unsupported length, *U*	Diameter at root, *Q*	Diameter at tip, *V*	Bore diameter	Tip thickness	Shielded length, *SL*	Helix dimensions: Length along shank	Major diameter (with strake)	Minor diameter (without strake)	Pitch	Strake height	Strake width
Startup transient temperature tests, 12-inch-diameter pipe														
Straight shank	89384-000	8.375	6.25	1.5, 0.75*	0.75	0.385	0.25	4						
Helical strake	89387-000	8.375	6.25	1.5, 0.787*	0.63	0.385	0.25	4	2.25	0.787	0.630	3.15	0.079	0.059
Vibration tests in 12-inch-diameter pipe														
Straight shank	89383-000	17.75	15.625	0.75	0.75	0.385	0.25	8						
Helical strake	89386-001	17.75	15.625	0.787	0.63	0.385	0.25	8	7.625	0.787	0.630	3.15	0.079	0.059
Vibration tests in six-inch-diameter pipe														
Straight shank	89382-000	10.125	7.875	0.75	0.75	0.385	0.25	5						
Helical strake	89385-000	10.125	7.875	0.787	0.63	0.385	0.25	5	2.875	0.787	0.630	3.15	0.079	0.059

* The shaft diameter is 1.5 inches for the first 4 inches of the unsupported length, and then narrows to the second listed diameter.

[1] ASME PTC 19.3 TW-2016, *Thermowells – Performance Test Codes*, American Society of Mechanical Engineers, New York, New York, USA, February 2016.

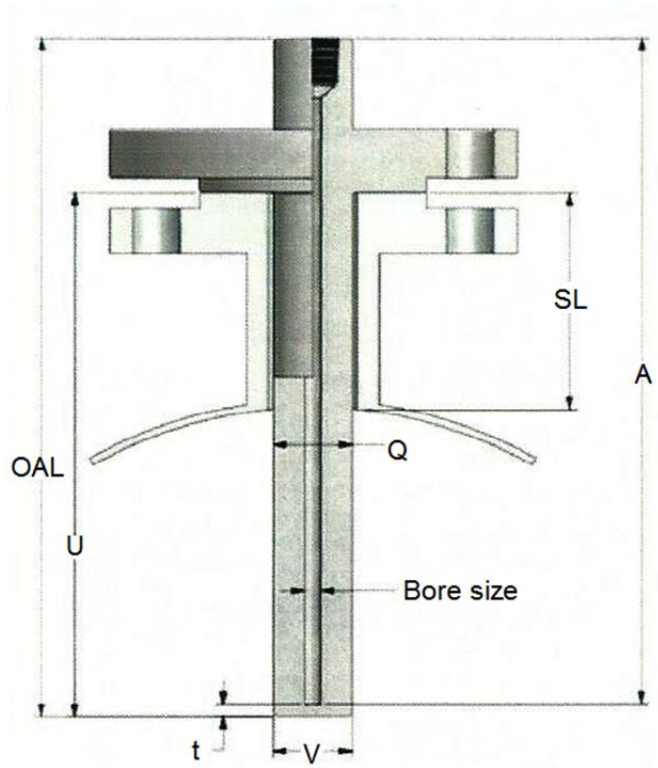


Figure 1. Illustration of Thermowell Dimensions
The dimensions and symbols shown here are used by Daily Thermetrics in thermowell fabrication. These may differ from symbols used in the ASME thermowell standard.

Figure 2. Thermowells Used in the Temperature Transient Tests
These thermowells were fabricated with short shanks to avoid resonant vibrations.

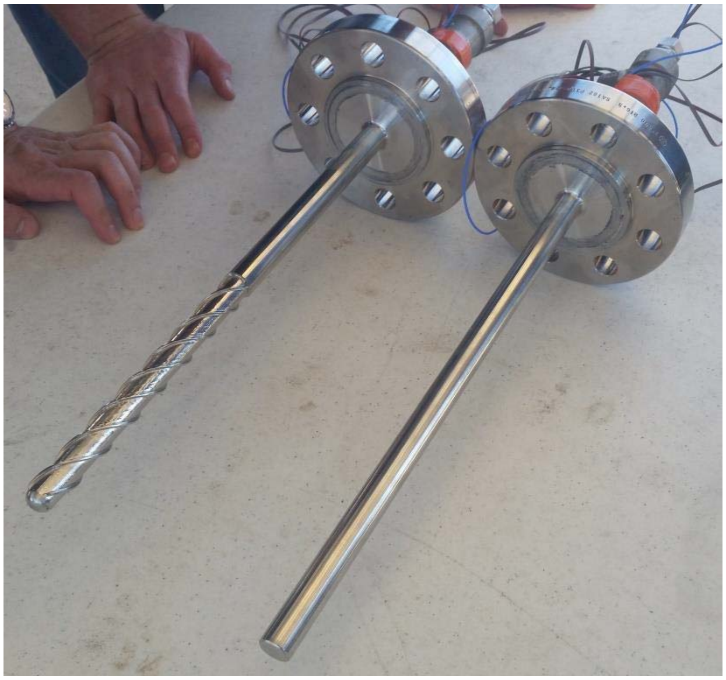


Figure 3. Thermowells Used in the Vibration Tests in the 12-Inch Test Run
While the two thermowell designs have identical unsupported lengths, the VE thermowell design has a hemispherical tip and a strake extending along part of its insertion length.

All the thermowells were made of 316L stainless steel and were fabricated with ANSI 600 raised-face flanges. Each thermowell was flange-mounted to a standoff perpendicular to the pipe axis. The standoffs on the 12-inch test spools were fabricated from two-inch-diameter pipe, while the standoffs on the six-inch test spools were fabricated from 1.5-inch-diameter pipe. The standoffs and thermowell lengths used for the vibration tests were chosen to produce a resonance vibration at flow velocities within the HPL flow range. The standoff and thermowell lengths used for the temperature transient tests were made shorter to avoid such vibrations (Figure 4).

The thermowells used for the vibration tests incorporated accelerometers and strain gauges, as discussed later in this report. To minimize the risk of a gas leak from a broken or fractured thermowell, Orbital filled portions of each upper thermowell assembly with an epoxy resin with a compressive strength in excess of 15,000 psi. As shown in Figure 5, the epoxy served to seal the space above the thermowell and around the leads from the accelerometers and strain gauges. A pressure gauge monitored the space for pressure leaks from the thermowells, and a ball valve was installed to cut through the leads and seal the assembly in the event of a leak.

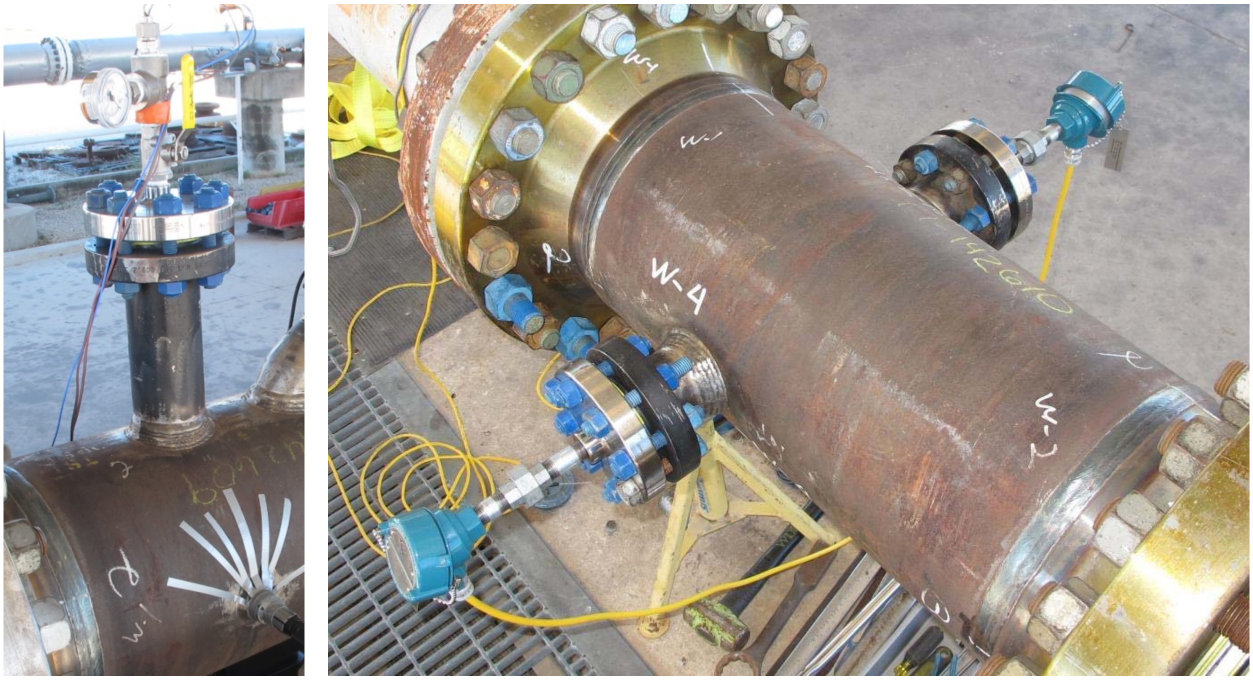


Figure 4. Thermowells Mounted in the Test Spools

The 12-inch test spool on the left included a single thermowell mounted in a long standoff designed to allow resonance vibration. The 12-inch test spool on the right was used for the temperature transient tests and used shorter thermowells and standoffs to avoid vibrations.

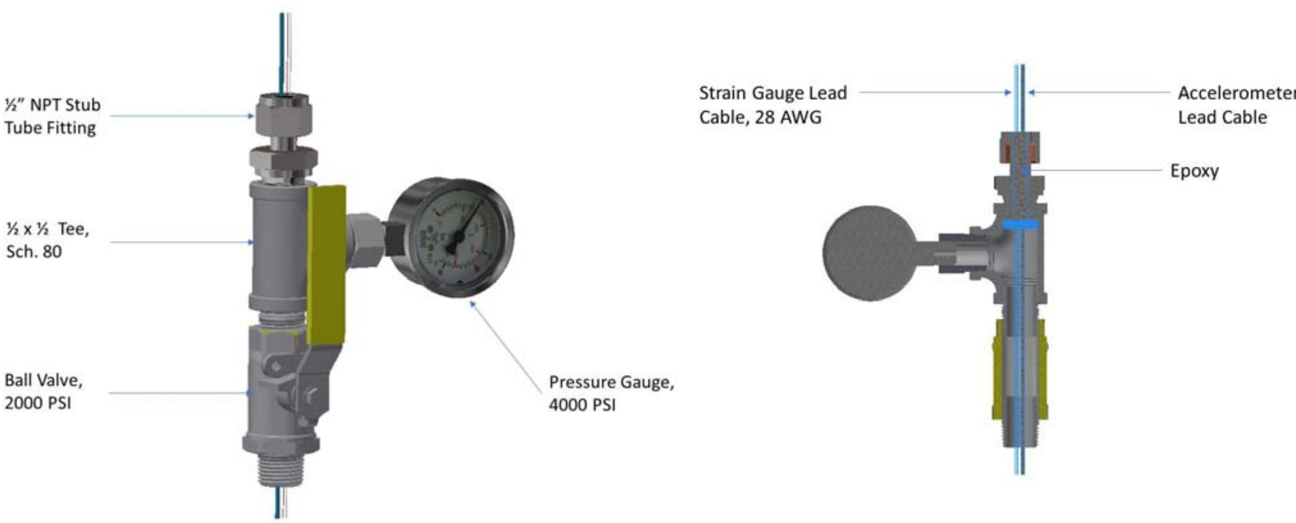
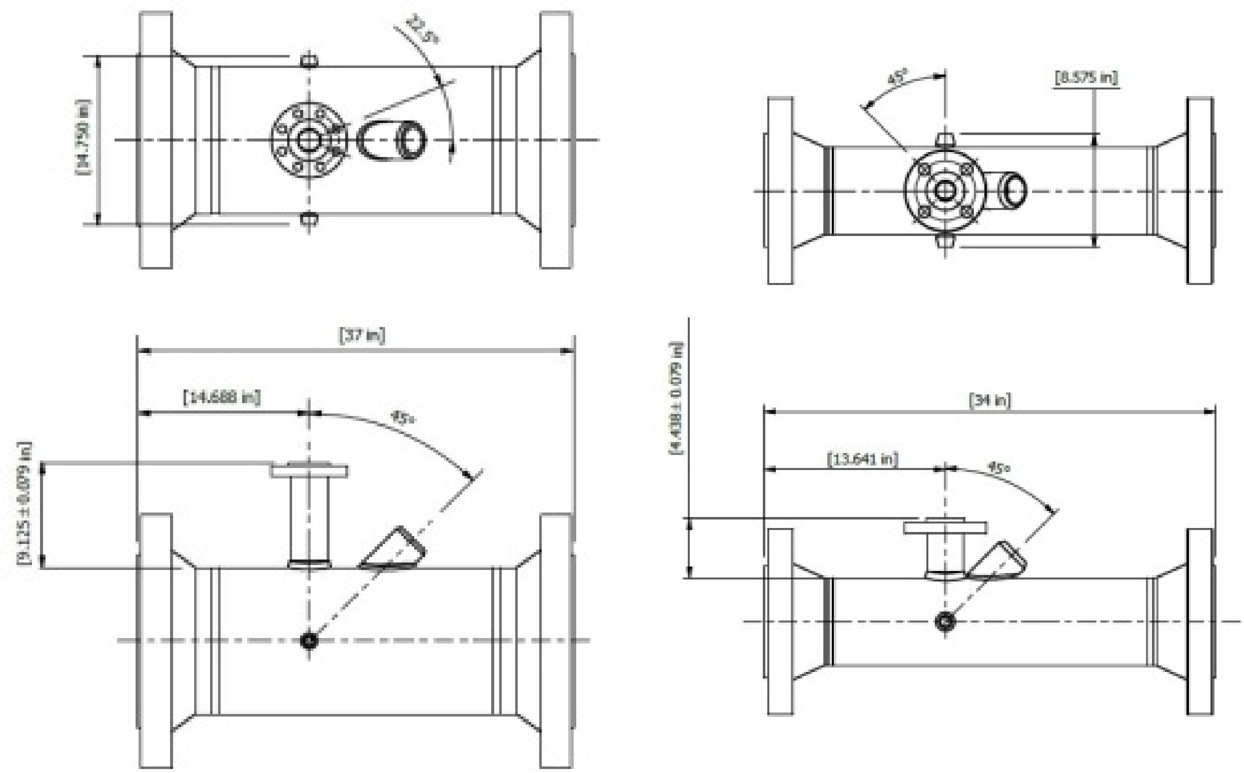


Figure 5. Thermowell Pressure Seal and Safety Features

The high-strength epoxy seal at the top of the assembly served as a pressure barrier in the event of thermowell structural failure. If the pressure gauge indicated a gas leak through the thermowell, closing the ball valve would act to seal the leak.

HPL Pipe Installations

Orbital and Daily provided the test spools with flanged standoffs for the tests. Four of the test spools were fabricated for the thermowell vibration tests (Figure 6). Two of these four spools were fabricated from 12-inch-diameter Schedule 40 pipe (nominal internal diameter 11.938 inches), with a single vertical standoff extending 9.1 inches above the outer pipe wall. The other two spools were fabricated from six-inch-diameter Schedule 40 pipe (nominal internal diameter 6.065 inches), and had a vertical standoff extending 4.4 inches above the outer wall. Each of the four spools for the vibration tests had a Latrolet downstream of the thermowell standoffs and two threadolets on an axis perpendicular to the standoff. These Latrolets were fitted with transparent windows rated to 4,000 psi to permit lighting and high-speed video recordings of the thermowells in the flow.



12-inch-diameter spools 6-inch-diameter spools

Figure 6. Dimensions of the Test Spools Used for the Thermowell Vibration Tests
Each test spool was fitted with a single standoff for mounting a thermowell. A downstream Latrolet and threadolets on the sides were fitted with high-pressure sight glasses for recording high-speed video of the thermowell vibrations.

A fifth test spool was fabricated for the temperature transient tests. This spool was built from 12-inch-diameter Schedule 40 pipe, and had two opposing horizontal standoffs extending 3.6 inches above the outer wall (Figure 7). This arrangement allowed the two thermowell designs to measure temperature at the same position in the flow without interfering with each other. Orbital and Daily also provided 12-inch and six-inch debris plates fabricated from pipe blinds. These were built to SwRI specifications to prevent large pieces of thermowell debris from reaching the MRF nozzle bank or compressor in the event of a broken or fractured thermowell.

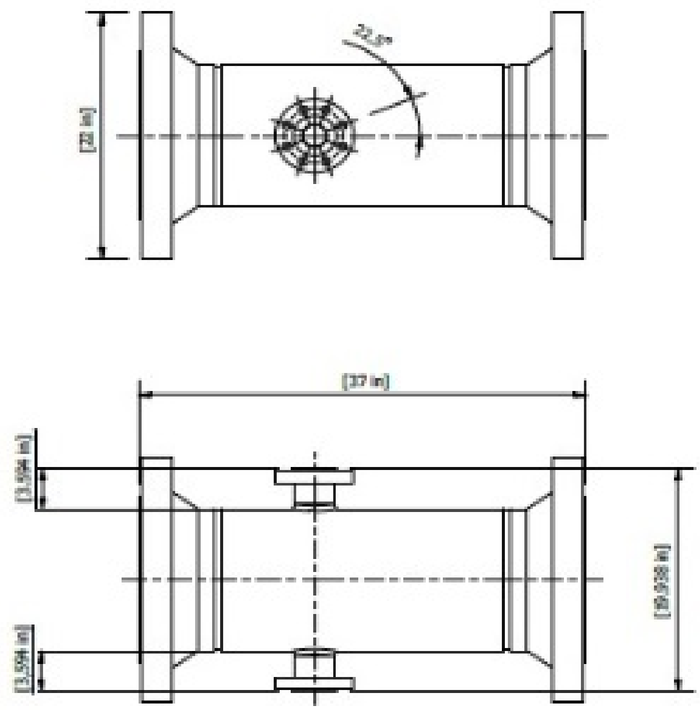


Figure 7. Dimensions of the Test Spool Used for the Temperature Transient Tests
The test spool was fitted with two opposing standoffs to position the straight and helical thermowells at the same point in the flow.

The test spools were installed in straight pipe runs using pipe spools from the MRF inventory. As built, the pipe runs separated the thermowells along the pipe axis by at least 100 thermowell diameters. This spacing allowed the flow disturbances created by each thermowell to die out and provided distance for the flow to fully develop between thermowells. The 12-inch and six-inch runs shown in Figure 8 were installed in the HPL test section in the west and east legs, respectively. Directly upstream of the test section, over 100 nominal diameters of 12-inch pipe provided a fully-developed flow at the entrance to the west leg and the first 12-inch test spool. A CPA 50E plate flow conditioner was installed in the six-inch run to establish pseudo-fully developed flow in the east leg. In both legs, the helical thermowell was installed in the upstream test spool. This arrangement was expected to minimize any flow disturbances reaching the straight-shank thermowell installed downstream. The final test spool in the 12-inch-diameter run held the two thermowells used in the temperature transient tests.

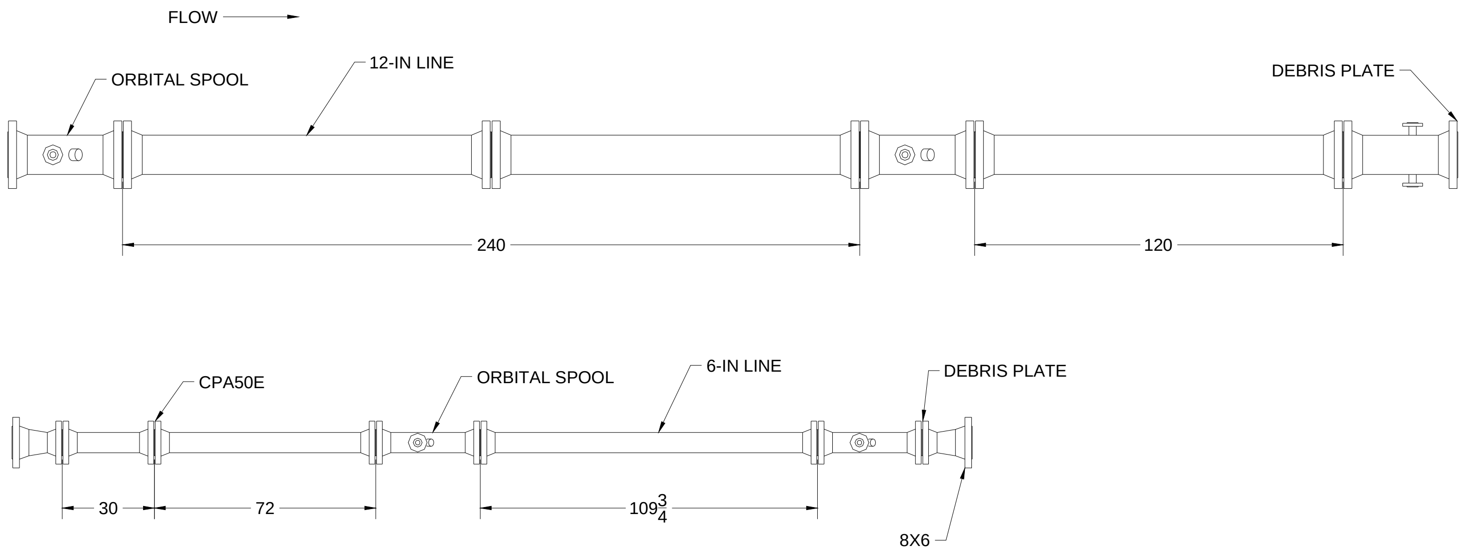


Figure 8. Pipe Runs Used in the Thermowell Tests

The two runs were installed in separate legs of the HPL test section to allow tests at different bulk flow velocities, if needed. The helical thermowells were installed in the upstream test spools, while the ASME thermowells were installed downstream. The last spool in the 12-inch run was used for the temperature transient tests. All of the dimensions are in inches.

Sensors and Data Acquisition

Thermowell Vibration Sensors. Orbital and Daily incorporated an accelerometer and strain gauges into each thermowell used in the vibration tests. To quantify the thermowell vibrations, a PCB Piezotronics Model 356A03 three-axis accelerometer was mounted at the tip of each thermowell bore using epoxy. Two Omega KFH series three-wire strain gauges were mounted to an aluminum plate that was force-fit into each thermowell bore. The plate provided a flat surface for mounting the strain gauges to measure horizontal and vertical strains just below the flange. Leads from these instruments passed through the epoxy seal at the upper safety assembly and terminated in appropriate signal connectors. The accelerometer cable terminated in a miniature four-socket plug, and a separate adapter converted the plug leads to three standard BNC connectors, one for each axis of motion. A set of three insulated wires provided connections to the bridge completion circuit that provided voltage measurements from the strain gauge.

Data were collected from the accelerometers and strain gauges in real time using a National Instruments® NI DAQ data acquisition system provided by SwRI's Fluid Machinery Systems Section. The NI DAQ collected voltage signals from the accelerometers via the BNC connectors and from the strain gauges via the signal wires. Multiplexers sent the voltage signals to a laptop computer, where a custom software application sampled the signals, displayed each signal and its frequency spectrum, and recorded the measurements for later analysis. The accelerometers and strain gauges were tested with the NI DAQ about two weeks before the flowing tests in the HPL to confirm that the sensors would function and communicate correctly,[2] and the findings were used to finalize the mounting arrangements described above.

Transient Temperature Sensors. For the transient temperature measurements, Daily Thermetrics provided two Model 310 industrial sensors with type-K thermocouples (Figure 9). These were inserted in the ASME and helical strake thermowells mounted opposite each other in the downstream 12-inch test spool. No conducting fluid was placed in the thermowell bores, but the sensors were spring-loaded to ensure solid contact between the thermocouples and the thermowell tips. For the reference temperature measurements, SwRI staff inserted a platinum resistance temperature device (RTD) approximately two feet upstream of the thermowells housing the thermocouples. This reference RTD was a Weed model 210-01B-C-4-A with a NIST-traceable calibration. The RTD was inserted directly into the flow without a thermowell to allow the fastest possible response to temperature transients. The small diameter of the RTD (1/8 inch) minimized its disturbance of the flow field reaching the thermowells under test.

[2] "Preparatory Sensor Checks for Orbital Thermowell Tests," SwRI Metering Research Facility report to Dan Hamill of Orbital, April 20, 2017.

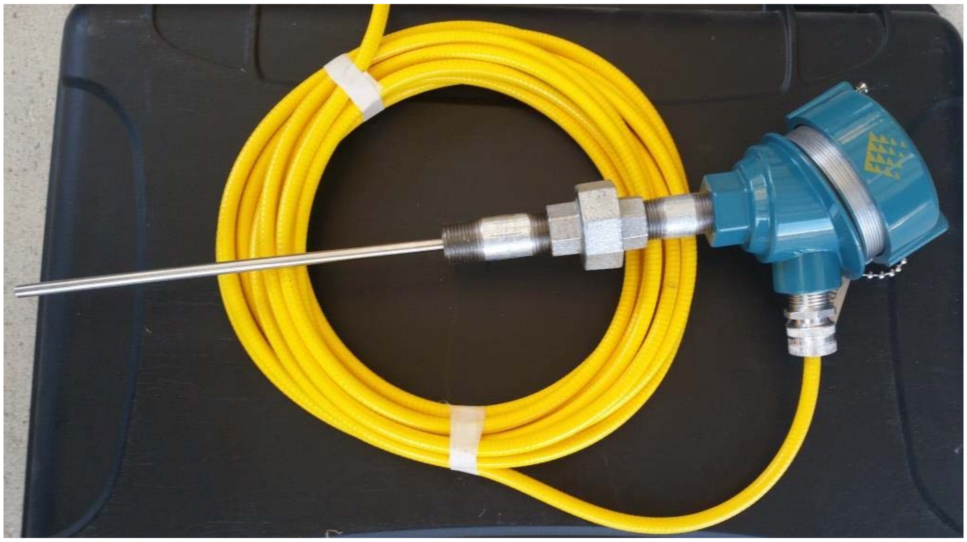


Figure 9. Daily Model 310 Industrial Sensor Used in the Transient Temperature Tests
Two identical sensors of this model were installed in the opposing ASME and helical strake thermowells to compare the effects of thermowell design on temperature response.

Temperature measurements from the two Daily sensors and the reference RTD were logged continuously by a Fluke model 1586A Super-DAQ precision temperature scanner. A two-prong type-K connector was used to connect the Model 310 thermocouples to the scanner via a termination bus. The four-wire output of the reference RTD was connected to the temperature scanner through the same bus.

HPL flow instrumentation. Flow conditions in the HPL were measured using Rosemount pressure transmitters, Weed RTDs, and a Daniel turbine meter as discussed above. Data from these were collected and recorded at one-second intervals using a custom MRF LabVIEW data acquisition application. A Daniel Model 590 gas chromatograph analyzed the HPL flowing gas composition at six-minute intervals. These analyses were logged and later used as input to the AGA-8 Detail equation of state[3] to calculate the density and viscosity of the flowing gas. Pressure and temperature transmitters installed in each thermowell test run and near the Daniel reference turbine meter were polled once per second by the MRF LabVIEW data acquisition software (independent from the LabVIEW system used for capturing the accelerometer and strain gauge data). These data were used as input to AGA-8, along with the local flowing temperature and pressure, to compute the gas properties at each location. The LabVIEW software also collected pulse outputs from the Daniel reference turbine meter and calculated the volumetric flow rate in the loop at one-second intervals.

Baseline Vibration Tests

Once the thermowells and test spools had arrived at SwRI, each thermowell was bolted to its standoff flange using a procedure requested by Orbital and Daily. The bolts were tightened in a cross pattern using a torque wrench set to the desired torque level. The bolts were tightened equally in a first pass to 50% of the final torque level, then in a second pass to 75% of the final level, and finally to 100% of the recommended torque. For the thermowells mounted on the 12-inch test spools, the final torque was 120 ft-lbs; for the thermowells on the 6-inch test spools, the bolts were tightened to 200 ft-lbs.

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[3] American Gas Association, *Compressibility of Natural Gas and Other Related Hydrocarbon Gases*, AGA Transmission Measurement Committee Report No. 8, American Gas Association, Washington, DC, USA, 1985.

The thermowells to be used in the vibration tests were then checked to find their natural resonance frequencies and to confirm that they had been mounted securely to the standoff flanges. Each test spool was placed on a concrete pad, and the thermowell accelerometer was connected to the NI DAQ system. The thermowell was then struck with a piece of lumber in the y-direction, parallel to the axis of the test spool. The oscillations were recorded and analyzed for frequency content. Because the thermowell strikes were not mechanically controlled, the resonant amplitudes were not considered useful.

Figures 10 and 11 present the vibration spectra of the four thermowells, with the primary frequencies marked in bold font. In the plots, acceleration on the y-axis is parallel to the pipe axis and represents vibrations in line with the flow direction. Acceleration in the z-axis is perpendicular to the pipe axis and represents transverse vibrations, while the x-axis data represent accelerations along the thermowell long axis. Independent of the thermowell design, the dominant vibration mode was in the z direction, perpendicular to the direction of the initial impulse on the y-axis.

The measured fundamental frequency of the 12-inch straight thermowell was 90 Hz, compared to a frequency of 85 Hz predicted using the ASME PTC 19.3 thermowell standard. The fundamental frequency of the six-inch straight thermowell was measured as 330 Hz, which compared well to a predicted frequency of 324 Hz. The predicted frequencies were used in advance to select HPL test conditions that would produce locked-in resonance of the ASME thermowells in the in-line and transverse directions. Given the closeness of the predicted and measured frequencies, little-to-no adjustment to the chosen flow rates during the testing was anticipated. The helical strake design serves to eliminate or reduce the formation of regular vortices.[4] Thus, a flow velocity cannot be easily predicted that would generate periodic vortices at its resonant frequency, if a fluid resonance could be established at all, so target flow rates were chosen based on the standard thermowell.

[4] Scruton, C., and Walshe, D. E. J., “A Means for Avoiding Wind-Excited Oscillations of Structures with Circular or Nearly Circular Cross-Section,” National Physics Laboratory Report NPL/AERO/335 (Great Britain), October 1957.

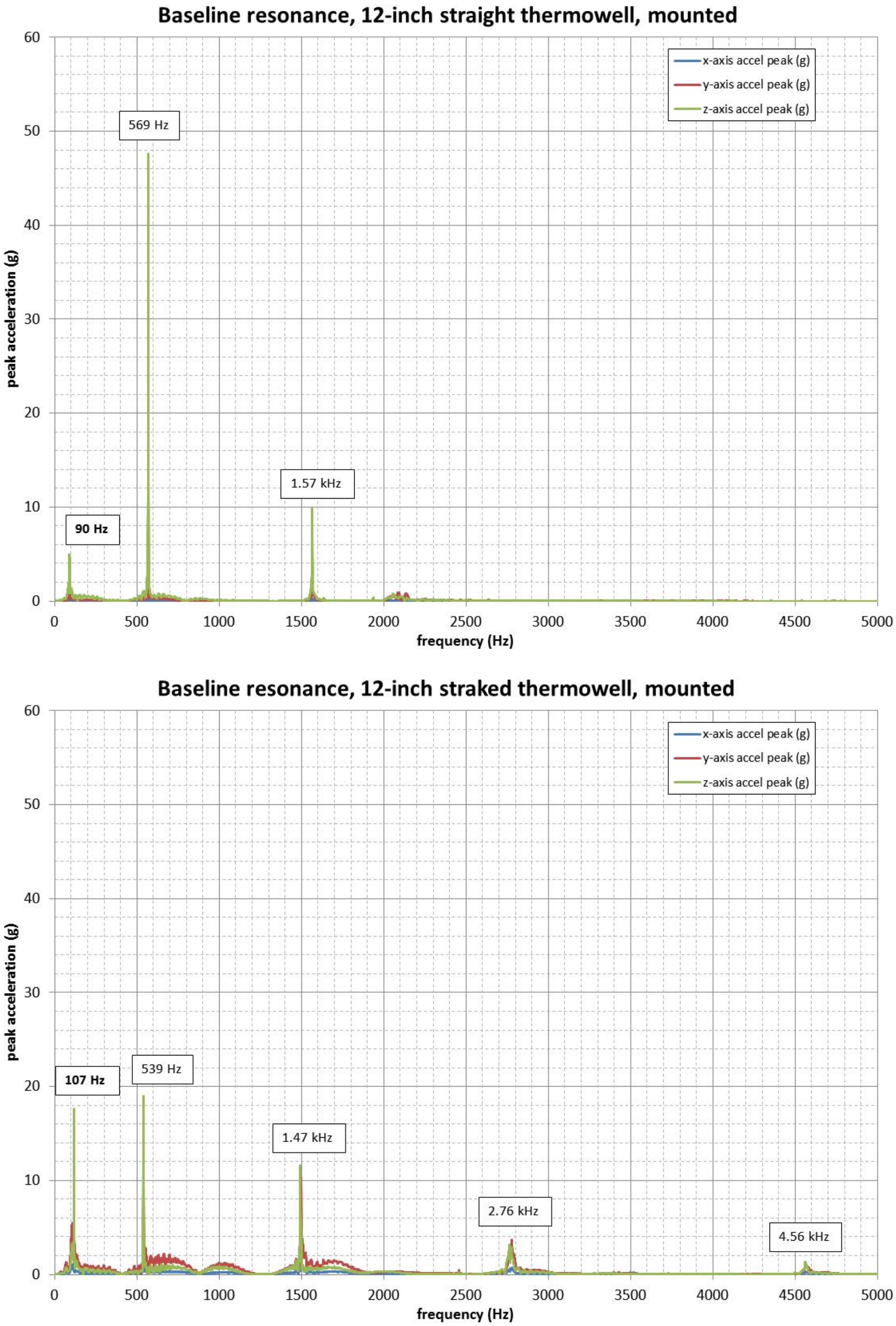
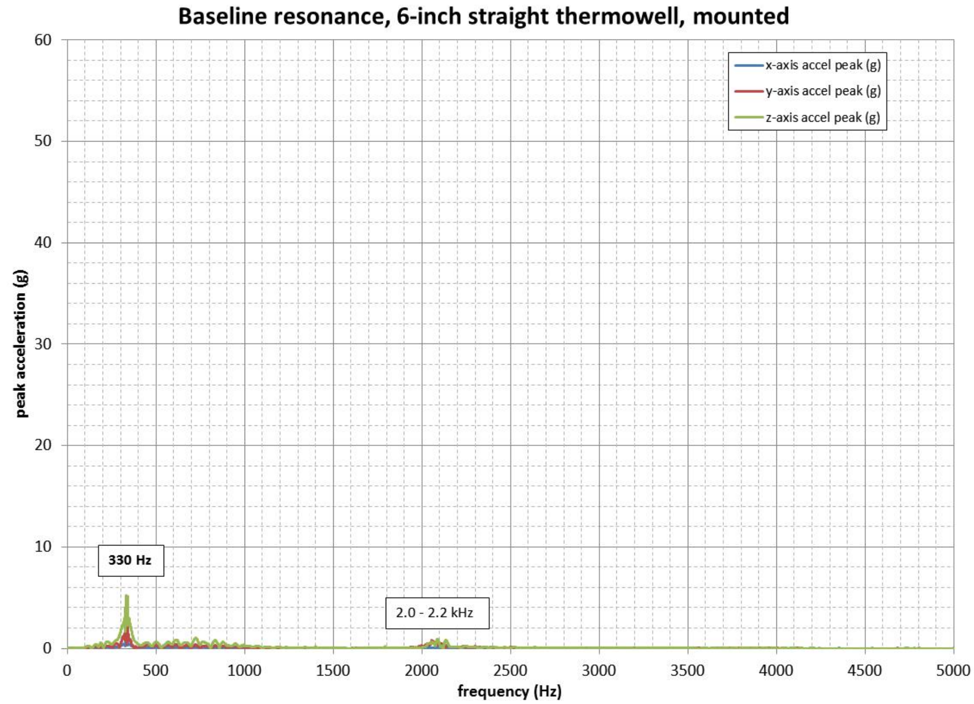


Figure 10. Comparison of the Natural Frequencies of the Thermowells in the 12-inch Baseline Tests

The helical strake thermowell had a natural frequency of 107 Hz, compared to the natural frequency of 90 Hz for the ASME straight thermowell. The dominant vibrations were along the z-axis, perpendicular to the direction of the initial impulse on the y-axis.



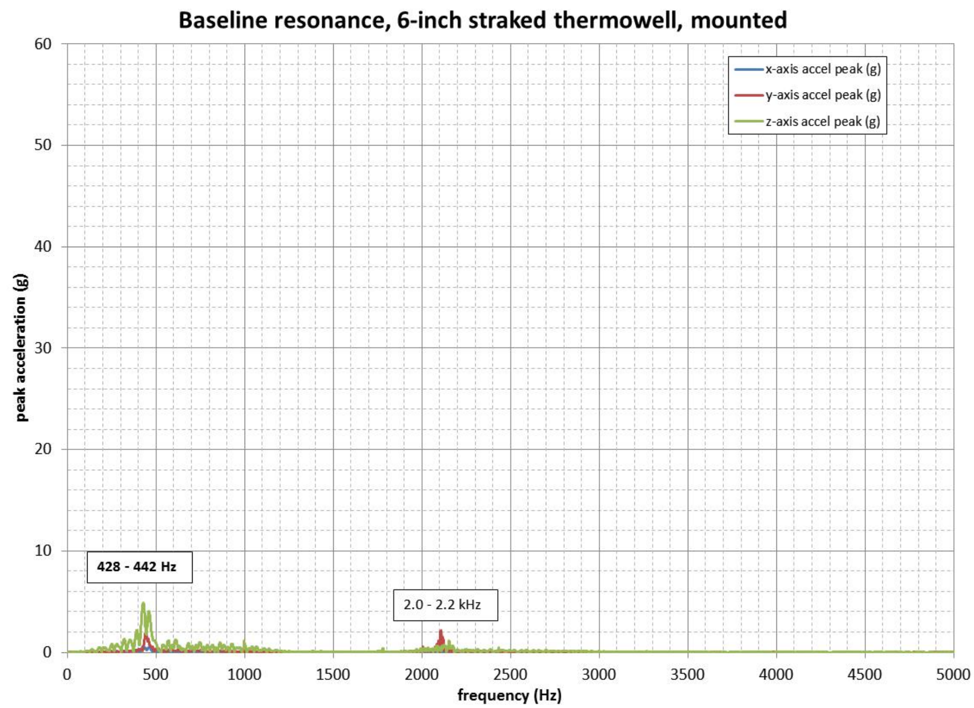


Figure 11. Comparison of the Natural Frequencies of the Thermowells in the Six-inch Baseline Tests

The helical strake thermowell had a natural frequency between 428 Hz and 442 Hz, compared to the natural frequency of 330 Hz for the ASME straight thermowell. As with the 12-inch thermowells, the dominant vibrations were perpendicular to the direction of the initial impulse. Note that the six-inch thermowells responded with significantly smaller accelerations than the 12-inch thermowells.

Flowing Tests

Flowing conditions. The HPL data acquisition system recorded temperatures, pressures, flow rates, and gas compositions continuously during all of the tests. The nominal flow conditions for each test were 40%, 80%, and 100% of the HPL volume flow capacity. The flow rates of 40% and 80% of the HPL capacity were chosen in combination with the thermowell lengths to produce resonant vibrations of the ASME thermowells in the in-line and transverse directions, respectively. The chosen flow rates achieved the desired resonant conditions, except for the test at 80% flow capacity in the six-inch-diameter run, where a small flow rate adjustment was needed to produce the maximum vibration amplitude. Full-flow capacity could not be achieved during the six-inch tests due to a high pressure drop across the debris plate, so the final test condition was approximately 94% of the HPL flow capacity.

Plots of the flow data were inspected to identify stable flow intervals at each test condition. A six-minute time interval was chosen from each stable interval over which thermowell responses would be analyzed. For the transient temperature tests, the data interval began with the start of flow in the 12-inch run and continued until the temperatures were declared stable. Figures 12 and 13 graph the flow rates and identify the intervals chosen for data analysis at each test condition.

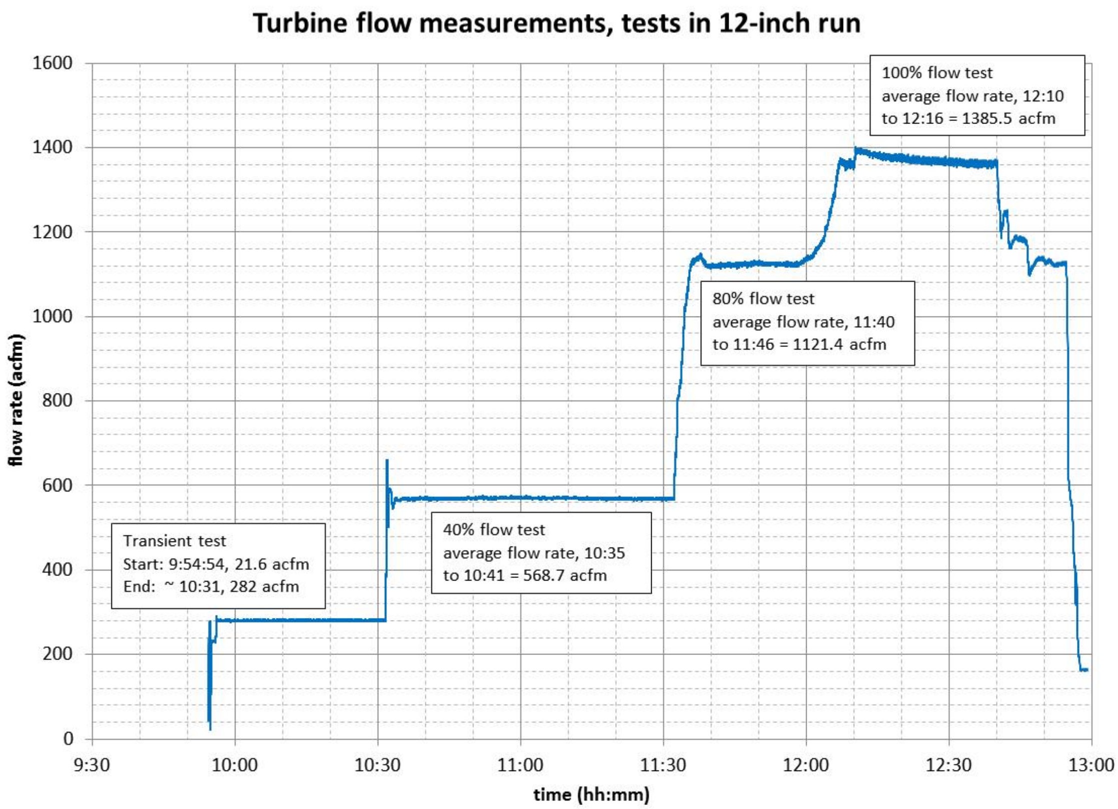


Figure 12. Flow Rates during the Transient Temperature and Vibration Tests in 12-inch Pipe
The boxes note the time intervals from which the thermowell data were collected and analyzed at each test condition. The transient test interval began with the start of flow in the 12-inch run, while the vibration test intervals began after the flow in the run had stabilized at each condition.

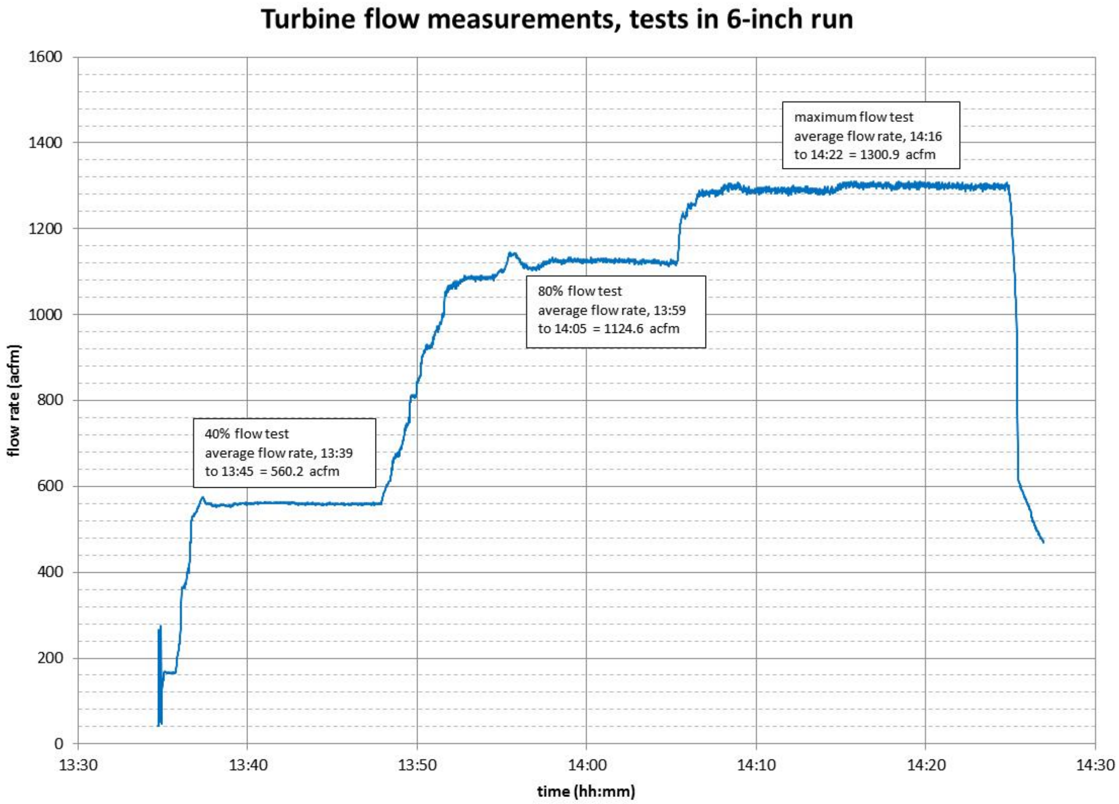


Figure 13. Flow Rates during the Vibration Tests in Six-inch Pipe

The boxes note the time intervals from which the thermowell data were collected and analyzed at each test condition. The vibration test intervals began after the flow in the run had stabilized at each condition. Note the small flow rate adjustment made during the 80% flow test to achieve the maximum vibration amplitude for the ASME straight thermowell.

The flow data were used to calculate the bulk flow velocity U at the thermowells and the Reynolds number of the flow based on the pipe diameter D ($Re_D = \rho UD/\mu$). Table 2 lists the average values of the measured and calculated flow parameters for each thermowell vibration test. Except for the gas density (ρ) and viscosity (μ), these averages were calculated from the temperature, pressure, and flow rate measurements taken every second over each six-minute analysis interval. Since the Daniel GC analyzed the gas composition once every six minutes, the gas density and viscosity were calculated from a single gas analysis and the average temperature and pressure over the analysis interval. The table also lists the repeatability of the measured flow parameters at the 95% confidence level. The repeatability values were computed from the sample standard deviations of the multiple measurements over each analysis interval.

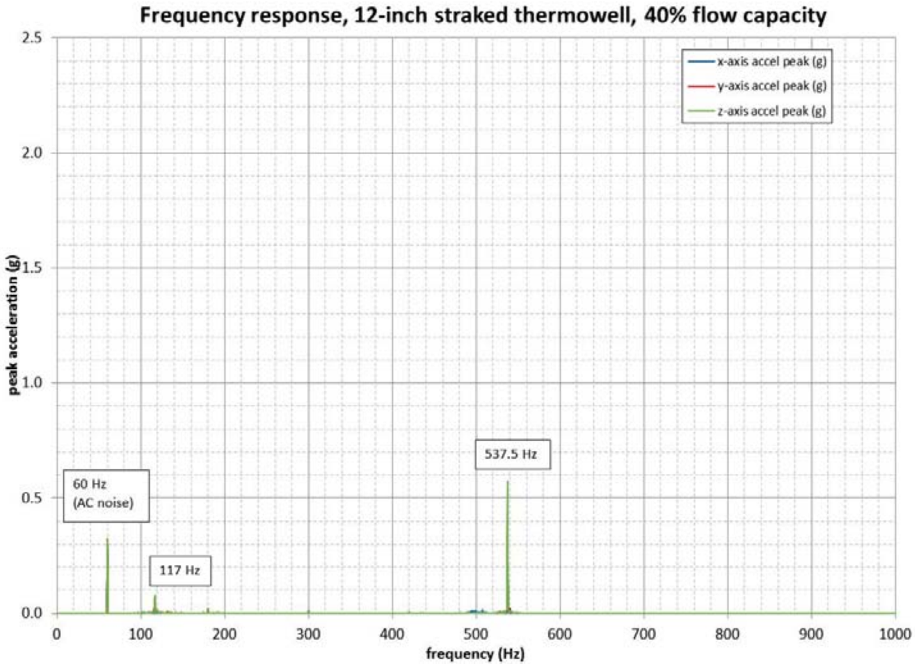
Table 2. Flow Conditions during the Thermowell Vibration Tests

The averages and repeatability values at the 95% confidence level were computed for each flow variable to quantify the stability of the flow conditions.

Test	Analysis interval	Volume flow rate (acfm)	Conditions in the thermowell test run					
			Pressure (psia)	Temperature (°F)	Bulk velocity (ft/s)	Density (lb_m/ft^3)	Viscosity (10^{-6} $lb_m/ft/s$)	Reynolds number, Re_D
12-inch run, 40% flow capacity	10:35 – 10:41	568.7 ± 3.0	964.4 ± 0.8	70.4 ± 0.4	12.2 ± 0.1	3.328	8.446	4.78×10^6
12-inch run, 80% flow capacity	11:40 – 11:46	1,121.4 ± 5.0	967.2 ± 0.3	69.9 ± 0.2	24.0 ± 0.1	3.344	8.447	9.47×10^6
12-inch run, 100% flow capacity	12:10 – 12:16	1,385.5 ± 13	967.7 ± 1.2	70.9 ± 0.1	29.7 ± 0.3	3.336	8.456	1.17×10^7
Six-inch run, 40% flow capacity	13:39 – 13:45	560.2 ± 3.6	967.2 ± 1.0	73.7 ± 0.2	46.5 ± 0.3	3.307	8.479	9.17×10^6
Six-inch run, 80% flow capacity	13:59 – 14:05	1,124.6 ± 6.7	968.0 ± 0.6	76.4 ± 0.2	93.4 ± 0.6	3.282	8.502	1.82×10^7
Six-inch run, maximum flow capacity	14:16 – 14:22	1,300.9 ± 8.6	966.0 ± 0.6	77.8 ± 0.3	108.1 ± 0.7	3.261	8.511	2.09×10^7

Thermowell vibrations. At each of the steady-state flow conditions in Table 2, accelerometer and strain gauge data were collected from the instrumented thermowells. Orbital and Daily staff also recorded high-speed video of the ASME and helical strake thermowells at the chosen flowing conditions. Although the recordings visibly show thermowell oscillations, the accelerometer data is used here to quantify the thermowell motion. The video recordings are being provided to SwRI as documentation, but are not being distributed with this report. Interested readers should contact Orbital and Daily staff for more information.

Figures 14 through 19 present the vibration spectra computed using the accelerometer data from each thermowell. Each graph presents the peak acceleration of the thermowell tip along each axis averaged over a six-minute analysis period. Acceleration is plotted in units of the standard gravitational acceleration, g (1 g = 32.174 ft/s^2). As noted earlier, the x axis follows the axis of the thermowell, the y axis corresponds to the direction of flow in the pipe, and the z axis is transverse to the flow. The graphs display only the spectra below 1,000 Hz, where the greatest majority of oscillations were observed. An examination of the graphs reveals several trends in the thermowell behavior.



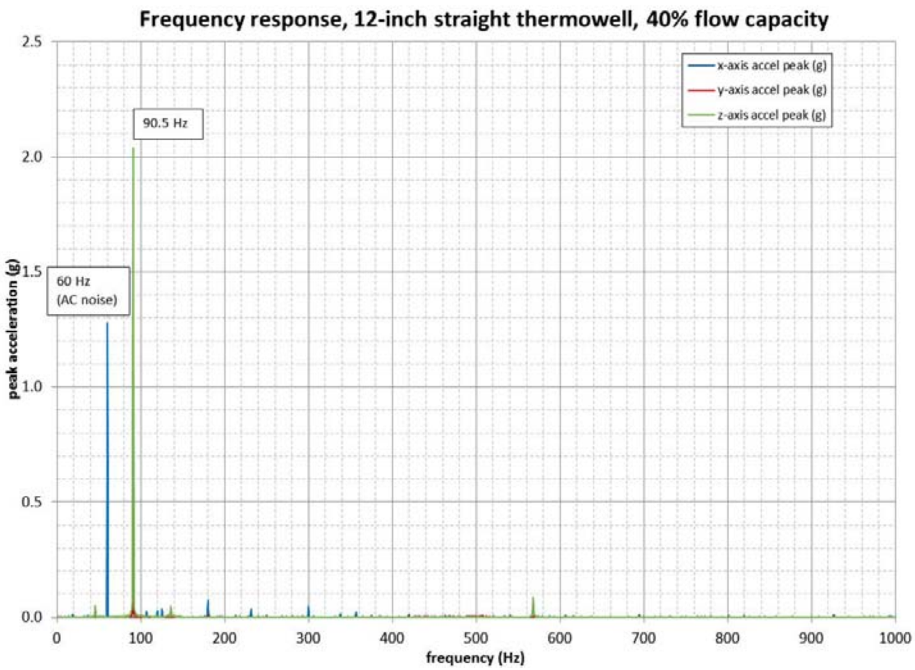


Figure 14. Frequency Responses of the Thermowells in the 12-inch Pipe at 12.2 ft/s

The helical strake thermowell (top graph) has a fundamental resonance frequency of 117 Hz, while the straight ASME thermowell (bottom graph) has a fundamental frequency of 90.5 Hz. At this flow rate, the acceleration on the straight thermowell has reached a maximum of 2.05 g's, compared to a peak acceleration of 0.6 g's for the helical strake design. Although this flow rate was chosen to "lock in" the ASME thermowell resonance in line with the flow, the dominant resonance occurred in the transverse direction. The 60 Hz frequency component appeared on only one of the three accelerometer channels for each thermowell and is attributed to electrical noise.

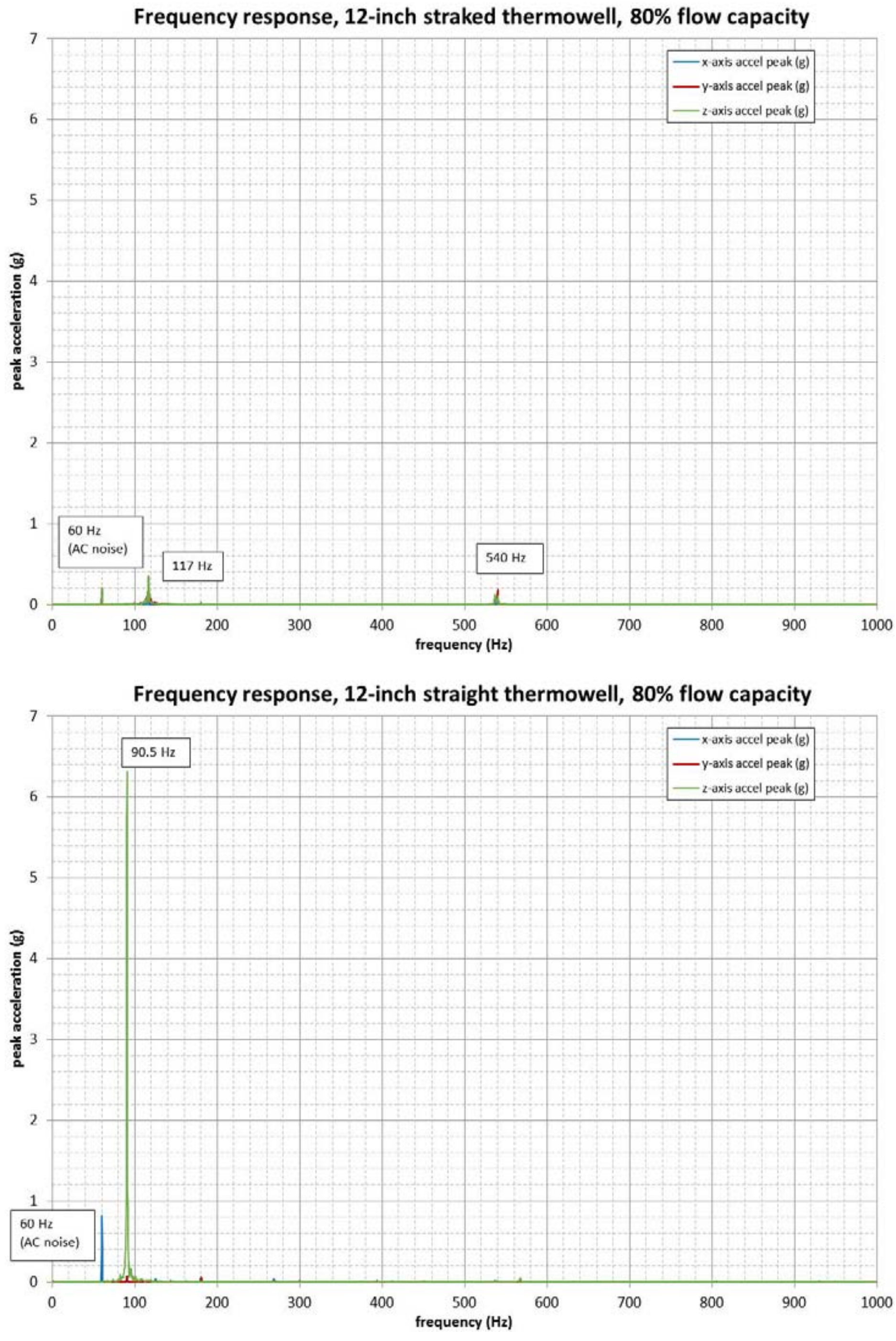


Figure 15. Frequency Responses of the Thermowells in the 12-inch Pipe at 24 ft/s

The fundamental frequencies of the helical strake and ASME straight thermowells at this flow rate are identical to their frequencies at 12.2 ft/s, but the straight thermowell has "locked in" at resonance and is experiencing 6.3 g's during the vibrations (bottom plot). By comparison, the straked thermowell is experiencing 0.35 g's. The 60 Hz frequency component is attributed to electrical noise.

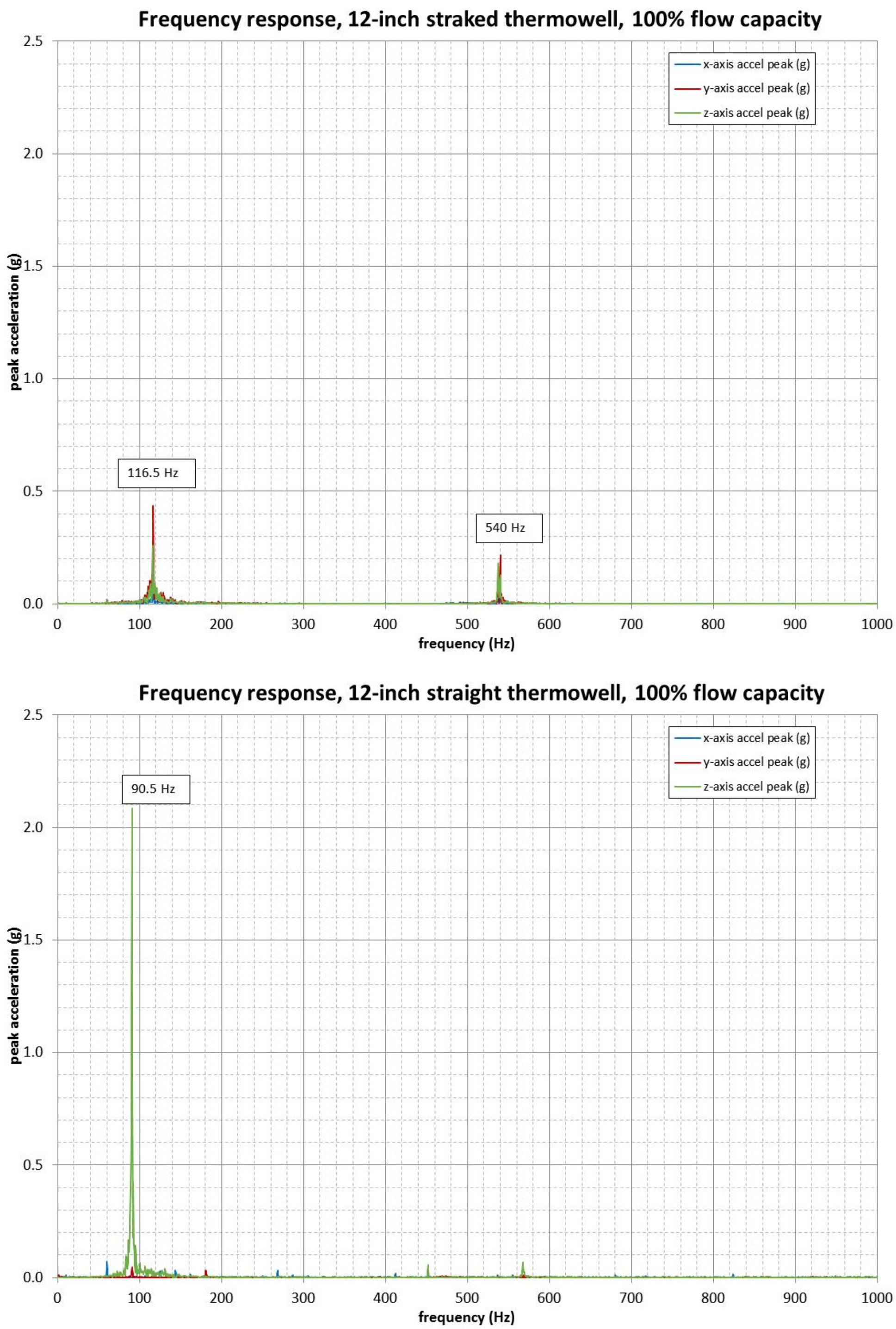


Figure 16. Frequency Responses of the Thermowells in the 12-inch Pipe at 29.7 ft/s

At this condition, the ASME straight thermowell (bottom plot) has passed its resonance flow rate, and while it is still resonating at its fundamental frequency, the maximum acceleration forces have decreased to 2.1 g's. By comparison, the straked thermowell design is experiencing a maximum of 0.45 g's at this highest flow rate, but the largest vibration is now along the y-axis in the direction of flow, not on the transverse z-axis.

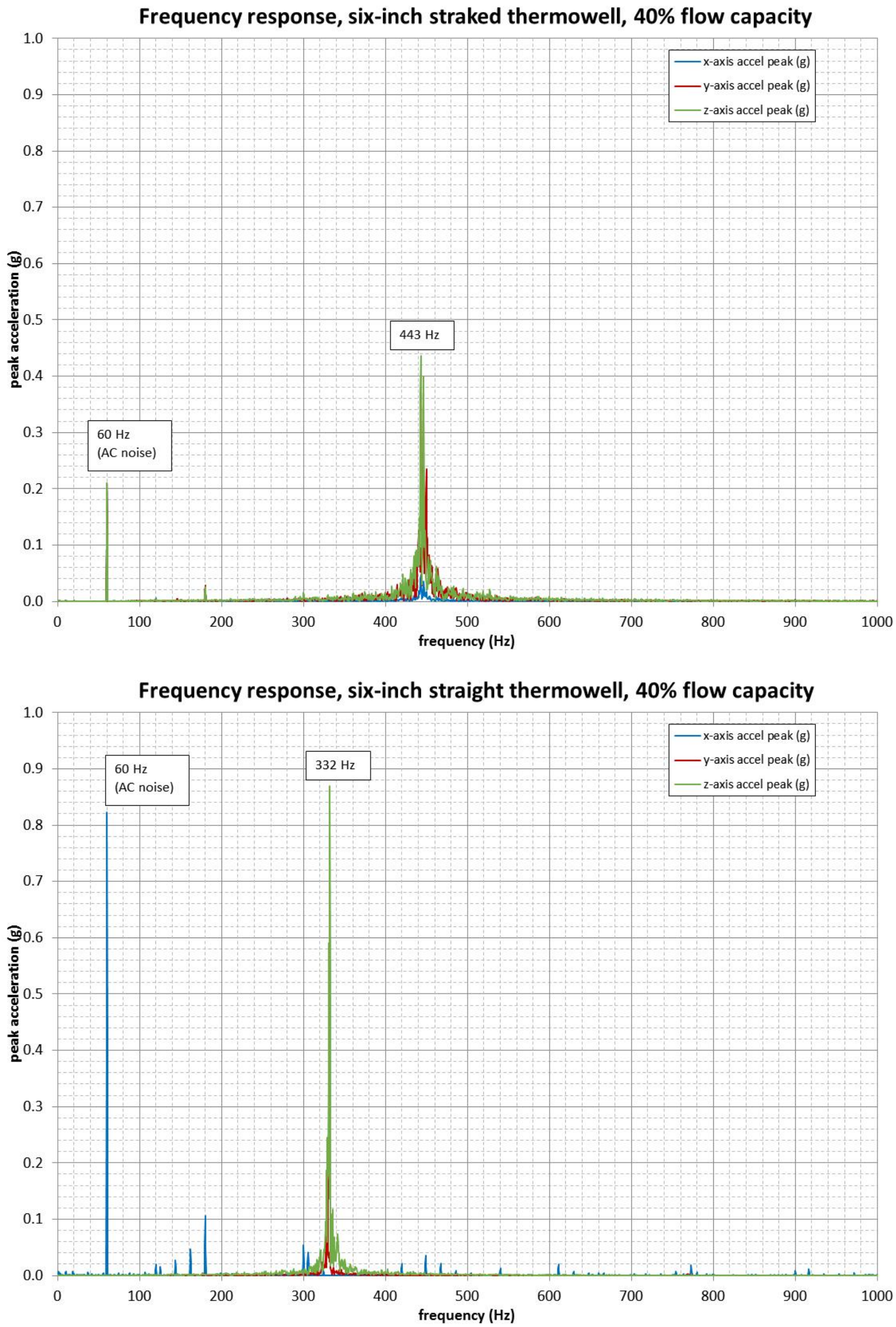
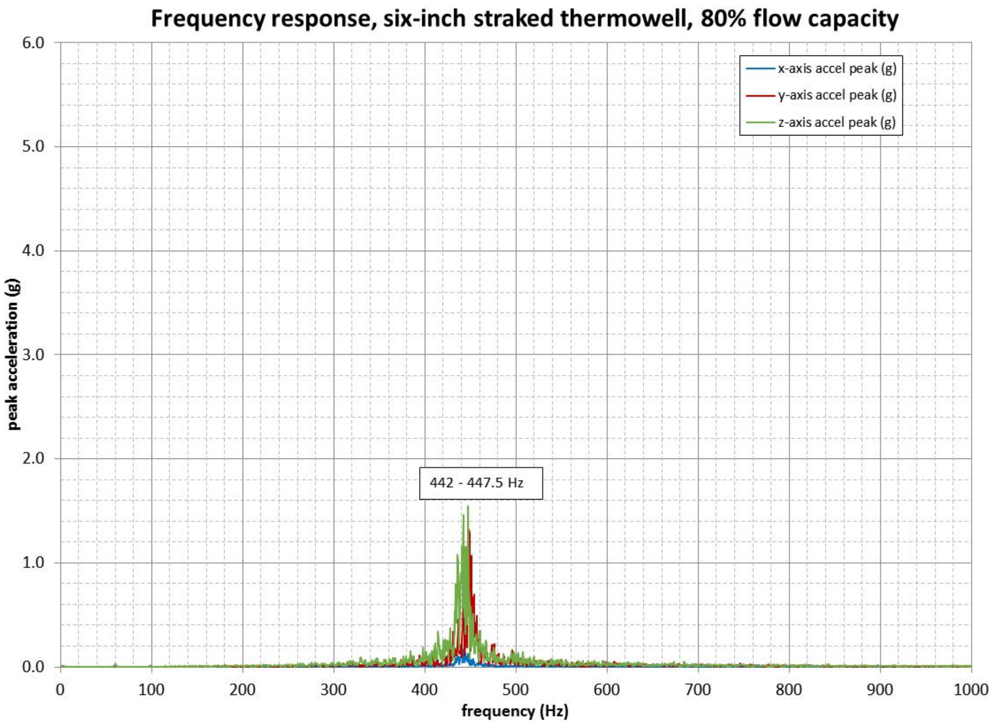


Figure 17. Frequency Responses of the Thermowells in the Six-inch Pipe at 46.5 ft/s

The helical strake thermowell (top graph) has a fundamental resonance frequency of 443 Hz, while the straight ASME thermowell (bottom graph) has a fundamental frequency of 332 Hz. At this flow rate, the straight thermowell is typically experiencing twice the acceleration from the vibrations as the helical strake design. The 60 Hz frequency component on individual accelerometer axes is attributed to electrical noise.



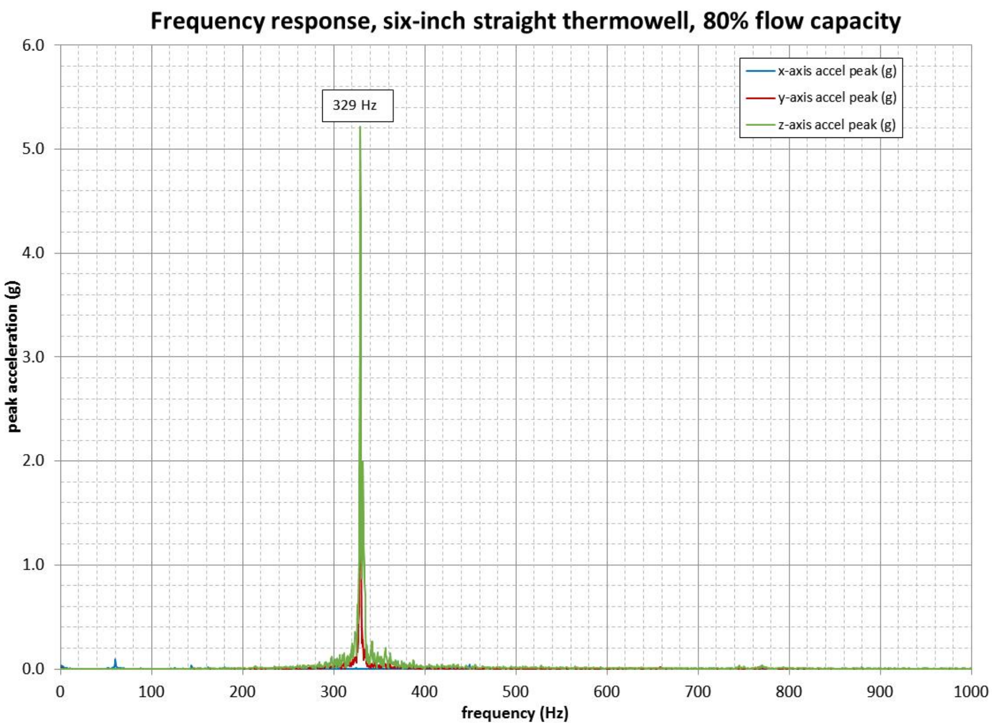


Figure 18. Frequency Responses of the Thermowells in the Six-inch Pipe at 93.4 ft/s

At this flow rate, the straight thermowell has "locked in" at resonance and is experiencing 5.2 g's of acceleration, primarily on the z-axis transverse to the flow direction (bottom plot). By comparison, the straked thermowell is experiencing 1.5 g's, and the oscillations are nearly equal in the y and z directions (in line with and transverse to the flow, respectively).

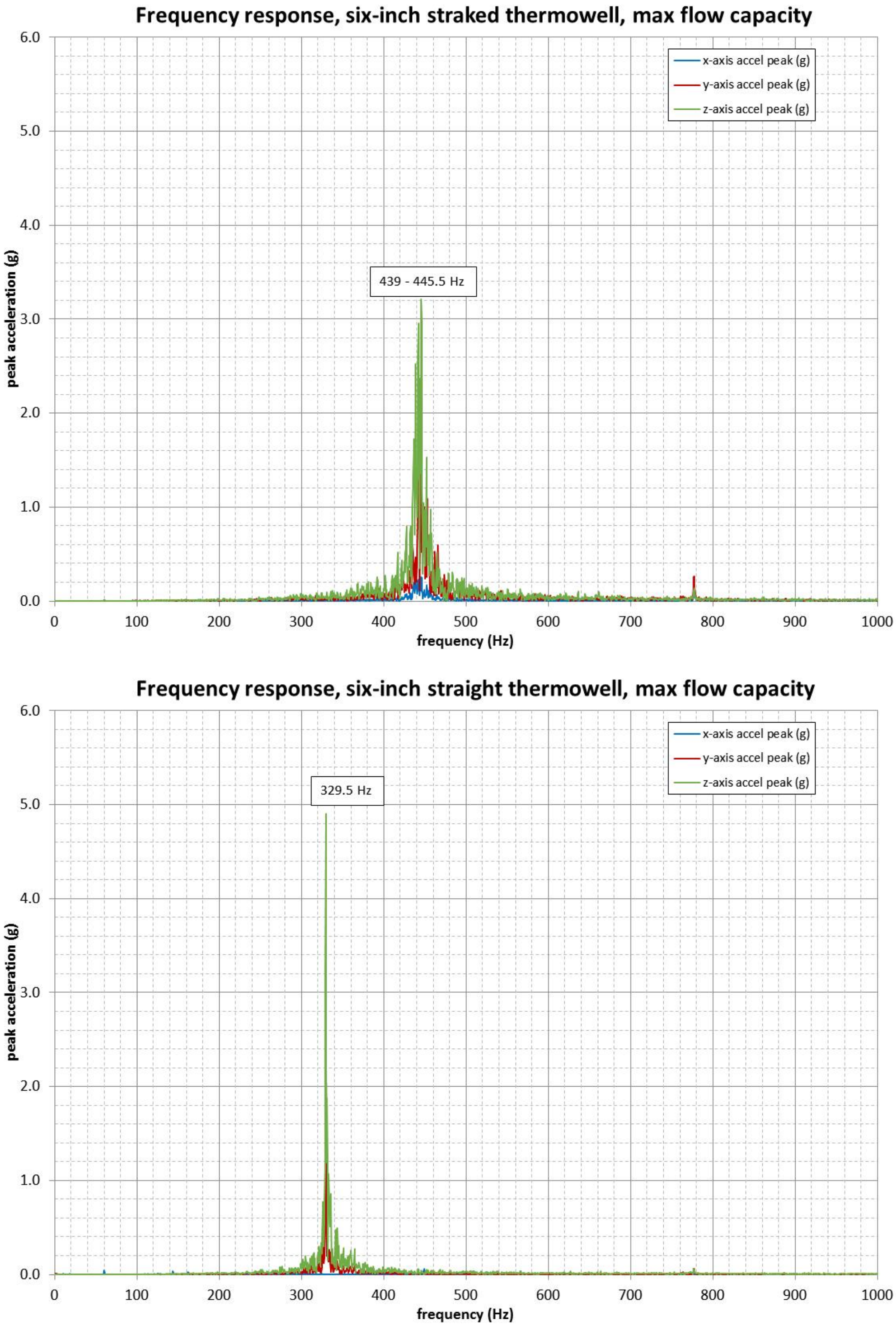


Figure 19. Frequency Responses of the Thermowells in the Six-inch Pipe at 108.1 ft/s
At this highest flow rate, the ASME straight thermowell (bottom plot) is still experiencing vibrations of about the same magnitude as in Figure 18. This suggests that both flow rates may be in the "lock in" resonance range for the ASME design. Accelerations on the helical thermowell have increased from the previous flow rate, but no conclusive evidence was found for the cause of the increase.

- The fundamental vibration frequencies of the four thermowells under flowing conditions were consistent with those found by the baseline measurements after the thermowells were mounted in the test spools.
- For the flow tests in the 12-inch run, the accelerations of the ASME straight thermowell were consistently larger than those of the helical strake thermowell, indicating that the straked thermowell experienced less vortex-induced vibration at the conditions tested. At 80% of the HPL flow capacity, corresponding to the transverse resonance condition for the ASME straight thermowell, the difference in peak acceleration (6.3 *g*'s for the straight thermowell vs. 0.35 *g*'s for the helical thermowell) is over an order of magnitude. At these flow conditions in the field, the helical strake thermowell of the same nominal dimensions as the ASME straight thermowell can be expected to experience less vortex-induced vibration.
- At a bulk flow velocity of 24 ft/s in the 12-inch pipe, the data indicate that the straight thermowell has "locked in" on a transverse resonance, as expected. At the highest flow rate of 29.7 ft/s, the straight thermowell experienced smaller accelerations, suggesting that the flow rate is beyond the "lock in" regime. For the helical thermowell, no pattern is seen in the acceleration magnitudes over the three flow rates, though the peak amplitudes at all flow rates are 0.6 *g*'s or less. Notably, the strongest vibrations of the helical thermowell at the highest flow rate of 29.7 ft/s are in the y direction, parallel to the flow.
- For the tests in the six-inch run, the ASME straight thermowell again experienced consistently larger vibrations than the helical strake thermowell. At 80% of the HPL flow capacity, corresponding to the transverse resonance condition for the ASME straight thermowell, the difference (5.2 *g*'s vs. 1.5 *g*'s) is over a factor of three. Again, replacing the ASME thermowell with the helical strake thermowell of the same nominal dimensions at these flow conditions should subject the installation to less vortex-induced vibration.
- Between the six-inch-pipe flow velocities of 93.4 ft/s (the predicted transverse resonance point for the ASME thermowell) and 108.1 ft/s (the maximum flow rate), the peak accelerations of the ASME thermowell decreased slightly from 5.2 *g*'s to 4.9 *g*'s. By comparison, the peak accelerations measured on the helical strake thermowell at the same flow rate increased from 1.5 *g*'s to 3.2 *g*'s. The data suggest that the straight thermowell has "locked in" on a transverse resonance at 93.4 ft/s. A review found no conclusive explanation for the large peak accelerations on both thermowells at the maximum flow rate, although pipe vibration was eliminated as a possible cause.

Table 3 lists several dimensionless parameters that can be used to characterize the flow and the thermowell behavior. The thermowell Reynolds numbers (Re_d) use the thermowell diameter d as the characteristic length. For the helical strake thermowells, these are computed using both the outer diameter of the strakes and the inner shaft diameter. The Strouhal number ($Str = fd/U$) characterizes the inertial forces of the flow and can be used to correlate flow oscillations to the Reynolds number. The reduced velocity, the reciprocal of the Strouhal number, is sometimes used for this same purpose. An examination confirms that the reduced velocities increase with Reynolds number.

Table 3. Dimensionless Parameters Characterizing Thermowell Performance

The thermowell Reynolds numbers are based on the characteristic thermowell diameters. The reduced velocity can be used to relate vortex shedding behavior to the pipe Reynolds number, and is seen to increase with Reynolds number.

Test	Pipe Reynolds number, Re_D	Bulk velocity (ft/s)	Helical thermowell values based on tip diameter			Helical thermowell values based on strake diameter			ASME straight thermowell values		
			Re_d	Str	Reduced velocity	Re_d	Str	Reduced velocity	Re_d	Str	Reduced velocity
12-inch run, 40% flow capacity	4.78×10^6	12.2 ± 0.1	2.52×10^5	0.503	1.989	3.15×10^5	0.628	1.593	3.00×10^5	0.464	2.156
12-inch run, 80% flow capacity	9.47×10^6	24.0 ± 0.1	5.00×10^5	0.254	3.931	6.24×10^5	0.318	3.147	5.95×10^5	0.235	4.251
12-inch run, 100% flow capacity	1.17×10^7	29.7 ± 0.3	6.15×10^5	0.206	4.857	7.69×10^5	0.257	3.888	7.32×10^5	0.190	5.252
Six-inch run, 40% flow capacity	9.17×10^6	46.5 ± 0.3	9.53×10^5	0.503	1.988	1.19×10^6	0.628	1.591	1.13×10^6	0.442	2.263
Six-inch run, 80% flow capacity	1.82×10^7	93.4 ± 0.6	1.89×10^6	0.251	3.979	2.37×10^6	0.314	3.185	2.25×10^6	0.220	4.543
Six-inch run, maximum flow capacity	2.09×10^7	108.1 ± 0.7	2.17×10^6	0.216	4.621	2.72×10^6	0.270	3.699	2.59×10^6	0.191	5.248

Finally, the accelerometer data from each six-minute analysis interval were used to quantify the physical vibrations of each thermowell. The accelerations were integrated to estimate the tip displacements at each test condition. The frequency data were also analyzed to calculate the power spectral density of each thermowell response, which is proportional to the energy of vibration of the thermowell. Table 4 lists the calculated maximum tip displacements and average power spectral densities for each thermowell at each test condition, along with the largest positive and negative accelerations experienced by each thermowell during the analysis interval. Several observations can be made from this table.

- The maximum displacements of the helical strake thermowell are estimated to be on the order of thousandths of an inch, with the z axis motion (perpendicular to the flow) slightly larger than the y axis motion (in the flow direction). The data also indicate a small but detectable oscillation along the long axis of the straked thermowell (on the x axis).
- By comparison, the estimated transverse displacements of the 12-inch straight thermowell approach half an inch in magnitude at resonance conditions. This is consistent with the observations on the high-speed video made by Orbital and Daily staff. For the six-inch straight thermowell, the largest estimated vibrations are on the order of 0.01 inches. No measurable vibrations at the natural frequency were observed on the x axis.
- The calculated power spectral densities for the 12-inch straight thermowell at resonance conditions exceed those of the helical strake thermowell by two orders of magnitude, indicating the level of energy involved in the vibrations.
- Consistent with the frequency plots in Figures 17 through 19, the calculated tip displacements of the six-inch helical strake thermowell increase as the flow rate increases. The calculated displacements of the helical thermowell are comparable to those of the straight thermowell at the highest flow rate.

Table 4. Acceleration Data and Computed Thermowell Displacements

The maximum displacements calculated for the ASME thermowells exceed those of the corresponding helical strake thermowells. For the tests in the 12-inch run, the calculated magnitudes are consistent with the vibrations observed on high-speed video.

Test	Pipe Reynolds number, Re_D	Bulk velocity (ft/s)	Measurement	Helical thermowell values			ASME straight thermowell values		
				x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
12-inch run, 40% flow capacity	4.78×10^6	12.2 ± 0.1	Max positive acceleration (*g*'s)	0.850	1.695	1.985	2.225	11.68	24.04
			Max negative acceleration (*g*'s)	-0.852	-1.397	-1.960	-2.338	-8.936	-23.90
			Average power spectral density, 0 – 1000 Hz (*g*'s)	1.092	2.479	3.521	3.293	22.14	59.96
			Max displacement (inches)	0.0012	0.0022	0.0028	n/a	0.0246	0.0572
12-inch run, 80% flow capacity	9.47×10^6	24.0 ± 0.1	Max positive acceleration (*g*'s)	2.314	4.403	4.652	2.167	4.695	190.6
			Max negative acceleration (*g*'s)	-2.525	-4.154	-4.284	-2.284	-133.6	-222.1
			Average power spectral density, 0 – 1000 Hz (*g*'s)	1.527	6.350	6.412	3.750	7.054	475.4
			Max displacement (inches)	0.0033	0.0062	0.0064	n/a	0.165	0.483
12-inch run, 100% flow capacity	1.17×10^7	29.7 ± 0.3	Max positive acceleration (*g*'s)	2.007	6.377	5.717	0.716	4.345	174.6
			Max negative acceleration (*g*'s)	-2.060	-5.892	-5.681	-0.707	-35.38	-174.5
			Average power spectral density, 0 – 1000 Hz (*g*'s)	2.224	11.39	10.19	0.857	5.701	413.3
			Max displacement (inches)	0.0029	0.0088	0.0082	n/a	0.0474	0.416
Six-inch run, 40% flow capacity	9.17×10^6	46.5 ± 0.3	Max positive acceleration (*g*'s)	0.893	5.247	7.152	1.142	2.715	37.97
			Max negative acceleration (*g*'s)	-0.965	-5.223	-7.152	-1.191	-2.749	-37.84
			Average power spectral density, 0 – 1000 Hz (*g*'s)	1.257	9.046	10.18	1.635	4.024	62.54
			Max displacement (inches)	0.0001	0.0005	0.0007	n/a	0.0005	0.0067
Six-inch run, 80% flow capacity	1.82×10^7	93.4 ± 0.6	Max positive acceleration (*g*'s)	6.534	33.30	41.47	0.863	24.55	59.75
			Max negative acceleration (*g*'s)	-6.970	-32.75	-41.70	-0.889	-24.29	-57.29
			Average power spectral density, 0 – 1000 Hz (*g*'s)	7.027	48.23	62.43	1.312	39.85	80.30
			Max displacement (inches)	0.0007	0.0032	0.0040	n/a	0.0044	0.0106
Six-inch run, maximum flow capacity	2.09×10^7	108.1 ± 0.7	Max positive acceleration (*g*'s)	7.760	50.15	63.37	0.941	23.48	51.33
			Max negative acceleration (*g*'s)	-8.446	-49.19	-65.45	-0.938	-23.59	-57.46
			Average power spectral density, 0 – 1000 Hz (*g*'s)	10.39	63.59	92.90	1.095	36.51	80.90
			Max displacement (inches)	0.0008	0.0047	0.0064	n/a	0.0041	0.0098

Strain gauge responses. The strain gauge data were also examined, but the data showed evidence of drift due to temperature effects. Since measurements of the thermowell surface temperatures were not available, corrections for the temperature drift were not possible, and the planned amplitude analysis of the strain data was set aside over concerns about the validity of the results. However, the differences in the magnitudes of the strain oscillations can be seen in Figure 20, which shows an example of the periodic nature of the strains measured in the 12-inch thermowells at 80% flow capacity.

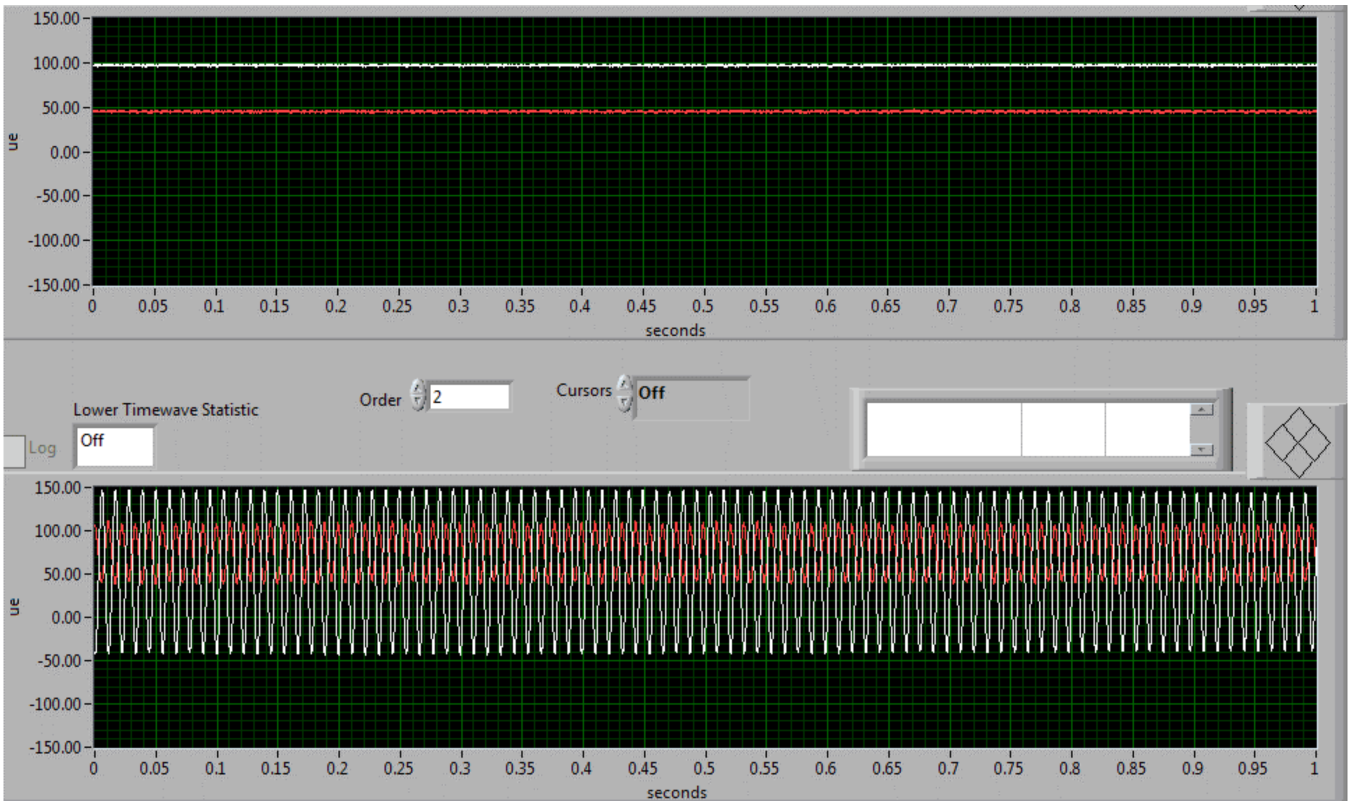


Figure 20. Measurements by the Strain Gauges in the 12-inch Thermowells at 24 ft/s
The upper plot shows the horizontal (white) and vertical (red) strain measurements within the helical strake thermowell over a period of one second. The lower plot shows the strain measurements taken within the ASME straight thermowell at the same time. Both plots are shown to the same scale to demonstrate the differences in strain magnitudes at the thermowell roots. The offsets from zero are due to temperature drifts in the data that could not be corrected with the available data.

Examination of the frequency content of the strain data revealed some consistencies with the accelerometer data and some significant differences. The next six figures present NI DAQ screen captures comparing the frequency spectra measured by the strain gauges mounted on the aluminum strips in the thermowell bores. In each figure, the frequency response of the helical strake thermowell is in the upper graph, while the response of the ASME straight thermowell is in the lower graph. The spectra are one-minute averages of data taken simultaneously from each thermowell, and each vertical scale is in units of microstrains (μe), or 10^{-6} inches per inch. Several of the strain frequency plots include a 60-Hz component that is attributed to electrical noise. Comparing Figures 21 through 26 to Figures 14 through 19, several trends in the thermowell behavior can be identified.

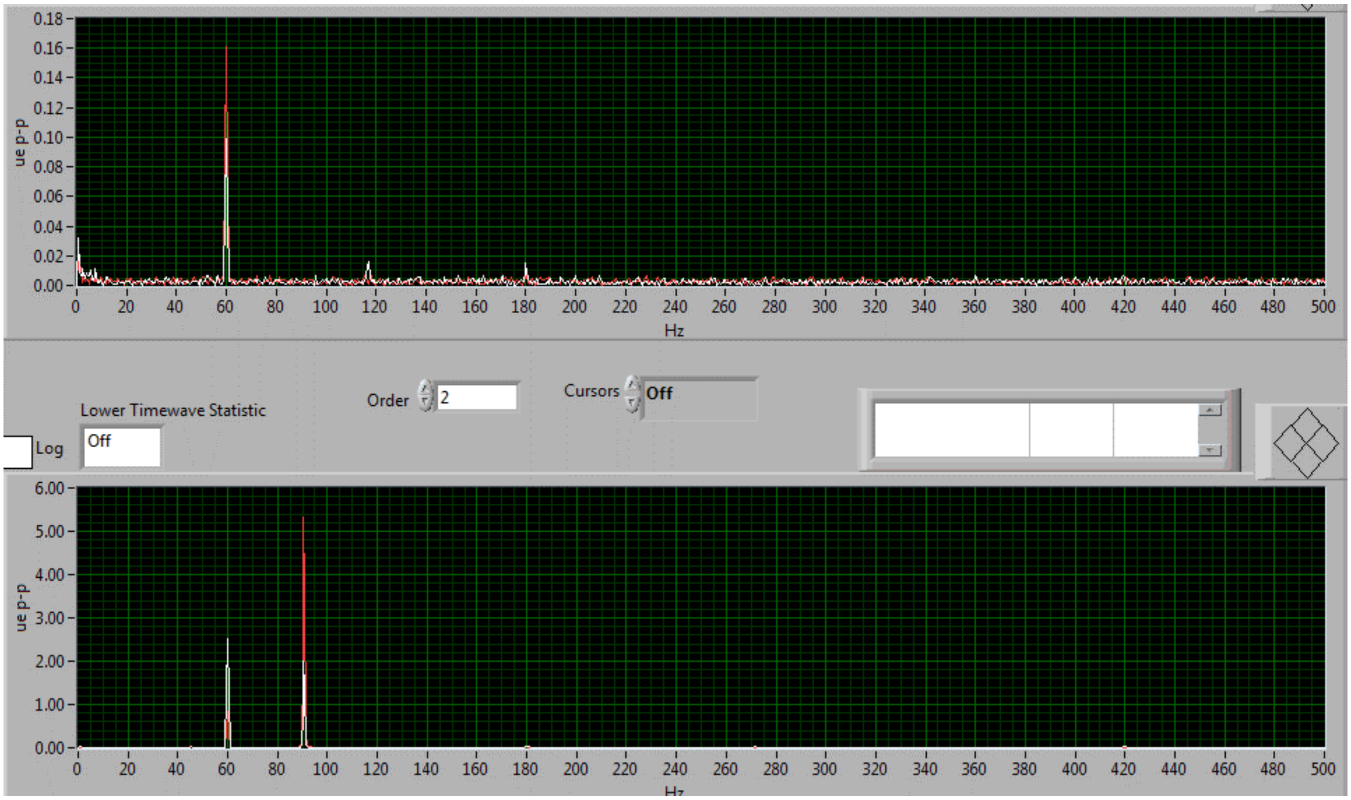


Figure 21. Frequency Responses of the Strain Gauges in the 12-inch Thermowells at 12.2 ft/s
The helical strake thermowell (top graph) shows a dominant strain frequency of 117 Hz, while the straight ASME thermowell (bottom graph) shows a dominant frequency of 90.5 Hz. These frequencies are consistent with the measured tip acceleration frequencies for both thermowells. Note that the peak strain amplitude is two orders of magnitude larger for the ASME thermowell. The 60 Hz frequency component in both spectra is attributed to electrical noise.

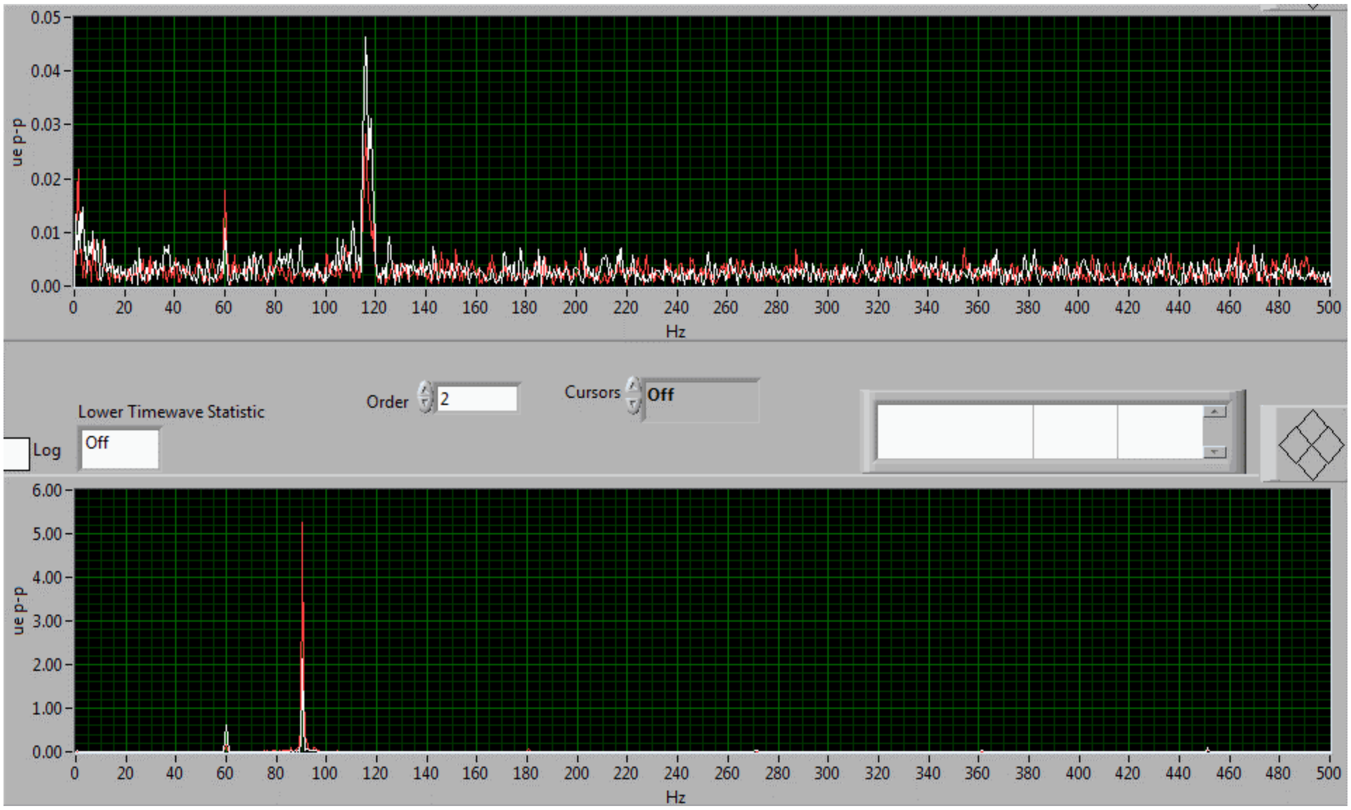


Figure 22. Frequency Responses of the Strain Gauges in the 12-inch Thermowells at 24 ft/s
As at the lower flow rate of 12.2 ft/s, the dominant frequencies of the cyclic strains are consistent with the frequencies of acceleration at the thermowell tips, and the magnitude of strain in the ASME thermowell is two orders of magnitude larger. The 60 Hz frequency component is attributed to electrical noise.

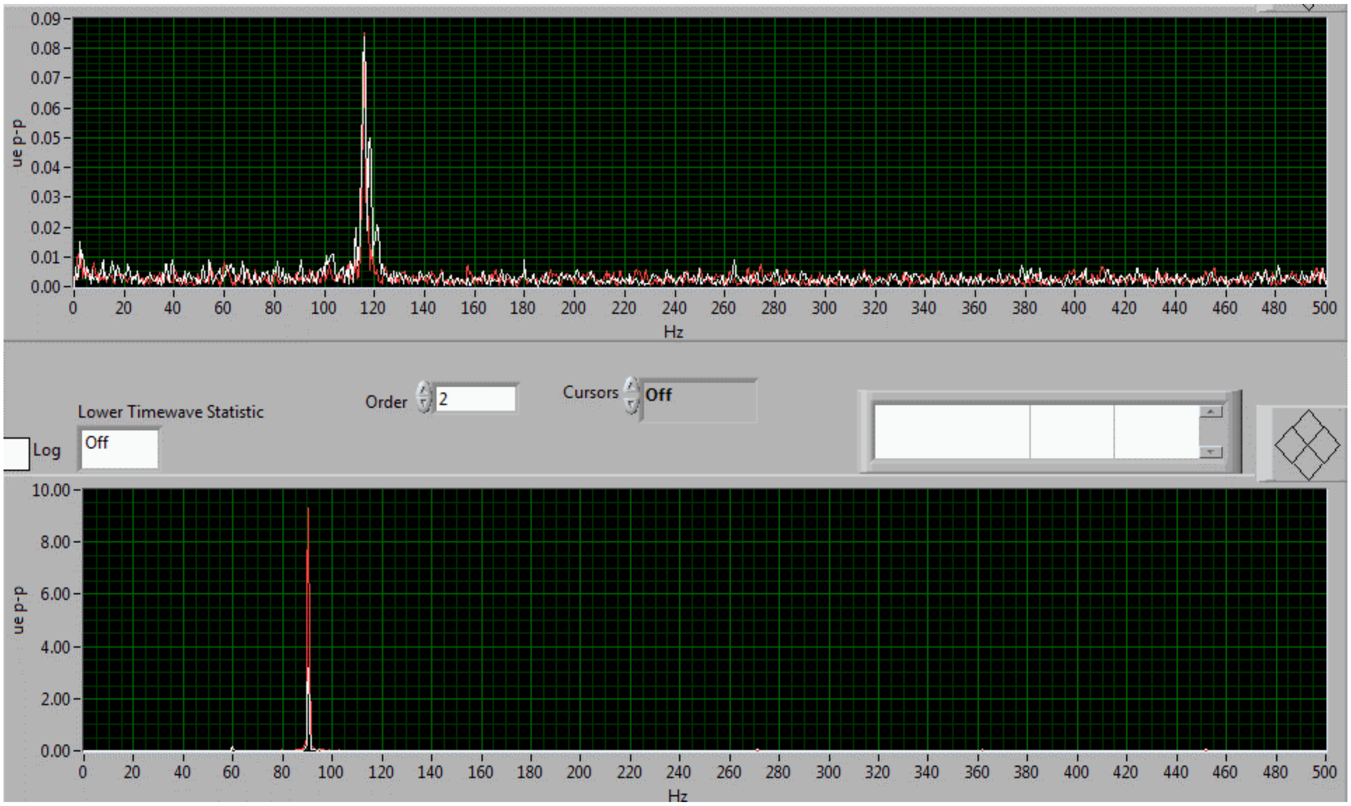


Figure 23. Frequency Responses of the Strain Gauges in the 12-inch Thermowells at 29.7 ft/s
As at the other flow conditions for these thermowells, the dominant frequencies of the cyclic strains are consistent with the frequencies of acceleration at the thermowell tips, and the magnitude of strain in the ASME thermowell is two orders of magnitude larger.

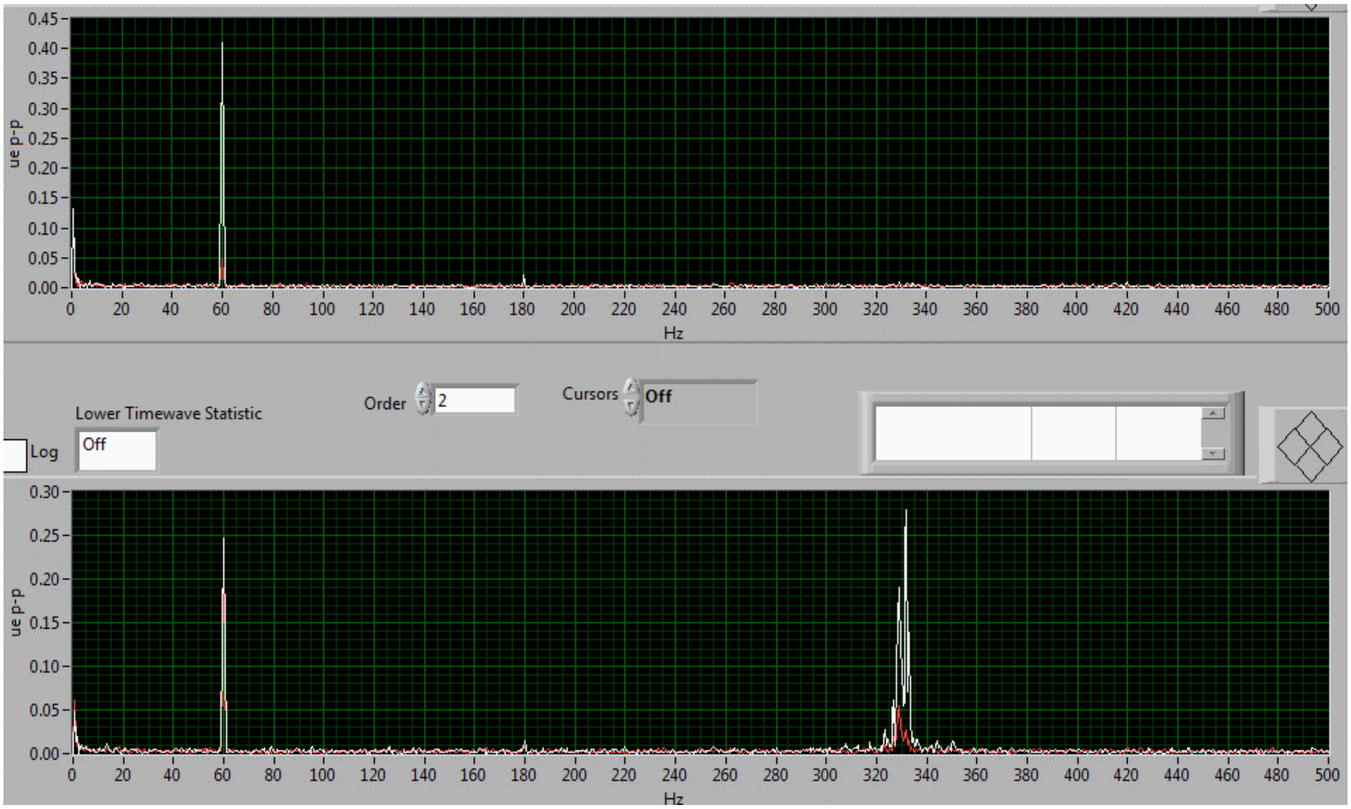


Figure 24. Frequency Responses of the Strain Gauges in the Six-inch Pipe at 46.5 ft/s
The strain gauges in the top of the ASME straight thermowell (bottom graph) measured a cyclic strain at a frequency of 332 Hz, consistent with the acceleration frequency of the tip, but the helical strake thermowell (top graph) registered no significant strains at the expected frequency of 443 Hz. The 60 Hz frequency component is attributed to electrical noise.

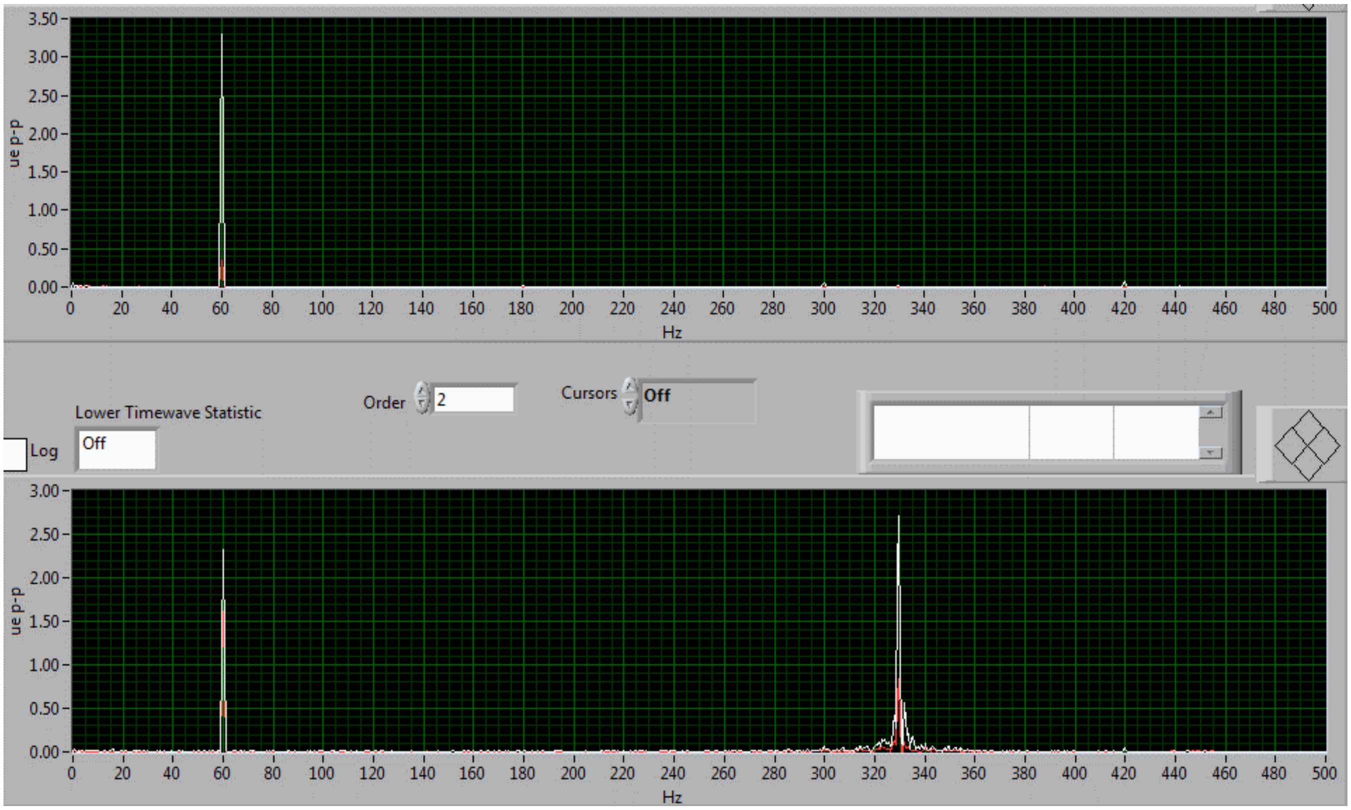


Figure 25. Frequency Responses of the Strain Gauges in the Six-inch Pipe at 93.4 ft/s
As in the previous figure, the primary frequency of the strains measured in the ASME straight thermowell (bottom graph) were consistent with the acceleration frequency of 329 Hz at the tip, but the helical strake thermowell (top graph) registered no significant strains. The 60 Hz frequency component is attributed to electrical noise.

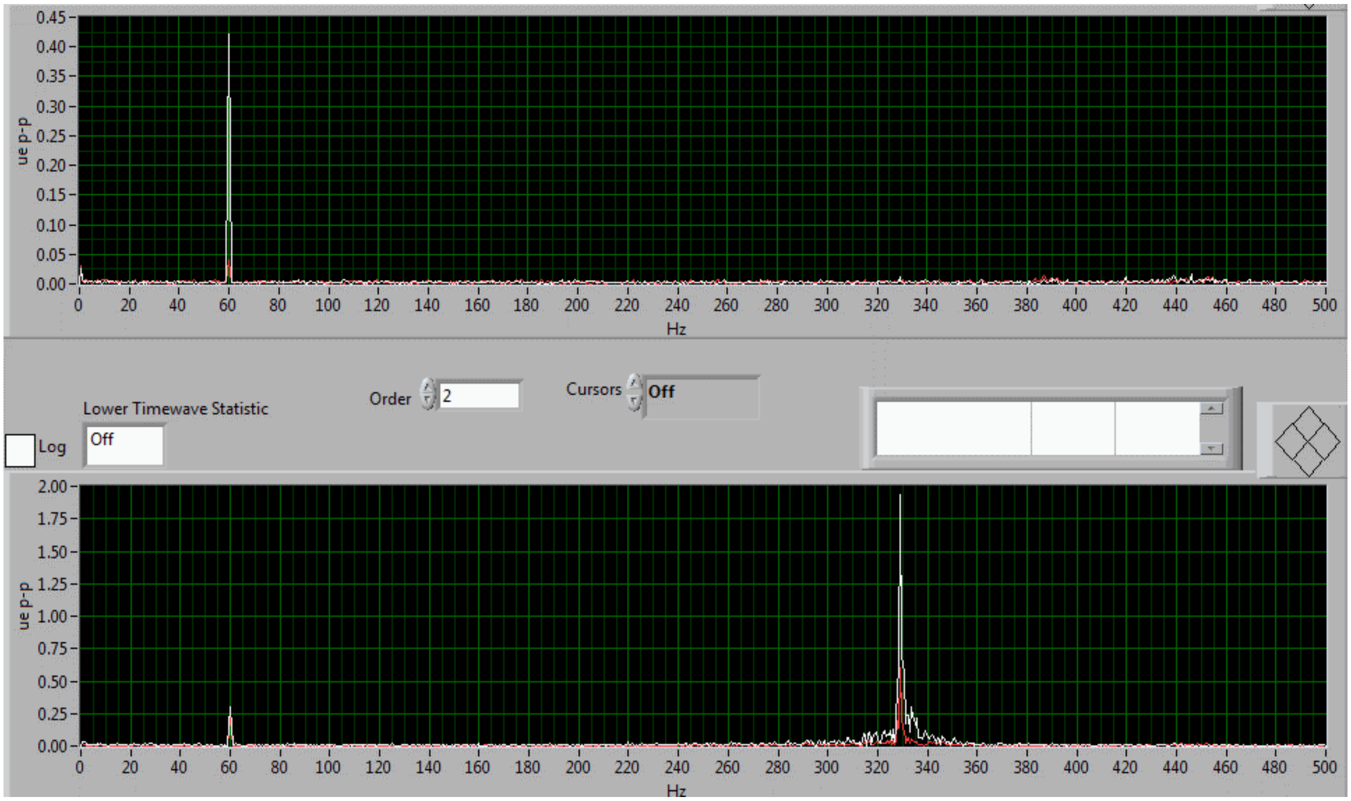


Figure 26. Frequency Responses of the Strain Gauges in the Six-inch Pipe at 108.1 ft/s
As in the previous two figures, the primary frequency of the strains measured in the ASME straight thermowell (bottom graph) were consistent with the acceleration frequency of 329.5 Hz at the tip, but the helical strake thermowell (top graph) registered no significant strains at the expected frequencies around 440 Hz. The 60 Hz frequency component is attributed to electrical noise.

- The dominant frequencies of the strain cycles on the ASME straight thermowell are consistent with the dominant oscillation frequencies of the tip. For the 12-inch thermowell, the strains at the root oscillate at a frequency of 90.5 Hz, which is consistent with the dominant accelerometer frequency. For the 6-inch thermowell, the measured strains oscillated at frequencies between 329 Hz and 332 Hz. Again, this range was nearly identical to the frequencies of the accelerations at the tip.
- The strain gauges in the 12-inch helical strake thermowell registered cyclic strains at a dominant frequency of approximately 117 Hz during the flow tests. This frequency is also consistent with the primary acceleration frequency measured at the tip. However, the peak magnitude of the strains measured in the helical stake thermowell ranged from 0.02 μe at 40% of flow capacity to 0.085 μe at full flow. By comparison, the measured strains in the ASME thermowell ranged from 5.2 μe to 8.3 μe over the same flows, a difference of two orders of magnitude.
- Given the trends in the data from the 12-inch helical strake thermowell, the strain gauges in the 6-inch helical strake thermowell would have been expected to measure strains at a cyclic frequency around 440 Hz. While 60-Hz noise was identified, no frequency content in the region around 440 Hz was measured above the typical noise level of 0.01 μe to

0.02 μe across the spectrum. No conclusive cause for this lack of data has been identified.

Transient temperature responses. Before the steady-state vibration tests, the first flowing test studied transient flow responses in the 12-inch run. Temperature data from the Daily thermocouple sensors and the MRF reference RTD were logged at five-second intervals, while the gas in the 12-inch run was brought from zero flow to 20% of the HPL flow capacity. Figure 27 plots the three temperature measurements for comparison, alongside the measured volume flow rate. Notably, the temperatures measured by the sensors in the ASME and helical strake thermowells were virtually identical during the test sequence.

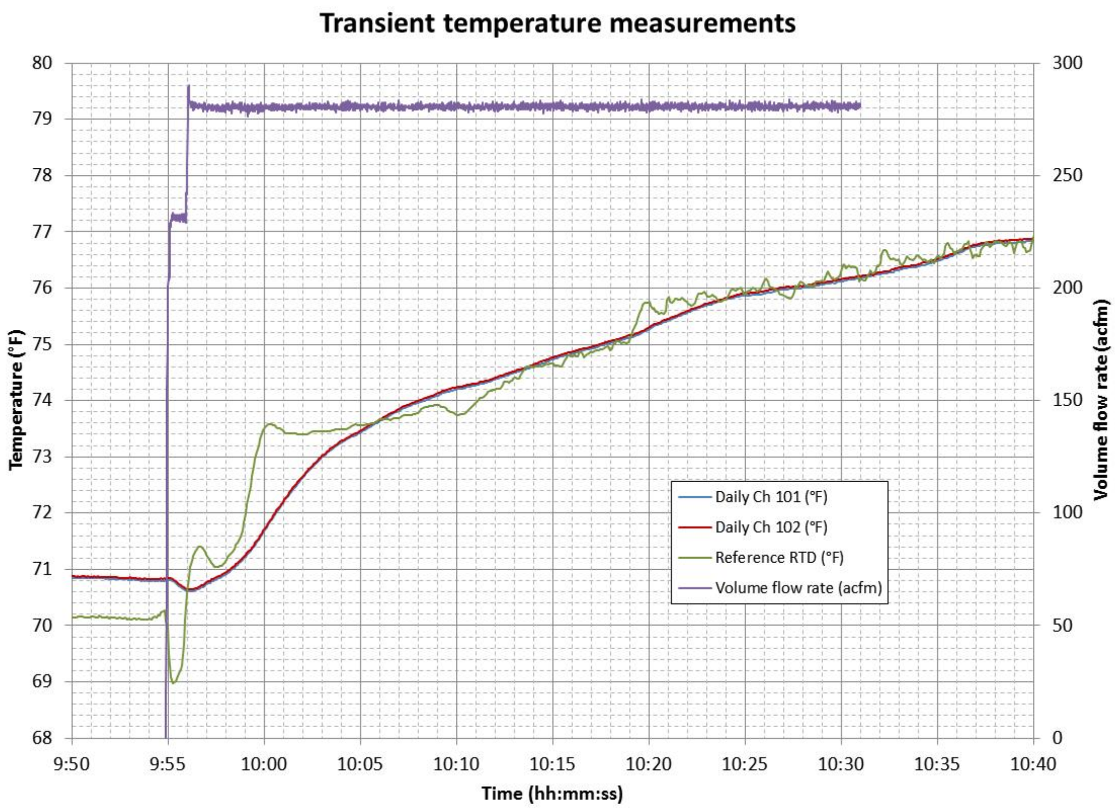


Figure 27. Temperature Measurements during the Startup Flow Transient

The data from the thermocouples in the ASME and helical strake thermowells are indistinguishable, indicating that the two designs respond almost identically to temperature transients. The offset between the Daily instruments and the MRF reference RTD at zero flow is likely due to thermal conduction from the pipe wall to the thermowell.

Before the flow began, the Daily sensors both registered a temperature of 70.8°F, while the reference bare RTD measured a gas temperature of 70.2°F. The difference is believed to be due to thermal conduction from the pipe wall along the length of each thermowell. As the flow started at 9:55 a.m., and the gas accelerated from zero flow to the brief plateau at 232 acfm, the reference bare RTD registered a drop of about 1.2°F in gas temperature over roughly 15 seconds. The RTD then measured a temperature rise as the flow increased. The sensors in the ASME and helical strake thermowells registered a much smaller drop lasting a full minute, suggesting that both designs experienced similar thermal lags. After the initial temperature fall and rise, the RTD measured two more local temperature drops lasting one or two minutes each, caused by the HPL's active temperature control system. After these events, the gas stabilized to a trend of generally increasing temperature. By 10:55 a.m., ten minutes after the start of the flow, the sensors in the two thermowells were in generally good agreement with the reference RTD.

In summary, the helical strake thermowell response to temperature transients was virtually identical to that of the straight ASME thermowell under identical flow conditions. Both designs also smoothed out the short-term fluctuations in temperature detected by the reference RTD in the same manner.

Conclusions

The following points summarize the observations of this test report.

- ASME-type straight thermowells and helical strake thermowells were tested in two line sizes at flow velocities chosen to cause vortex-induced resonant vibrations in the straight thermowell. The thermowells in each line size had the same unsupported lengths and unshielded lengths. The thermowells were fitted with accelerometers to quantify thermowell motion and strain gauges to measure strains near the root of each thermowell.
    - In the tests in a 12-inch pipe run, oscillations of the straight thermowell were one to two orders of magnitude larger than those of the helical strake thermowell at the target conditions. The straight thermowell experienced average accelerations approaching 6 *g*'s and calculated deflections approaching 0.5 inch.
    - In the tests in a six-inch pipe run, the straight thermowell approached average accelerations of 5 *g*'s and calculated deflections on the order of 0.01 inches. At the highest velocity, the helical strake thermowell experienced accelerations and calculated deflections approximately one-third to one-half of these values.
    - Under the flowing conditions tested here, the helical strake thermowells exhibited smaller tip vibrations and accelerations as the ASME straight thermowells of the same nominal dimensions.
    - Successful strain measurements identified cyclic strains near the roots of both ASME straight thermowells with the same primary frequencies as the accelerations at the tip. For the helical strake thermowell tested in the 12-inch pipe run, the primary frequency of the cyclic strains was also consistent with the oscillation frequency at the tip. The strain magnitudes were two orders of magnitude larger for the ASME thermowell than for the helical strake thermowell, again consistent with the accelerometer data.
- A standard straight thermowell and a helical strake thermowell were also used to measure temperature transients during a flow startup in the MRF HPL. Differences in the temperatures recorded by identical temperature sensors in the two thermowells during the transient were negligible. The differences in thermowell design were observed to have no impact on sensor response to temperature transients.

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It has been our pleasure to work with you on this project and to provide you with the data and findings in this report. Please let me know if you have any questions. I can be reached by telephone at 210-522-2355, or by e-mail at darin.george@swri.org.

Best Regards,

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