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Multifunctional Low-Pressure Turbine for Core Noise Reduction, Improved Efficiency, and Nitrogen Oxide (NO_x) Reduction

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Summary

This work studied the feasibility of using Helmholtz resonator cavities embedded in low-pressure-turbine (LPT) airfoils to (1) reduce core noise by damping acoustic modes; (2) use the synthetic jets produced by the liner hole acoustic oscillations to improve engine efficiency by maintaining turbulent attached flow in the LPT at low-Reynolds-number cruise conditions; and (3) reduce engine nitrogen oxide emissions by lining the internal cavities with materials capable of catalytic conversion. Flat plates with embedded Helmholtz resonators, designed to resonate at either 3000 or at 400 Hz, were simulated using computational fluid dynamics. The simulations were conducted for two inlet Mach numbers, 0.25 and 0.5, corresponding to Reynolds numbers of 90 000 and 164 000 based on the effective chordwise distance to the resonator orifice. The results of this study are (1) the region of acoustic treatment may be large enough to have a benefit; (2) the jets may not possess sufficient strength to reduce flow separation (based on prior work by researchers in the flow control area); and (3) the additional catalytic surface area is not exposed to a high velocity, so it probably does not have any benefit.

Introduction

The low-pressure turbine (LPT) of an aircraft jet engine operates over a wide range of Reynolds numbers between takeoff and cruise. The Reynolds number can reach low values (approximately 50 000) at cruise, at which point the laminar boundary layer is no longer able to navigate the adverse pressure gradient downstream of the crown region on the suction side of the blade. The boundary layer can then either separate and reattach, if the shear layer transitions, or stay separated. Both scenarios lead to drastic loss of lift and translate to approximately 5 percent in efficiency reduction. For a review of LPT flows see Hodson and Howell (2005). Currently, either boundary layer separation at low Reynolds number is accepted or the blading is designed for reduced loading to avoid the problem. In the research arena, various modes of flow control have been attempted to mitigate separation or to reattach separated flow.

Passive control mechanisms involve the use of trips and other geometry modifications designed to locally distribute the pressure gradient or to trip the boundary layer and energize it. Although they are usually useful for low-Reynolds-number regimes, these mitigations can lead to increased losses at higher Reynolds numbers. White (2010) shows the drag coefficient on a flat plate as a function of Reynolds number for various ratios of feature (passive) geometric heights to flow length scale. For a given passive geometric feature above a certain Reynolds number, the flow perceives the feature(s) as roughness, which sets the maximum drag coefficient; see Volino (2003a) for more on passive tripping in a low-Reynolds-number LPT flow environment. This does not necessarily apply to control using resonators or self-actuated compliant walls. These are then areas that deserve further exploration.

Active control typically involves the use of an external energy source to dynamically modify the “design” state of the system. Therefore, active control systems are more complicated to implement than passive control systems. Examples of these systems are vortex generating jets (VGJs), plasma actuators, synthetic jets, and piezoelectric actuators. It is desirable to conceive of a system that can respond to the changing environment of the engine but does not involve the complexities of actively controlled systems. A brief review of literature related to the present work follows.

Synthetic jets, zero-net-mass devices that eject and intake flow, have been studied extensively mainly in context of external flows. The only synthetic jet in LPT flow was studied by Volino (2003b), showing high effectiveness in suppressing separation on Pack-B airfoil (Woods et al., 2006).

Pulsed vortex generating jets (PVGJs) are not zero-net-mass devices because they eject momentum into the flow. They have been studied by several authors, including Bons et al. (2000, 2002), Volino et al. (2011), Bloxham (2009), Reimann et al. (2007), and McQuilling (2004). Volino et al. (2011) used VGJs on the suction side of a cascade of blades. All the authors used the aft loaded very high lift airfoil, L1A (Marks et al., 2009; "A" denotes aft loading), for the blade cross section. The jets were placed at the inviscid minimum pressure location on the suction side and spaced 10 diameters apart. The holes were inclined at 30° to the suction surface of the L1A LPT blade (from surface tangent) and at 90° to the main flow direction. These studies varied duty cycle, pulsing frequency, and blowing ratio at Reynolds numbers of 25 000 and 50 000 on the basis of the suction surface length and the average boundary layer edge velocity. Flow was pulsed through the holes at dimensionless jet frequencies, $F = (fL_{\text{jet-}TE}/U_{\text{ave}})$, between 0.0 (steady) and 0.56, where f is the frequency of jet pulsing in hertz, $L_{\text{jet-}TE}$ is the length from the jet location to the trailing edge along the suction side, and U_{ave} is the average free-stream velocity in the vicinity of the jet. The blowing ratios studied ranged from $B = 0.25$ to 3.0. The turbulence intensity at the inlet plane was approximately 4 percent and decayed to 1.4 percent upstream of the adverse pressure gradient region.

The referenced authors found that pulsed jets were more effective than steady jets. At high pulsing frequency, they found that separation control was possible with a low duty cycle and blowing ratio. At $F = 0.56$, a blowing ratio of 0.75 with a duty cycle of 10 percent showed a significant performance improvement. Increasing B to 1.0 reattached the boundary layer. However, increasing B above 1.0 did not change the results significantly (because the flow had reattached). For performance to improve even further, separation would have to be prevented in the first place. From the literature surveyed, at lower frequencies, control was less feasible unless the blowing ratio was above 2.0. Higher duty cycles enhanced control at the higher blowing ratio. Thus, pulsing at a 50-percent duty cycle and at frequencies ranging from 100 Hz at a Reynolds number of 25 000, to 200 Hz at a Reynolds number of 50 000 is most efficacious. The blowing ratio should be maintained as low as possible to minimize turbine performance losses and PVGJ power requirements. These parameters can serve as a good guideline for the development of pulsed actuation on the suction surface.

For the L1A LPT airfoil, Kartuzova (2010) numerically investigated the effect of steady and pulsed blowing using VGJs at $B = 0.25$ to 3.0 for Reynolds numbers of 25 000, 50 000, and 100 000. Only two jet velocities were used, but the blowing ratio changed because the Reynolds number changed. Kartuzova found that, for a duty cycle of 10 percent and $F > 0.28$, separation control was feasible, and that raising the duty cycle could allow the frequency to be reduced. A blowing ratio of 1.0 was found to be the minimum required for effective control. Memory et al. (2008) and Memory (2010) numerically investigated the same range of Reynolds numbers as Kartuzova (2010) for reduced frequencies ranging from $F = 0.035$ to 0.56. Duty cycles were varied from 5 to 50 percent, and blowing ratios were varied from 0.05 to 1.5. In short, the findings were that a minimum blowing ratio of 1.0 is required for flow control at a Reynolds number of 25 000.

Bloxham (2009) studied the effect of phase difference between wake passage and VGJ blowing on separation control, finding that synchronous wake passage and actuation was the most beneficial, although exact parameters for optimizing the phase difference were not presented. Holes were spaced 10 hole diameters apart along the span of a Pack-B blade with the same inclination as that of Volino et al. (2011). Bloxham reports blowing ratios of 2.0 and 2.5, with performance improvement presented in all cases as a time-averaged quantity. The cause of reattachment is explained as transition due to the disturbance created by the VGJ. It has been found that jet duration, duty cycle, and blowing ratio are the major

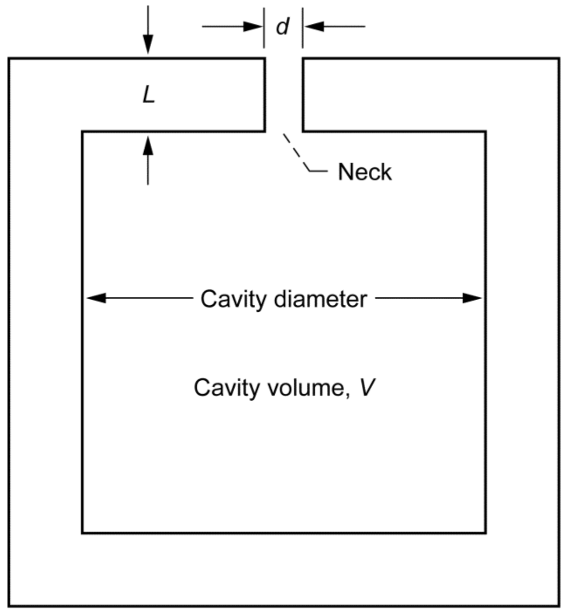

Figure 1.—Schematic of a Helmholtz resonator; cross-sectional area of the neck, $S = \pi r^2$, where $r = d/2$.

factors in control (Bons et al., 2000, 2002; Volino et al., 2011; Bloxham, 2009; Reimann et al., 2007; and McQuilling, 2004). Some researchers, such as Bernardini et al. (2013), also found that the starting and ending of the pulse are major factors in the reattachment of the separation bubble.

Bernardini et al. (2013) used a 250-W speaker upstream of a cascade of L1M blades (Marks et al., 2009; "M" demotes mid-chord loading) to introduce disturbances into the free stream. They found that separation could be controlled by actuating the speaker at the subharmonic frequency of the most amplified mode of the separated shear layer. This was found to be more effective because control was largely independent of turbulence intensity and was feasible even for low-amplitude perturbation.

The source of the passively generated synthetic jet is a Helmholtz resonator (Fig. 1) causes air to oscillate in response to an unsteady pressure. A change in pressure at the opening of the neck causes a flow of air in or out of the neck and the cavity. This causes a rise or fall, respectively, in the pressure in the cavity. Upon removal of the imposed pressure, the cavity then causes air to be either pushed out or sucked in, respectively. If the imposed pressure is repeated, the process can continue indefinitely. Such a resonator can be "tuned" to oscillate at the same frequency as the unsteady loading across its opening to maximize the massflow of air in and out of the neck. Such devices have been studied extensively and applied for noise reduction, making use of the viscous losses created in the unsteady flow.

Han (2008) reviews the various configurations of Helmholtz resonators that have been used for acoustic attenuation. The geometry needed to maximize acoustic attenuation is not necessarily suitable for flow control. However, as a preliminary study, the present work used geometry similar to that used in acoustic attenuation research. From Figure 1, the resonator is characterized by the length of the neck L, the volume of the cavity V, and the cross-sectional area of the neck S. The resonant frequency f of the resonator is then given by

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$$

where c is the speed of sound.

Future engine architectures are moving to smaller and more highly loaded cores. As a consequence, core noise is anticipated to increase while aircraft engine core noise simultaneously becomes a larger relative contribution to total aircraft noise as fan and jet noise sources are reduced. The smaller future core designs are also forcing the turbine to operate at ever lower Reynolds numbers. Problems at low Reynolds numbers prompted NASA to host a large international LPT aerodynamics workshop in 2010. LPT efficiency is known from system studies to have the strongest impact on reducing engine specific fuel consumption because the LPT is the heaviest component in the engine. Hollow LPT blades have been envisioned as a way to reduce engine weight. Reducing blade weight as well as reducing the cruise performance loss would doubly benefit future engine designs, which are attempting to reduce weight by increasing the per-stage work and thereby reducing stage count. Reducing the boundary layer separation on the last turbine vane could improve turbine efficiency by 2 to 7 percent (Volino, 2009; Bohl and Volino, 2006).

Core noise is predicted to be a significant contributor to the future engine architectures identified in the Fundamental Aeronautics Program—Fixed Wing Project system studies (D'Angelo et al., 2010; Greitzer et al., 2010; and Bruner et al., 2010), and assessments relative to the goals for generation 3 (N+3) designs. Finding space in an engine to add acoustic treatment is a challenge, and using the LPT volume is a new approach, although at this point a quantitative assessment is still lacking. In addition, this LPT could reduce nitrogen oxides (NO_x), but current designs are well below both the less aggressive current limits as well as the more aggressive project goals, so this capability is a lower priority.

If successful, this multifunctional approach would introduce thick, hollow LPT blades with Helmholtz resonators, an embodiment of which is shown in Figure 2, to enable weight reduction. The blades would result in engine core (combustor and/or turbine rotor-stator interaction) noise reduction, aerodynamic performance improvement, and NO_x reduction—the three metrics associated with NASA's subsonic aircraft project goals.

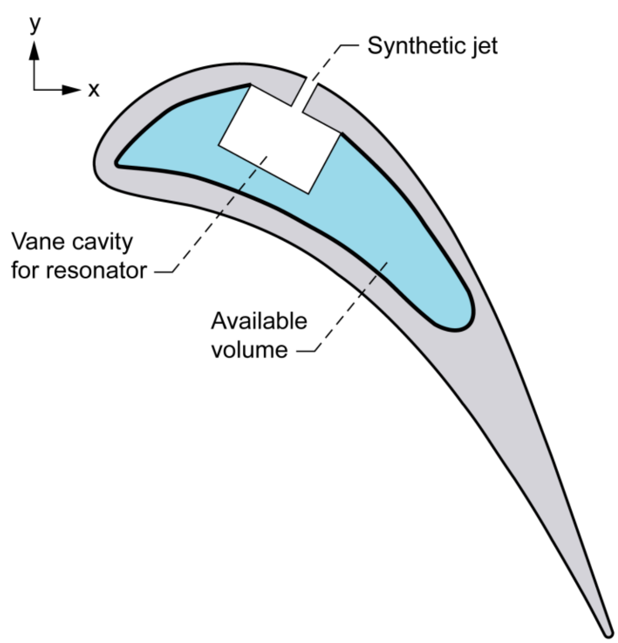

Figure 2.—Representative turbine vane geometry showing the vane volume available for the Helmholtz resonator and the approximate location of the neck (hole) location on the suction surface. The induced synthetic jet might energize the low-Reynolds-number boundary layer.

Symbols

B	blowing ratio, $v_{\text{jet}}/U_{\text{ave}}$
c	speed of sound
d	hole diameter
F	dimensionless jet pulsing frequency
f	dimensional frequency of jet pulsing, Hz
L	Helmholtz resonator neck length
$L_{\text{jet-}TE}$	length from the jet location to the trailing edge along the suction side
n	number of holes
P_{ref}	reference total pressure
ΔP_t	amplitude of imposed unsteady total pressure
POA	percent open area
S	cross-sectional area of the neck
U_{ave}	average free-stream velocity in the vicinity of the jet
V	cavity volume
v_{jet}	velocity of jet
x, y, z	dimensions
y^+	dimensionless distance from the wall

Approach

The intended approach is to embed Helmholtz resonator cavities within thick, hollow LPT airfoils to absorb core acoustic energy, reduce low-Reynolds-number laminar separation, and reduce NO_x emissions. The airfoil surface will employ an array of small holes to absorb combustor and LPT acoustic energy. The holes will act as passive synthetic jets (Bader and Grosche, 1998) that can trip the laminar boundary layer in the LPT, (see for example, Fig. 3) reducing susceptibility to low-Reynolds-number laminar separation—the primary cause of LPT performance degradation at cruise. Very little aerodynamic penalty is caused by small-amplitude synthetic jets, making this concept ideal for combined acoustic attenuation and performance improvement. Up to now, powered synthetic jet flow control has never been feasible in

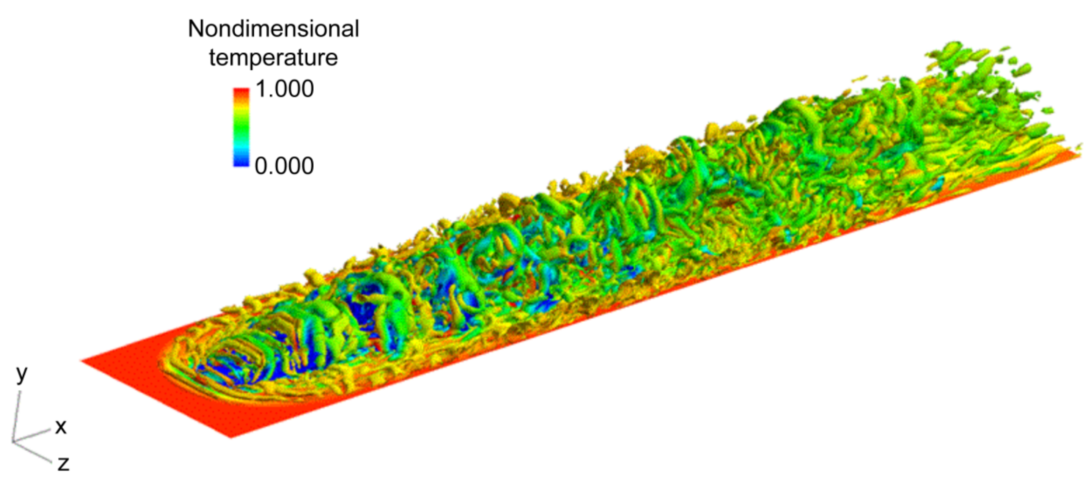

Figure 3.—Isosurfaces of Q-criterion (colored by nondimensional temperature) illustrating the creation of turbulence by a jet stream issuing into the main crossflow. The main flow is in the positive x direction, and the jet is at 90° to the main flow (Shyam et al., 2013).

LPT blades because of the volume required and the lack of materials for the vibrating membrane required for actuation. The current approach overcomes these hurdles by allowing the jets to be produced naturally through the acoustic and unsteady flow energy absorbed into the cavities. This project is making the assumption that the effective blowing ratios, frequencies, and duty cycle determined in the pulsed VGJ studies will be the same the passive synthetic jet.

Determining feasibility was divided into three steps that parallel the three aspects of the concept: (1) use representative resonator geometric features (cavity volume and spanwise-repeating liner holes) and a representative unsteady excitation to characterize the synthetic jet (e.g., Fig. 4) produced on a simplified airfoil geometry (three-dimensional rectilinear slice); (2) evaluate the ability of this synthetic jet to affect an appropriately low-Reynolds-number boundary layer in the presence of the expected adverse pressure gradient; and (3) determine the catalytic conversion ability of the additional treated surfaces in the presence of the synthetic jet versus the baseline hard wall structure. The performance of the concept can be compared with the expected performance of conventional approaches for each aspect: separate acoustic treatment, boundary layer excitation, and catalytic treatment. From the literature reviewed, it appears that the wake-passing frequency, the shear layer mode or a subharmonic frequency of the shear layer instability could be a good candidate frequency to which the resonator should be tuned. The blowing ratio could be as low as 0.25 to see some improvement in performance, but it should be approximately 1.0 for any substantial effect.

Computational Model

The complex flow path of a turbine vane was simplified for an unsteady Reynolds-Averaged Navier Stokes (RANS) computational fluid dynamics (CFD) analysis of resonator response to incoming excitation, and the subsequent excitation of the low-Reynolds-number boundary layer. The unsteady RANS solver Glenn-HT (Steinthorsson et al., 1993, 1997; Ameri, 2012) was used for the simulations. As shown in Figure 4, the CFD domain is a rectilinear slice with a spanwise (short-axis) periodicity, and it has an extent in the spanwise direction of three hole diameters, 0.096 in., with the hole centered. The liner

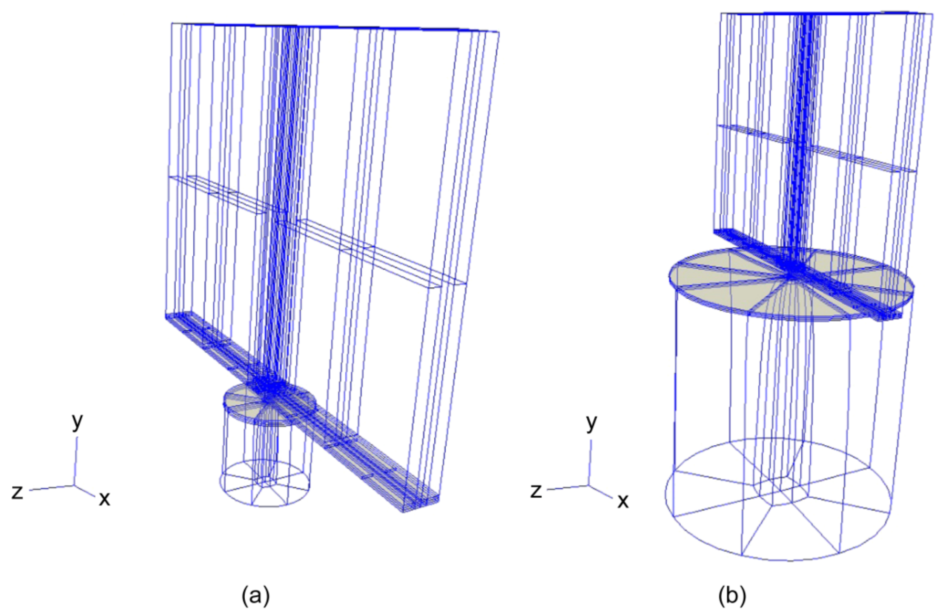

Figure 4.—Outline of grid blocks for cylindrical Helmholtz resonators shown coupled to the simple computational fluid dynamics (CFD) blade surface model with rectilinear periodic flow passage, 0.032-in.-diameter face sheet hole, and resonator cavity sized by the correct volume (but not with a shape that could be packaged in the vane). Coordinates are +x—downstream, +y—normal to the wall, and +z—right-handed, cross stream. (a) 3000-Hz resonator. (b) 400-Hz resonator.

TABLE I.—SUMMARY OF CASES
[Test parameters are provided in detail in the appendixes.]

Case name	Frequency, Hz	Amplitude, $\Delta P_t/P_{ref}$	Free-stream Mach number
3000HzAmpHiFlowLo	3000	0.004	0.25
3000HzAmpLoFlowLo	3000	.001	.25
400HzAmpHiFlowLo	400	.004	.25
400HzAmpLoFlowLo	400	.001	.25
AmpNoFlowLo	-----	-----	.25
3000HzAmpHiFlowHi	3000	.004	.50
3000HzAmpLoFlowHi	3000	.001	.50
400HzAmpHiFlowHi	400	.004	.50
400HzAmpLoFlowHi	400	.001	.50
AmpNoFlowHi	-----	-----	.50

TABLE II.—CHARACTERISTIC PROPERTIES USED TO MAKE THE CODE DIMENSIONLESS

Pressure, Pa	101 325
Temperature, K	293
Density, g/m^3	1.2039
Length, m (in.)	0.0008128 (0.032)
Time (i.e., length/velocity), s	2.832×10^{-6}
Velocity, m/s	287
Gamma	1.4

face sheet thickness of 0.032 in. and the hole diameter, also 0.032 in., are representative of current acoustic liner practice. The flat-plate wall starts 20 hole diameters upstream of the resonator hole.

Flow over a flat plate with a spanwise array of Helmholtz resonators was simulated numerically for several flow conditions. Two Helmholtz resonators were considered—one sized to resonate at 3000 Hz, representative of a wake-passing frequency, and one sized for 400 Hz, representative of the combustor tone. Both resonators were simulated at four test conditions—two free-stream Mach numbers, 0.25 and 0.50, and two forcing amplitudes, 0.1 and 0.4 percent of the inflow total pressure ($\Delta P_t/P_{ref}$). In addition, for comparison purposes, two simulations, at Mach 0.25 and 0.50, were carried out with no unsteadiness in the free stream. Table I summarizes the test cases and lists the case names.

The resonator for each geometry was sized using the available empirical correlation, which relates hole diameter, neck length, and resonator volume to the resonant frequency f. The resonator shape was chosen to be cylindrical with height equal to diameter. As mentioned above, for the two resonators considered, the hole diameter and neck length were set equal, and the spanwise spacing between holes was chosen to be three hole diameters.

A body-fitted multiblock grid was generated that contained roughly 500 000 cells. Grid points were clustered to the wall to produce y^+ values below 3 everywhere, except for a few cells near the hole lip. A no-slip boundary condition was imposed on all solid surfaces, and periodicity was enforced in the spanwise direction. The inlet condition consisted of a sinusoidal variation in total pressure and a constant total temperature. At the exit, the static pressure was fixed at a value that would produce the desired average Mach number. Initial attempts were made to run a nonreflecting boundary condition, but numerical stability issues were encountered. Subsequently, modifications were made to the code that allowed the nonreflecting boundary condition to work. When one of the cases was run with the nonreflecting boundary condition, it was determined that the exit condition had very little effect on the magnitude of the unsteadiness in and around the resonator. Only a shift in phase was observed, which, it was decided, would not affect the conclusions.

The code uses a set of characteristic quantities (shown in Table II) to make each property dimensionless.

TABLE III.—PROBE LOCATIONS
[The center of the hole at the plate face is at (0, 0, 0).]

Probe location name	Nondimensional location[a]		
	x/*d*, axial and downstream	y/*d*, normal to the wall	z/*d*, spanwise (crossflow)
Inlet	–19.99	15.00	–0.01
Above	.02	15.00	–.01
Outlet	18.99	15.00	–.01
WithinUp	–.45	–.50	0.00
Within	0.00	–.50	–.01
WithinDn	.45	–.50	0.00
NearWallUp	–2.00	.02	–.50
NearWallDn	2.00	.02	–.50
Below	0.00	–4.00	–.01

[a]*d*, hole diameter.

Each case was allowed to run through multiple cycles of the forcing period to reach periodicity and then the final few cycles were averaged. In addition, the root mean square (rms) of the variation was produced at each grid point. During the final cycle, the instantaneous solution was stored at 20 time values. Data also were collected, at every time step, for nine probe locations. Table III lists the probe locations and the name given to them. In addition, Appendix A shows the induced unsteady amplitude, phase, and period for the largest two modes for each probe in each case, and Appendix B shows the steady results from the two unforced cases at the nine probe locations.

In an effort to make at least some observations about the effect of the VGJs on the boundary layer downstream of the hole, the results from the x-momentum at the NearWallDn probe were compared for the AmpHiFlowLo cases. These cases were chosen because they produced the largest effect at each frequency. The x-momentum from the AmpNoFlowLo case (the unforced case) at the low flow of Mach 0.25 was 0.0324. For the corresponding 3000- and 400-Hz cases, the mean x-momenta were 0.0353 and 0.0321, respectively. This represents a 9-percent increase for the 3000-Hz case. The 400-Hz cases (both AmpHi and AmpLo) show a 1-percent decrease, which is probably not significant. All of the other cases also show very little effect. So the 3000-Hz case is really the only case that produced a noticeable change to the average value. The fact that the mean x-momentum was increased by 9 percent at this location downstream of the hole could be indicative of a fuller, more turbulent boundary layer that could be more resistant to separation.

The highest excitation frequency, 3000 Hz, is representative of wakes from an upstream blade row. The predicted unsteady flow through the hole is one of the results needed for the synthetic jet and catalytic conversion evaluation. Figure 5 shows velocity vectors along a surface that intersects the centerline of the Helmholtz resonator hole. For clarity, the figure only presents velocity vectors at every other grid point. The time-averaged result does not show a striking difference between the boundary layer upstream and downstream of the hole. However, the maximum inflow and outflow images show that the boundary layer changes dramatically throughout the period. At the time of maximum inflow, the downstream boundary layer is much fuller. At the time of maximum outflow, the downstream boundary layer is separated near the hole.

Four figures of merit were recorded to assess the effect of the resonator: the hole mass flux amplitude for each case and the peak values of the rms of the x-, y-, and z-momenta. Table IV shows the results for the eight cases. For all figures of merit, the 3000-Hz AmpHiFlowLo case shows values significantly higher than for the other cases.

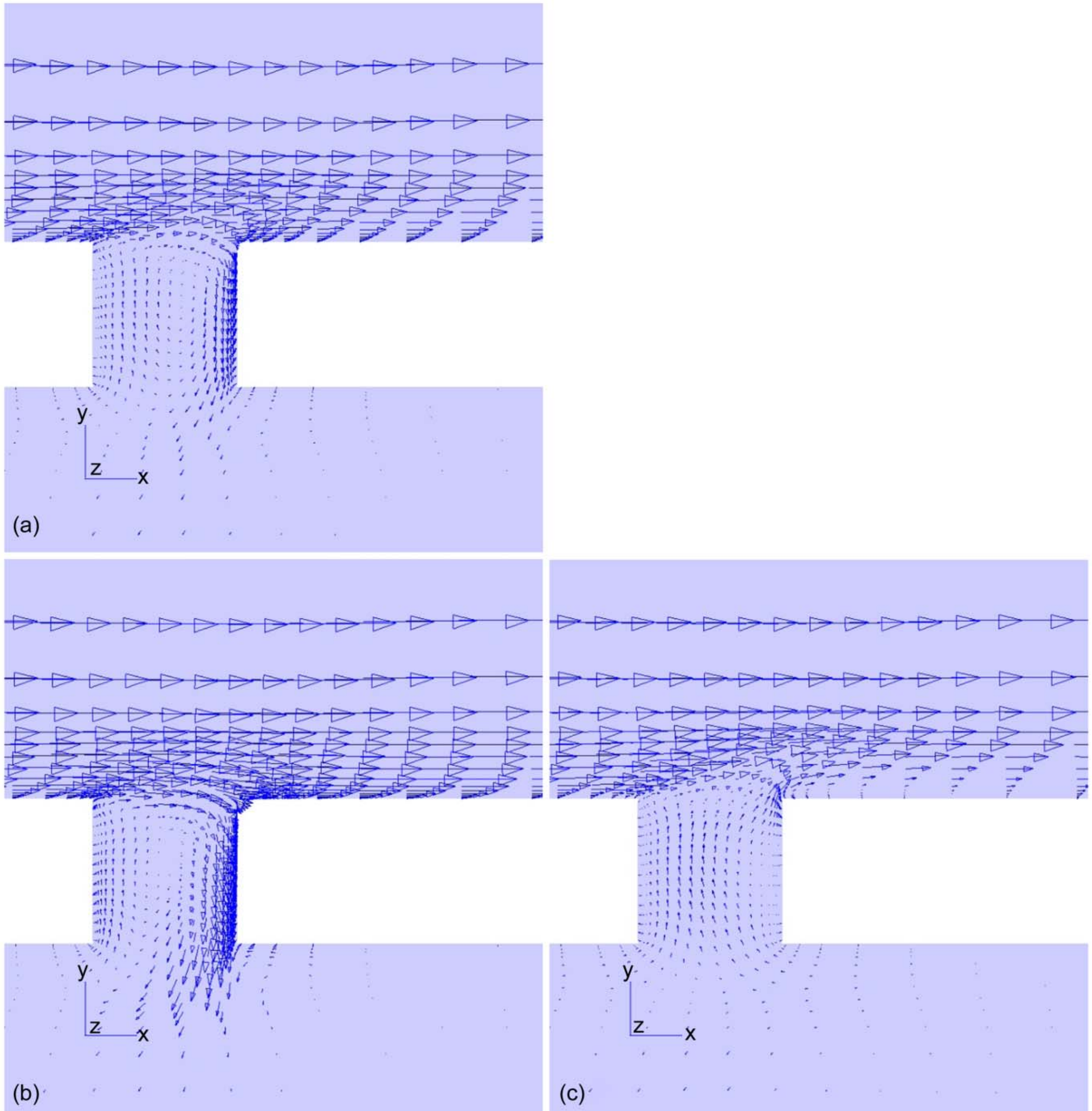

Figure 5.—Velocity vectors at midhole (z = 0) for the 3000HzAmpHiFlowLo case. Vectors are shown at every other grid point for clarity. (a) Time-averaged result. (b) At moment of maximum inflow. (c) At moment of maximum outflow.

TABLE IV.—FIGURES OF MERIT
[Maximum in column is in bold font.]

Name	Frequency, Hz	Blowing ratio	Peak rms x-momentum[a]	Peak rms y-momentum[a]	Peak rms z-momentum[a]
3000HzAmpHiFlowHi	3000	.041	.106	.138	.0348
3000HzAmpLoFlowHi	3000	.020	.106	.0626	.0202
400HzAmpHiFlowHi	400	.011	.107	.0607	.0213
400HzAmpLoFlowHi	400	.0022	.106	.0599	.0211
3000HzAmpHiFlowLo	3000	**0.070**	**0.258**	**0.239**	**0.0990**
3000HzAmpLoFlowLo	3000	.021	.0934	.0993	.0268
400HzAmpHiFlowLo	400	.028	.142	.170	.0453
400HzAmpLoFlowLo	400	.016	.0895	.0652	.0171

[a]Peak momenta are normalized by the freestream momentum: FlowHi values by 0.511 and FlowLo values by 0.287

In terms of absolute mass flux through the hole relative to the free-stream mass flux, none of the cases appear to be overly energetic. If it is a requirement that a blowing ratio approaching one must be produced, then none of these cases came close. However, these cases did generate much larger levels of unsteadiness than was present in the free stream.

The following conclusions can be drawn from these results: Higher frequencies and lower crossflow velocities produce stronger effects. The fact that the larger forcing amplitudes produced larger results seems like an obvious result.

Figures 6 to 8 show a more global view of the results by presenting surfaces of constant rms x-, y-, and z-momenta. Figure 6 shows a large image of the result for the 3000-Hz AmpHiFlowLo case. It is important to note that, in all of the isosurface plots in Figures 6 to 8, the rms x-momentum isovalue is 20 times larger than the rms y- and z-momenta isovalues (0.079 versus 0.0039, and 0.14 versus 0.0071). These x-momentum isovalues are many times larger than what occurs far above the plate. The pocket of intense rms x-momentum (as well as the rms y- and z-momenta regions) persists several hole diameters downstream.

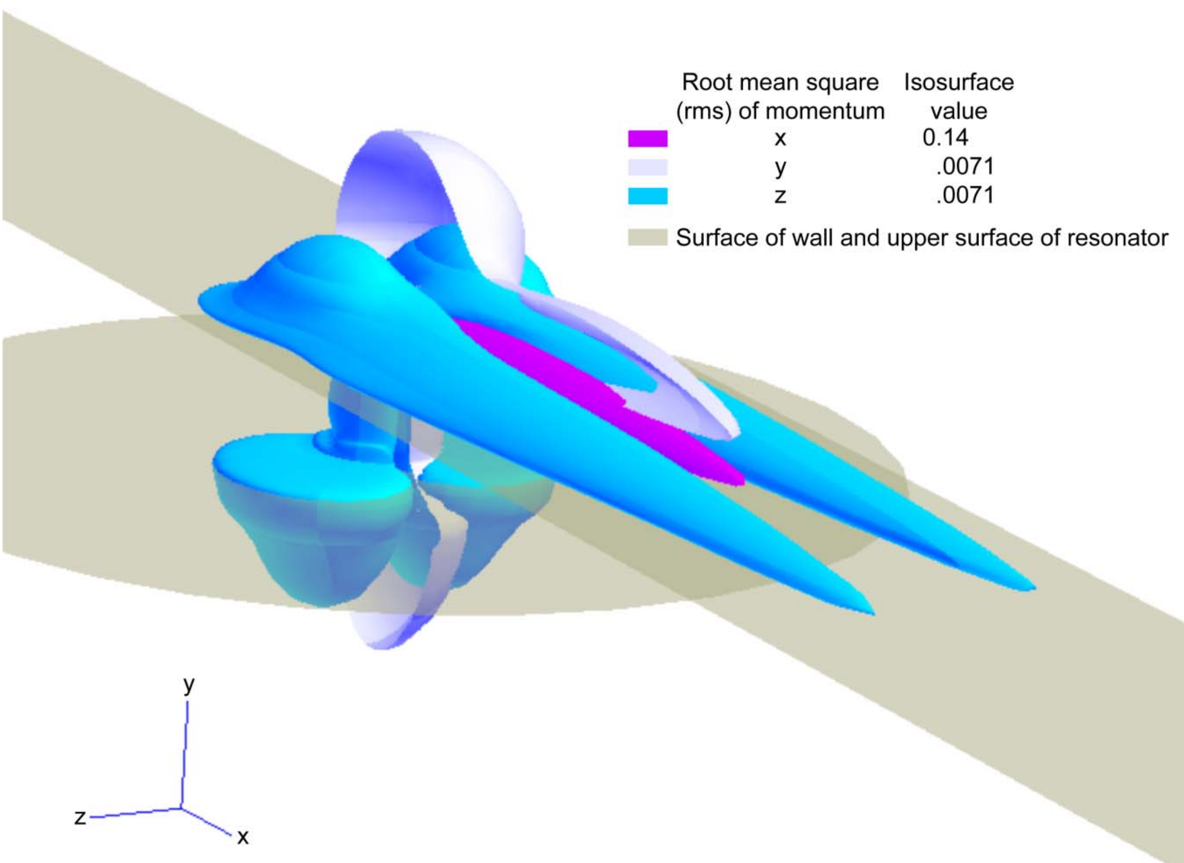

Figure 6.—Isosurfaces of rms of x-, y-, and z-momenta normalized by the cross-flow momentum (hence similar to blowing ratio) for the 3000HzAmpHiFlowLo case, where the effect of the vortex-generating jets (VGJs) was the largest. Note that the y-momentum was trimmed at z = 0 to reveal detail.

Figure 7 shows the same isosurfaces as in Figure 6 but for different (FlowHi) normalized isovalues. Among the 0.5 Mach number cases that were simulated, the 3000HzAmpHiFlowHi case in the lower left stands out from the rest. The vertical extent of the y-momentum unsteadiness and the downstream extent of the x-momentum unsteadiness are greater than for the other three Mach 0.5 cases.

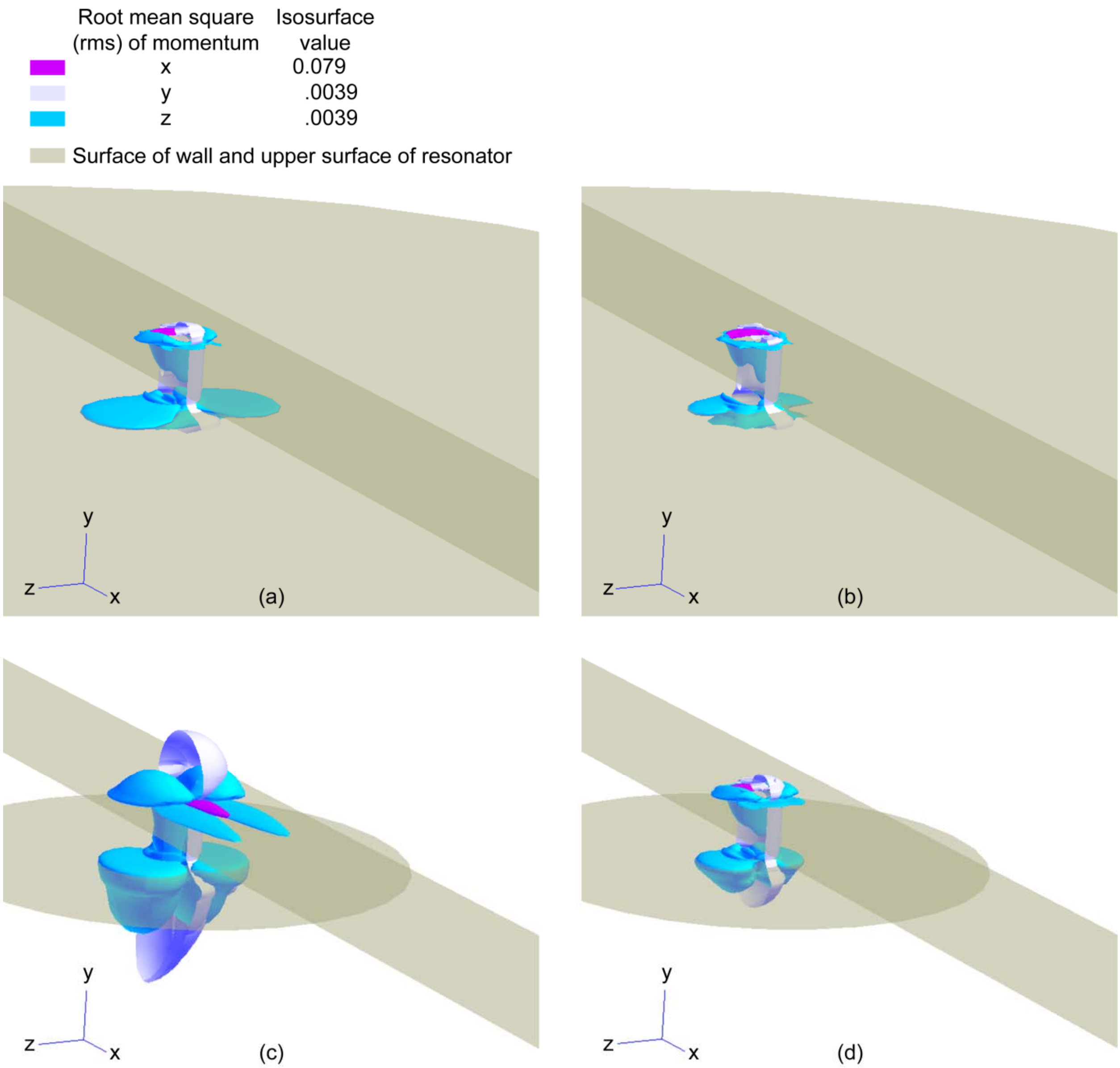

Figure 7.—Isosurfaces of rms of x-, y-, and z-momenta normalized by cross-flow momentum (hence similar to blowing ratio) for Mach 0.5. (a) 400HzAmpHiFlowHi. (b) 400HzAmpLoFlowHi. (c) 3000HzAmpHiFlowHi. (d) 3000HzAmpLoFlowHi.

Figure 8 contains the isosurfaces for the four 0.25 Mach number cases. For this lower Mach number, the high amplitude 3000Hz case (lower left) once again stands out from the other three cases. The unsteadiness persists over a larger region than for the 0.5 Mach number case.

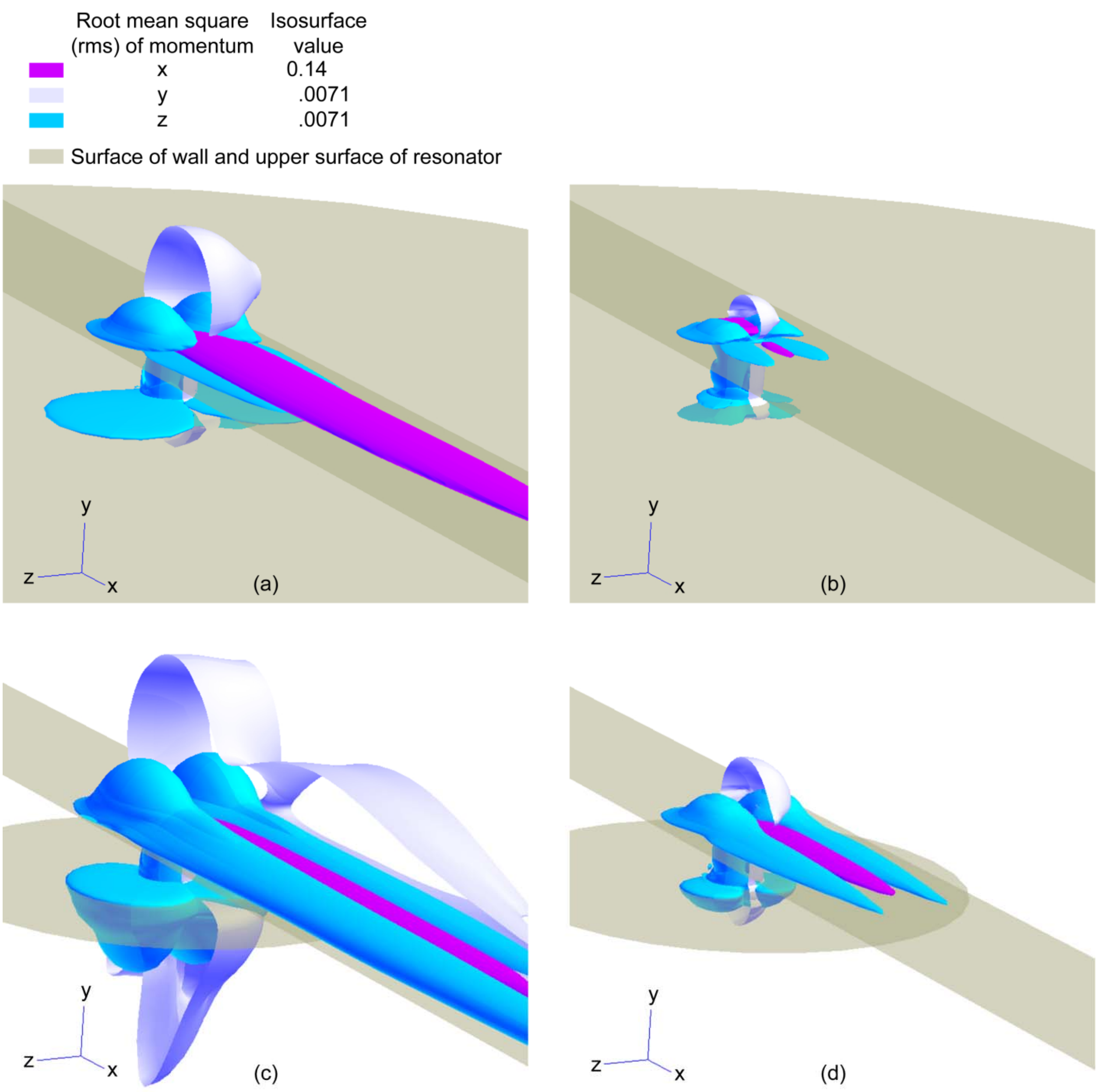

Figure 8.—Isosurfaces of rms of x-, y-, and z-momenta normalized by cross-flow momentum (hence similar to blowing ratio) for Mach 0.25. (a) 400HzAmpHiFlowLo. (b) 400HzAmpLoFlowLo. (c) 3000HzAmpHiFlowLo. (d) 3000HzAmpLoFlowLo.

Discussion

Synthetic Jet Feasibility

The model problem comprising a single hole (normal to the surface) in a three-dimensional periodic spanwise channel was evaluated for two frequencies—400 Hz, the primary tone from combustion in the combustor, and 3000 Hz, the anticipated upstream rotor wake-passing frequency, at two Mach numbers—0.5, the anticipated flow speed, and the much lower 0.2, to investigate the sensitivity. Table V shows the parameters used in the study by Volino et al. (2011), for which there was complete removal of the separation bubble on the L1A airfoil (Fig. 10).

Because of the lack of data for synthetic (zero-net-mass) jets, this work will compare VGJ flow control parameters with the results from pulsed VGJ studies. The parameters in Table VI indicate that although the reduced frequencies F of the synthetic jets are in the appropriate range for a pulsed VGJ, the induced blowing ratios B are all at least an order of magnitude smaller than required for a single row of VGJs to control the boundary layer separation. However, complete removal of the separation bubble may not be necessary for performance improvement, although data are not available to indicate this. For example, the lowest blowing ratio case of Volino et al. (2011) was 1.0 for $F = 0.14$ at a Reynolds number of 25 000. The resonator ostensibly operated at a duty cycle closer to 50 percent, which is typically difficult for VGJs to achieve because of the physical limitations of the solenoid valves that control them. Also, for a given flow Mach number, the higher frequency produces 2 to 3 times more blowing ratio. Both of these observations tend to point to the feasibility of using the higher frequency Helmholtz resonator as a flow control device.

TABLE V.—BLOWING RATIOS REQUIRED FOR BENEFICIAL EFFECT ON THE L1A AIRFOIL

Reynolds number, Re	Blowing ratio, B, required for benefit			
	Reduced frequency, F			
	0.14	0.28	0.56	1.12
25 000	>3	>2	>1	>0.75
50 000	>1.5	>1	>0.75	

TABLE VI.—ESTIMATED INDUCED JET FLOW CONTROL PARAMETERS

Pulsing frequency, f, Hz	400	3000	400	3000
Average Mach number from injection site to trailing edge	0.2	0.2	0.5	0.5
Dimensionless jet frequency, $F = (f\, L_{\text{jet-}TE}/U_{\text{ave}})$	0.18	1.36	0.07	0.55
Jet Reynolds number	65 089	65 089	162 722	162 722
Blowing ratio, $B = v_{\text{jet}}/U_{\text{ave}}$	0.028	0.070	0.011	0.024

The preliminary CFD analysis found that the induced synthetic jet response to both frequencies, even at the high incident amplitude of 146 dB, was unable to affect the boundary layer, although a jet normal to the airfoil surface, as used in this model, was not optimal for flow control. As seen in Table VI, none of the conditions created a sufficient blowing ratio ($B > 1$) from a single hole. Whether a field of induced synthetic jets could create enough additional turbulence to keep the boundary layer attached is still to be determined.

Acoustic Attenuation Feasibility

The L1A airfoil (Fig. 9), designed at the Air Force Research Laboratory, is a modern highly loaded turbine vane geometry that is roughly 10-percent thick. For a 3000-Hz Helmholtz resonator, sizing the required cavity volume per face sheet hole shows that a very large number (<79) of resonators can be accommodated in each hole-diameter-thick slice of span. This indicates that implementing a chordwise patch of several tens of resonator holes should be feasible.

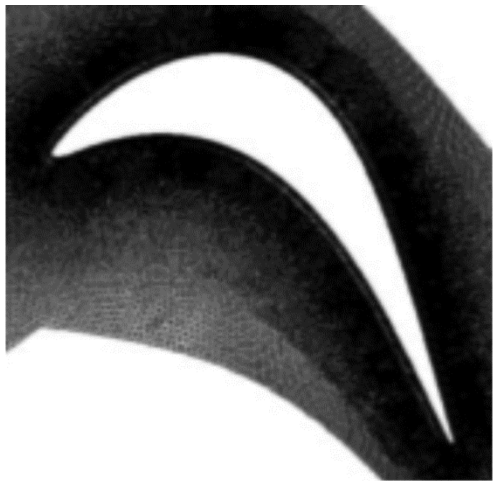

Figure 9.—L1A airfoil contour.

In the current "soft vane" concept (Envia, 2012; Elliott, 2010; Jones, 2009), useful attenuation is achieved with a treatment patch covering as little as 10 percent of the chord. It is expected that a treatment patch covering up to 40 percent of the chord (i.e., from 20 to 60-percent chord) can be implemented. Current perforated face sheet designs use hole diameters in the range of $d = 0.025$ to 0.070 in., with open areas from 5 to 15 percent. Given the periodic hole pattern shown in Figure 10, the percent open area (POA) for n holes of diameter d in any periodic patch is given by

$$\mathrm{POA} = \frac{\pi d^2}{4n^2 d^2} = \frac{\pi}{4n^2}$$

In practice, the hole-to-hole spacing ratios range from 4 (5-percent POA) to 2.3 (15-percent POA). A spacing ratio of 3, used in the CFD model, is representative of a 9-percent POA face sheet. In summary, it is feasible that a sufficiently large acoustic attenuator can be installed in an LPT vane. Note that this application on the LPT is similar to the soft vane concept for the fan bypass duct that has been demonstrated for frequencies from 1000 to 5300 Hz (Jones et al., 2009). Lower frequencies will require more volume but appear to be well within reach.

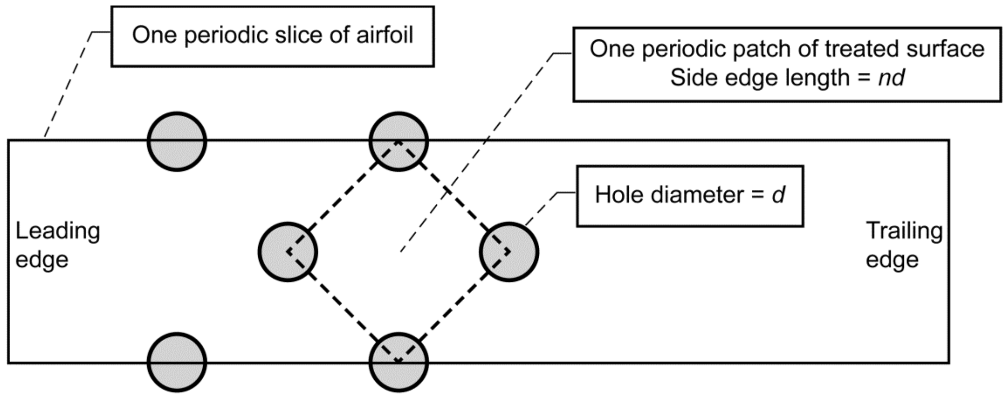

Figure 10.—Representative treated airfoil surface with unrealistically large holes for illustration only; *n*, number of holes; *d*, hole diameter.

Holes that are more effective for flow control—for example, skewed (90° from the mean flow) and grazing (30° from the surface)—have higher resistivity than the holes used in this initial model, which are normal to the surface. This higher resistance, as well as the longer neck length, reduces the resonator tuning frequency, makes the resonance peak narrower and sharper, and reduces the broad-band acoustic reduction. These effects would be taken into account when designing the liner once the feasibility of flow control is established.

Quantitative numbers for the acoustic reduction, which depend on the size and characteristics of the treatment, require a more detailed analysis using a model of the actual turbine vane geometry. In bypass duct applications with high-bypass-ratio fans, a soft stator has shown, Elliott et al. (2010), 1 dB of additional broadband acoustical attenuation.

Catalytic Converter Feasibility

The induced velocities in the cavity are near zero, and the peak velocity induced through the resonator holes is well below the velocities in the free stream. So although the residence time in the cavity and the additional surface area of the cavity would hint at feasible catalytic conversion capability, the lack of bulk flow transport means that there is no significant impact on the nitrogen oxide level in the output stream.

Conclusions

This study addresses the feasibility of all three aspects of the proposed multifunctional LPT liner: flow control, acoustic attenuation and increased catalytic converter performance. Increased acoustic attenuation is feasible as the region of acoustic treatment may be large enough to have a benefit and the implementation is similar to soft vane designs for the fan bypass duct. It was shown that a single row of inducted VGJs are not strong enough to reduce flow separation (based on prior work by researchers in the flow control area), but multiple chordwise jets might be a feasible approach. Lastly, the additional catalytic surface area is not exposed to a high velocity, so it probably does not have any benefit.

Appendix A.—Induced Unsteady Flow Properties at Probe Locations

The following pages contain the Fast Fourier Transform analysis of the flow property time histories at the nine probes (described in Table III) recorded for each of the eight unsteady cases. For each probe, all variables are analyzed. The period, amplitude, and phase of the two largest modes are presented, as well as the average value.

Computational Variables

rho	normalized density
xmom	normalized x momentum
ymom	normalized y momentum
zmom	normalized z momentum
rhoe	specific energy
k	turbulent kinetic energy
omega	specific dissipation

Case: 3000HzAmpHiFlowHi

```
==============================================================================================================
Case: 3000HzAmpHiFlowHi

probe_Inlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
```

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	120.00	120.00	120.00	120.00	120.00	120.00	120.00
period_amp_2nd:	60.00	60.00	20.00	60.00	60.00	60.00	60.00
freq_amp_max:	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333
freq_amp_2nd:	0.016667	0.016667	0.050000	0.016667	0.016667	0.016667	0.016667
phase_amp_max:	-19.85	27.56	143.38	87.12	-16.17	37.69	26.61
phase_amp_2nd:	-52.69	128.42	24.66	6.78	-50.60	115.94	110.83
average:	0.886395	0.508915	0.000027	-0.000000	2.257729	0.000044	0.049323
amp_max:	0.003085	0.003661	0.000002	0.000000	0.008001	0.000001	0.000479
amp_2nd:	0.000009	0.000012	0.000001	0.000000	0.000020	0.000000	0.000002
amp_2nd_percent_of_amp_max:	0.298982%	0.316058%	28.832334%	0.600628%	0.254578%	0.574306%	0.349103%

```
=============================================================================================
Case: 3000HzAmpHiFlowHi

probe_Above.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
           period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
           period_amp_2nd:       30.00      60.00      60.00      30.00      30.00      60.00      60.00
             freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
             freq_amp_2nd:    0.033333   0.016667   0.016667   0.033333   0.033333   0.016667   0.016667
            phase_amp_max:      -17.39     -45.86     175.31     -57.69      -2.96     -28.33     -32.00
            phase_amp_2nd:      178.79      21.89    -169.61      94.05     178.92     -46.46     -47.40
                  average:    0.885901   0.509781   0.000828  -0.000000   2.256662   0.000038   0.043118
                  amp_max:    0.002926   0.002489   0.000091   0.000000   0.010796   0.000001   0.000462
                  amp_2nd:    0.000027   0.000003   0.000021   0.000000   0.000087   0.000000   0.000002
amp_2nd_percent_of_amp_max:    0.932615%  0.127577% 22.582292%  5.401394%  0.804122%  0.518873%  0.349044%
```



```
=============================================================================================
Case: 3000HzAmpHiFlowHi

probe_Outlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
           period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
           period_amp_2nd:       60.00      60.00      60.00      30.00      30.00      60.00      60.00
             freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
             freq_amp_2nd:    0.016667   0.016667   0.016667   0.033333   0.033333   0.016667   0.016667
            phase_amp_max:      141.78     -57.41    -110.14    -130.02     -35.10    -143.21    -153.54
            phase_amp_2nd:      126.82      50.30    -159.64     -37.37     -75.87     139.54     141.27
                  average:    0.885219   0.510972   0.000953  -0.000000   2.255172   0.000033   0.038420
                  amp_max:    0.000907   0.003362   0.000066   0.000000   0.002246   0.000000   0.000239
                  amp_2nd:    0.000007   0.000011   0.000007   0.000000   0.000007   0.000000   0.000002
amp_2nd_percent_of_amp_max:    0.815417%  0.319375% 11.323878%  1.592272%  0.311370%  0.782964%  0.753449%
```

==

Case: 3000HzAmpHiFlowHi

probe_WithinUp.dat

Number of time steps per cycle: 600
Number of cycles in file : 5
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	120.00	120.00	120.00	120.00	120.00	120.00	120.00
period_amp_2nd:	60.00	60.00	60.00	60.00	60.00	60.00	60.00
freq_amp_max:	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333
freq_amp_2nd:	0.016667	0.016667	0.016667	0.016667	0.016667	0.016667	0.016667
phase_amp_max:	152.39	10.56	-40.53	-107.20	169.22	-98.06	-88.81
phase_amp_2nd:	89.92	-2.39	-15.78	155.31	-157.43	-139.49	-11.11
average:	0.878184	-0.000245	0.030311	0.000103	2.102089	0.000184	1.396031
amp_max:	0.002169	0.000739	0.009519	0.000729	0.002877	0.000089	0.160064
amp_2nd:	0.000998	0.000730	0.003897	0.000314	0.001218	0.000050	0.052133
amp_2nd_percent_of_amp_max:	46.019305%	98.790319%	40.937243%	43.043478%	42.347400%	56.498715%	32.569865%

==

Case: 3000HzAmpHiFlowHi

probe_Within.dat

Number of time steps per cycle: 600
Number of cycles in file : 5
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	120.00	120.00	120.00	120.00	120.00	120.00	60.00
period_amp_2nd:	60.00	60.00	60.00	60.00	60.00	60.00	40.00
freq_amp_max:	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333	0.016667
freq_amp_2nd:	0.016667	0.016667	0.016667	0.016667	0.016667	0.016667	0.025000
phase_amp_max:	161.64	-95.35	-144.69	134.23	158.58	-63.46	90.47
phase_amp_2nd:	-144.25	-45.56	-157.40	40.09	-155.97	93.50	134.62
average:	0.867206	-0.000680	0.007893	0.000164	2.100186	0.000509	0.534258
amp_max:	0.002247	0.008407	0.010309	0.000720	0.003681	0.000137	0.103249
amp_2nd:	0.000547	0.004032	0.002073	0.000247	0.001373	0.000101	0.051822
amp_2nd_percent_of_amp_max:	24.324958%	47.956318%	20.109421%	34.317520%	37.288905%	73.966924%	50.190920%

==

Case: 3000HzAmpHiFlowHi

probe_WithinDn.dat

Number of time steps per cycle: 600
Number of cycles in file   : 5
Number of cycles used in fft : 1
Timestep size   : 0.2
Nyquist criterion   : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	120.00	120.00	120.00	120.00	120.00	120.00	120.00
period_amp_2nd:	60.00	60.00	60.00	60.00	60.00	60.00	60.00
freq_amp_max:	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333
freq_amp_2nd:	0.016667	0.016667	0.016667	0.016667	0.016667	0.016667	0.016667
phase_amp_max:	154.51	-171.28	160.11	-42.39	-12.24	-25.39	-8.47
phase_amp_2nd:	-77.00	-65.08	-149.94	80.14	-19.39	63.30	114.67
average:	0.859298	-0.006720	-0.116580	0.001515	2.112319	0.001314	3.421909
amp_max:	0.003249	0.004982	0.096559	0.001446	0.011104	0.000927	1.056404
amp_2nd:	0.000534	0.001909	0.014976	0.000305	0.002560	0.000148	0.347917
amp_2nd_percent_of_amp_max:	16.422643%	38.322759%	15.509887%	21.127135%	23.051504%	15.966141%	32.934103%

==

Case: 3000HzAmpHiFlowHi

probe_NearWallUp.dat

Number of time steps per cycle: 600
Number of cycles in file   : 5
Number of cycles used in fft : 1
Timestep size   : 0.2
Nyquist criterion   : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	120.00	120.00	120.00	120.00	120.00	120.00	120.00
period_amp_2nd:	60.00	60.00	60.00	60.00	60.00	60.00	60.00
freq_amp_max:	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333
freq_amp_2nd:	0.016667	0.016667	0.016667	0.016667	0.016667	0.016667	0.016667
phase_amp_max:	-6.66	-20.21	-120.68	-10.58	-3.96	-29.60	-45.65
phase_amp_2nd:	-122.49	2.86	168.18	15.52	-116.12	-17.53	27.88
average:	0.853350	0.185718	0.000025	-0.000109	2.131979	0.003057	14.446430
amp_max:	0.002397	0.002798	0.000027	0.000120	0.009332	0.000049	0.081276
amp_2nd:	0.000050	0.000094	0.000002	0.000008	0.000147	0.000002	0.000907
amp_2nd_percent_of_amp_max:	2.081525%	3.374159%	6.141551%	6.999462%	1.575552%	3.387601%	1.115458%

```
===============================================================================================================
Case: 3000HzAmpHiFlowHi

probe_NearWallDn.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho        xmom        ymom        zmom        rhoe           k       omega
           period_amp_max:      120.00      120.00      120.00      120.00      120.00      120.00      120.00
           period_amp_2nd:       60.00       60.00       60.00       60.00       60.00       60.00       60.00
             freq_amp_max:    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333
             freq_amp_2nd:    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667
            phase_amp_max:        0.99      -29.27      -34.21      170.33       -4.24      -34.45      -34.26
            phase_amp_2nd:      -14.52       -8.96       97.38      -80.53        3.47       -2.20      -12.80
                  average:    0.853384    0.170052   -0.000022    0.002041    2.126390    0.002737   13.789984
                  amp_max:    0.003570    0.011650    0.000080    0.004155    0.014406    0.000160    0.368110
                  amp_2nd:    0.000063    0.000926    0.000007    0.000299    0.000321    0.000017    0.030726
amp_2nd_percent_of_amp_max:    1.760993%   7.950192%   8.887512%   7.202398%   2.228037%  10.918123%   8.346859%

===============================================================================================================
Case: 3000HzAmpHiFlowHi

probe_Below.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho        xmom        ymom        zmom        rhoe           k       omega
           period_amp_max:      120.00      120.00      120.00      120.00      120.00      120.00      120.00
           period_amp_2nd:       60.00       60.00       60.00       60.00       60.00       60.00       60.00
             freq_amp_max:    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333
             freq_amp_2nd:    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667
            phase_amp_max:     -104.08     -157.86     -159.82        7.57      -89.45       76.24      119.19
            phase_amp_2nd:      131.94       96.86       99.22     -109.74      -74.12       95.48       17.13
                  average:    0.882773   -0.001969    0.000262   -0.000103    2.105120    0.000007    0.012086
                  amp_max:    0.000766    0.000470    0.000401    0.000024    0.001563    0.000000    0.000993
                  amp_2nd:    0.000085    0.000087    0.000106    0.000006    0.000070    0.000000    0.000291
amp_2nd_percent_of_amp_max:   11.049389%  18.483458%  26.340634%  23.984367%   4.452861%  32.682750%  29.314438%
```

Case: 3000HzAmpHiFlowLo

```
=========================================================================================
Case: 3000HzAmpHiFlowLo

probe_Inlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:      60.00      60.00      40.00      60.00      60.00      60.00      60.00
              freq_amp_max:   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:   0.016667   0.016667   0.025000   0.016667   0.016667   0.016667   0.016667
             phase_amp_max:      -4.51      35.13     152.28      99.76      -2.88      49.72      34.61
             phase_amp_2nd:     -37.99     134.66     -88.21    -131.69     -32.80     127.56     124.80
                   average:   0.969666   0.283899   0.000016  -0.000000   2.436039   0.000012   0.022716
                   amp_max:   0.003861   0.001670   0.000002   0.000001   0.009720   0.000000   0.000188
                   amp_2nd:   0.000005   0.000023   0.000001   0.000000   0.000012   0.000000   0.000003
amp_2nd_percent_of_amp_max:   0.138101%  1.397191% 37.359416%  0.705381%  0.120349%  1.836259%  1.363417%

=========================================================================================
Case: 3000HzAmpHiFlowLo

probe_Above.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:      60.00      60.00      40.00      24.00      60.00      60.00      60.00
              freq_amp_max:   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:   0.016667   0.016667   0.025000   0.041667   0.016667   0.016667   0.016667
             phase_amp_max:      29.79     -67.60     178.27     -91.90       2.78     -83.56     -89.62
             phase_amp_2nd:      78.26      79.49     -51.77      37.67      64.48     100.01      98.09
                   average:   0.969546   0.284438   0.000384  -0.000000   2.435779   0.000011   0.020312
                   amp_max:   0.001599   0.001830   0.000097   0.000000   0.008322   0.000000   0.000054
                   amp_2nd:   0.000028   0.000006   0.000026   0.000000   0.000083   0.000000   0.000002
amp_2nd_percent_of_amp_max:   1.760445%  0.317843% 26.459530%  3.924558%  1.002661%  2.404127%  3.517995%
```

```
==========================================================================================================
Case: 3000HzAmpHiFlowLo

probe_Outlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:       60.00      60.00      40.00      60.00      60.00      60.00      60.00
              freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:    0.016667   0.016667   0.025000   0.016667   0.016667   0.016667   0.016667
             phase_amp_max:      -34.92     -67.95     116.04    -158.59     -39.17      44.27      25.74
             phase_amp_2nd:     -162.60      -4.63     -68.58     170.74      41.94      38.70      33.40
                   average:    0.969424   0.284924   0.000423   0.000000   2.435534   0.000010   0.018424
                   amp_max:    0.001199   0.003715   0.000031   0.000000   0.001213   0.000000   0.000068
                   amp_2nd:    0.000005   0.000023   0.000004   0.000000   0.000008   0.000000   0.000001
amp_2nd_percent_of_amp_max:    0.376899%  0.610756% 14.019055% 19.880982%  0.624284%  1.098926%  0.852312%
```



```
==========================================================================================================
Case: 3000HzAmpHiFlowLo

probe_WithinUp.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:      120.00      60.00     120.00     120.00      60.00      60.00     120.00
            period_amp_2nd:       40.00      40.00      30.00      40.00      40.00      40.00      40.00
              freq_amp_max:    0.008333   0.016667   0.008333   0.008333   0.016667   0.016667   0.008333
              freq_amp_2nd:    0.025000   0.025000   0.033333   0.025000   0.025000   0.025000   0.025000
             phase_amp_max:      135.86     -76.56     -90.63    -171.94     147.45     119.54     -47.88
             phase_amp_2nd:      171.20    -153.29      27.49     -75.65     125.88      19.22    -157.90
                   average:    0.969257  -0.000567   0.008312   0.000177   2.391549   0.000001   1.187166
                   amp_max:    0.000463   0.000585   0.016185   0.000544   0.001319   0.000000   0.124610
                   amp_2nd:    0.000167   0.000352   0.000951   0.000055   0.000558   0.000000   0.077068
amp_2nd_percent_of_amp_max:   36.145196% 60.253739%  5.874619% 10.165161% 42.333085% 71.942287% 61.847550%
```

```
==============================================================================================================
Case: 3000HzAmpHiFlowLo

probe_Within.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:      120.00     120.00     120.00       60.00     120.00     120.00      60.00
            period_amp_2nd:       60.00      60.00      60.00       30.00      40.00      40.00      40.00
              freq_amp_max:    0.008333   0.008333   0.008333    0.016667   0.008333   0.008333   0.016667
              freq_amp_2nd:    0.016667   0.016667   0.016667    0.033333   0.025000   0.025000   0.025000
             phase_amp_max:       91.81    -130.13     179.54       -7.07     130.01     -75.02      -6.09
             phase_amp_2nd:      162.21    -170.43      84.63      -28.73     147.26      15.21       0.13
                   average:    0.964296  -0.004055   0.014075   -0.000071   2.391060   0.000011   0.306199
                   amp_max:    0.001738   0.012025   0.025331    0.000536   0.001945   0.000005   0.082655
                   amp_2nd:    0.001683   0.004618   0.002917    0.000125   0.000518   0.000002   0.045299
amp_2nd_percent_of_amp_max:   96.806692% 38.401953% 11.516373% 23.347090% 26.601305% 48.917624% 54.804785%
```



```
==============================================================================================================
Case: 3000HzAmpHiFlowLo

probe_WithinDn.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:      120.00     120.00     120.00      120.00     120.00     120.00     120.00
            period_amp_2nd:       60.00      60.00      60.00       30.00      60.00      60.00      40.00
              freq_amp_max:    0.008333   0.008333   0.008333    0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:    0.016667   0.016667   0.016667    0.033333   0.016667   0.016667   0.025000
             phase_amp_max:      129.78     175.28     146.01     -142.43     -20.28     -48.52      16.57
             phase_amp_2nd:       86.82     179.51     126.11       -9.96     -59.98     -56.75      58.12
                   average:    0.961695  -0.002966  -0.070459    0.000347   2.396325   0.000016   1.920490
                   amp_max:    0.001014   0.004179   0.088563    0.000268   0.007414   0.000019   0.354658
                   amp_2nd:    0.000511   0.002090   0.027250    0.000265   0.002914   0.000005   0.298711
amp_2nd_percent_of_amp_max:   50.366297% 50.009457% 30.769234% 98.773332% 39.305510% 29.251117% 84.225170%
```

```
==========================================================================================================
Case: 3000HzAmpHiFlowLo

probe_NearWallUp.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:      60.00      60.00      60.00      60.00      60.00      60.00      60.00
              freq_amp_max:   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:   0.016667   0.016667   0.016667   0.016667   0.016667   0.016667   0.016667
             phase_amp_max:       7.55     -38.54    -132.48     -18.45       4.23     -32.33    -149.06
             phase_amp_2nd:     155.38     -50.08      99.36     -66.91     158.96    -128.81     -92.87
                   average:   0.959290   0.035803   0.000016  -0.000073   2.394756   0.000002   8.211789
                   amp_max:   0.002163   0.003040   0.000018   0.000344   0.007437   0.000000   0.123827
                   amp_2nd:   0.000027   0.000095   0.000001   0.000018   0.000093   0.000000   0.002513
amp_2nd_percent_of_amp_max:   1.264168%  3.124296%  6.244737%  5.298664%  1.253703%  3.447918%  2.029332%

==========================================================================================================
Case: 3000HzAmpHiFlowLo

probe_NearWallDn.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:      60.00      60.00      60.00      60.00      60.00      60.00      60.00
              freq_amp_max:   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:   0.016667   0.016667   0.016667   0.016667   0.016667   0.016667   0.016667
             phase_amp_max:      -3.55     -60.04     -18.14     148.12      -7.57     -62.07    -168.58
             phase_amp_2nd:      57.72    -129.23     -79.25    -107.62      58.74    -142.44     -71.54
                   average:   0.959782   0.035297   0.000000   0.001792   2.394048   0.000006   8.201745
                   amp_max:   0.003100   0.012884   0.000071   0.009084   0.010424   0.000001   0.343839
                   amp_2nd:   0.000136   0.004906   0.000042   0.001490   0.000085   0.000001   0.076060
amp_2nd_percent_of_amp_max:   4.372408% 38.079625% 58.665907% 16.404336%  0.816642% 54.848899% 22.120758%
```

```
==============================================================================================================
Case: 3000HzAmpHiFlowLo

probe_Below.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:      40.00      60.00      60.00      60.00      60.00      60.00      60.00
              freq_amp_max:   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:   0.025000   0.016667   0.016667   0.016667   0.016667   0.016667   0.016667
             phase_amp_max:    -101.97     160.18     176.07     -20.77     -92.52     -34.02     -25.88
             phase_amp_2nd:     -70.22      34.51      52.50    -174.28    -127.60     -99.66    -109.31
                   average:   0.969085  -0.002663  -0.003410  -0.000146   2.392955   0.000001   0.019866
                   amp_max:   0.000792   0.000292   0.000518   0.000012   0.002598   0.000000   0.000514
                   amp_2nd:   0.000019   0.000080   0.000097   0.000003   0.000108   0.000000   0.000048
amp_2nd_percent_of_amp_max:   2.422947% 27.576252% 18.778109% 21.922892%  4.157238%  7.997340%  9.405796%
```


Case: 3000HzAmpLoFlowHi

```
==============================================================================================================
Case: 3000HzAmpLoFlowHi

probe_Inlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     120.00     120.00      20.00     120.00     120.00     120.00     120.00
            period_amp_2nd:      30.00      30.00      17.14      30.00      30.00      30.00      30.00
              freq_amp_max:   0.008333   0.008333   0.050000   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:   0.033333   0.033333   0.058333   0.033333   0.033333   0.033333   0.033333
             phase_amp_max:     -19.73      27.41      34.36      87.14     -16.07      37.53      26.47
             phase_amp_2nd:     -39.30     129.59     -97.33      42.76     -34.37     113.98     111.37
                   average:   0.886390   0.508928   0.000027  -0.000000   2.257719   0.000044   0.049325
                   amp_max:   0.000771   0.000913   0.000001   0.000000   0.002000   0.000000   0.000120
                   amp_2nd:   0.000004   0.000007   0.000000   0.000000   0.000009   0.000000   0.000001
amp_2nd_percent_of_amp_max:   0.517891%  0.751506% 20.957822%  0.251577%  0.441298%  0.997363%  0.749672%
```

```
===================================================================================================
Case: 3000HzAmpLoFlowHi

probe_Above.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom         zmom       rhoe          k      omega
           period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
           period_amp_2nd:       30.00      20.00      20.00      30.00      30.00      30.00      30.00
             freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
             freq_amp_2nd:    0.033333   0.050000   0.050000   0.033333   0.033333   0.033333   0.033333
            phase_amp_max:      -17.58     -45.91     173.54     -57.74      -3.05     -28.45     -32.14
            phase_amp_2nd:      171.66     -37.71    -114.18      88.49     171.62     142.51     152.38
                  average:    0.885896   0.509789   0.000824  -0.000000   2.256649   0.000038   0.043118
                  amp_max:    0.000728   0.000622   0.000024   0.000000   0.002687   0.000000   0.000115
                  amp_2nd:    0.000022   0.000001   0.000016   0.000000   0.000070   0.000000   0.000001
amp_2nd_percent_of_amp_max:    3.030593%  0.083642% 65.725281% 17.725772%  2.608697%  0.971004%  1.175782%
```



```
===================================================================================================
Case: 3000HzAmpLoFlowHi

probe_Outlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom         zmom       rhoe          k      omega
           period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
           period_amp_2nd:       30.00      30.00      20.00      30.00      30.00      30.00      30.00
             freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
             freq_amp_2nd:    0.033333   0.033333   0.050000   0.033333   0.033333   0.033333   0.033333
            phase_amp_max:      141.81     -57.53    -110.46    -130.00     -35.20    -143.37    -153.74
            phase_amp_2nd:      -39.96    -130.96      35.40     -59.08     -66.67      -8.99     -12.73
                  average:    0.885215   0.510980   0.000954  -0.000000   2.255174   0.000033   0.038420
                  amp_max:    0.000226   0.000839   0.000017   0.000000   0.000561   0.000000   0.000059
                  amp_2nd:    0.000002   0.000006   0.000002   0.000000   0.000008   0.000000   0.000000
amp_2nd_percent_of_amp_max:    1.028481%  0.747046%  9.780423%  4.215494%  1.442938%  0.693115%  0.655876%
```

```
==========================================================================================
Case: 3000HzAmpLoFlowHi

probe_WithinUp.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho        xmom        ymom        zmom        rhoe           k       omega
            period_amp_max:      120.00      120.00      120.00      120.00      120.00      120.00      120.00
            period_amp_2nd:       60.00       60.00       60.00       60.00       60.00       60.00       60.00
              freq_amp_max:    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333
              freq_amp_2nd:    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667
             phase_amp_max:      144.96       18.68      -31.86      -85.04      169.35     -110.63      -26.54
             phase_amp_2nd:      102.95       -0.25       -8.92      152.28     -149.98     -142.99       -7.51
                   average:    0.872147    0.000628    0.038622    0.000031    2.102173    0.000234    1.586180
                   amp_max:    0.001338    0.000433    0.002715    0.000177    0.000982    0.000046    0.045414
                   amp_2nd:    0.000149    0.000078    0.000259    0.000038    0.000110    0.000004    0.011400
amp_2nd_percent_of_amp_max:   11.155240% 17.952429%  9.544024% 21.586185% 11.194196%  8.310857% 25.101895%
```



```
==========================================================================================
Case: 3000HzAmpLoFlowHi

probe_Within.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho        xmom        ymom        zmom        rhoe           k       omega
            period_amp_max:      120.00      120.00      120.00      120.00      120.00      120.00      120.00
            period_amp_2nd:       60.00       60.00       60.00       60.00       60.00       60.00       60.00
              freq_amp_max:    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333
              freq_amp_2nd:    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667    0.016667
             phase_amp_max:      140.81      -66.60     -127.99      134.21      157.88      -90.94      -81.59
             phase_amp_2nd:      100.68      -28.48     -127.43       70.31     -146.27      124.80      121.96
                   average:    0.866466    0.001604    0.005026    0.000097    2.099868    0.000480    0.482789
                   amp_max:    0.000854    0.002045    0.002771    0.000233    0.001180    0.000041    0.021608
                   amp_2nd:    0.000045    0.000399    0.000304    0.000043    0.000099    0.000009    0.008001
amp_2nd_percent_of_amp_max:    5.297844% 19.526989% 10.975706% 18.496921%  8.346893% 21.842479% 37.028653%
```

```
=============================================================================================================
Case: 3000HzAmpLoFlowHi

probe_WithinDn.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:     120.00     120.00     120.00     120.00     120.00     120.00     120.00
           period_amp_2nd:      30.00      60.00      60.00      60.00      60.00      60.00      60.00
             freq_amp_max:   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
             freq_amp_2nd:   0.033333   0.016667   0.016667   0.016667   0.016667   0.016667   0.016667
            phase_amp_max:     141.39    -163.63     163.01     -45.69     -13.81     -20.61      -2.90
            phase_amp_2nd:      50.79     -29.00    -129.43     145.48     -19.68      79.35     143.03
                  average:   0.857923  -0.007544  -0.123977   0.001906   2.110363   0.001467   3.667771
                  amp_max:   0.001077   0.001139   0.026320   0.000382   0.002971   0.000246   0.234146
                  amp_2nd:   0.000030   0.000135   0.001029   0.000043   0.000173   0.000011   0.023314
amp_2nd_percent_of_amp_max:   2.814087% 11.819338%  3.910348% 11.382634%  5.840207%  4.412401%  9.956875%


=============================================================================================================
Case: 3000HzAmpLoFlowHi

probe_NearWallUp.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:     120.00     120.00     120.00     120.00     120.00     120.00     120.00
           period_amp_2nd:      30.00      20.00      20.00      60.00      30.00      20.00      20.00
             freq_amp_max:   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
             freq_amp_2nd:   0.033333   0.050000   0.050000   0.016667   0.033333   0.050000   0.050000
            phase_amp_max:      -6.83     -20.90    -123.02     -11.20      -4.11     -30.09     -45.80
            phase_amp_2nd:     -11.78     150.56      58.36      18.39     -11.54    -158.11      17.57
                  average:   0.853318   0.185797   0.000025  -0.000106   2.131904   0.003059  14.448084
                  amp_max:   0.000588   0.000723   0.000007   0.000032   0.002300   0.000013   0.020696
                  amp_2nd:   0.000018   0.000009   0.000001   0.000001   0.000062   0.000000   0.000654
amp_2nd_percent_of_amp_max:   3.104026%  1.181866% 17.292582%  2.242315%  2.695203%  1.265040%  3.158974%
```

```
==========================================================================================
Case: 3000HzAmpLoFlowHi

probe_NearWallDn.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho        xmom        ymom        zmom        rhoe           k       omega
            period_amp_max:      120.00      120.00      120.00      120.00      120.00      120.00      120.00
            period_amp_2nd:       30.00       60.00       30.00       30.00       30.00       60.00       60.00
              freq_amp_max:    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333
              freq_amp_2nd:    0.033333    0.016667    0.033333    0.033333    0.033333    0.016667    0.016667
             phase_amp_max:        0.99      -29.94      -34.41      169.45       -4.92      -34.67      -34.69
             phase_amp_2nd:        4.14       -7.83      -95.75       57.17        1.25       -3.23      -10.34
                   average:    0.853199    0.170268   -0.000014    0.001649    2.126542    0.002737   13.796579
                   amp_max:    0.000913    0.003092    0.000021    0.001083    0.003660    0.000042    0.097706
                   amp_2nd:    0.000019    0.000068    0.000001    0.000025    0.000061    0.000001    0.002080
amp_2nd_percent_of_amp_max:    2.056719%  2.211431%  5.898263%  2.321718%  1.655441%  2.912414%  2.129231%


==========================================================================================
Case: 3000HzAmpLoFlowHi

probe_Below.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho        xmom        ymom        zmom        rhoe           k       omega
            period_amp_max:      120.00      120.00      120.00      120.00      120.00      120.00      120.00
            period_amp_2nd:       60.00       60.00       60.00       60.00       15.00       60.00       60.00
              freq_amp_max:    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333    0.008333
              freq_amp_2nd:    0.016667    0.016667    0.016667    0.016667    0.066667    0.016667    0.016667
             phase_amp_max:     -118.67      121.80      126.25      -32.73      -90.97       81.34      -39.76
             phase_amp_2nd:      -52.75       65.66       67.29     -107.92      -88.77       89.95      -84.92
                   average:    0.883509   -0.000423    0.001618   -0.000025    2.105602    0.000003    0.004843
                   amp_max:    0.000133    0.000106    0.000111    0.000002    0.000419    0.000000    0.000005
                   amp_2nd:    0.000017    0.000017    0.000017    0.000000    0.000017    0.000000    0.000004
amp_2nd_percent_of_amp_max:   13.004567% 16.543784% 15.098437% 14.192825%  4.139340% 37.143115% 75.718980%
```

Case: 3000HzAmpLoFlowLo

```
===============================================================================
Case: 3000HzAmpLoFlowLo

probe_Inlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
             period_amp_max:    120.00     120.00     120.00     120.00     120.00     120.00     120.00
             period_amp_2nd:     24.00      24.00      13.33      24.00      24.00      24.00      24.00
               freq_amp_max:  0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
               freq_amp_2nd:  0.041667   0.041667   0.075000   0.041667   0.041667   0.041667   0.041667
              phase_amp_max:     -4.43      34.94     140.86      99.57      -2.82      49.89      34.50
              phase_amp_2nd:      6.98     166.84     123.23    -108.59      17.78     145.60     144.86
                    average:  0.969659   0.283930   0.000016  -0.000000   2.436024   0.000012   0.022719
                    amp_max:  0.000966   0.000411   0.000001   0.000000   0.002432   0.000000   0.000046
                    amp_2nd:  0.000001   0.000005   0.000000   0.000000   0.000003   0.000000   0.000001
amp_2nd_percent_of_amp_max:   0.124801%  1.245025% 17.979158%  1.768000%  0.113448%  1.533001%  1.164924%

===============================================================================
Case: 3000HzAmpLoFlowLo

probe_Above.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
             period_amp_max:    120.00     120.00     120.00     120.00     120.00     120.00     120.00
             period_amp_2nd:     24.00      24.00      60.00      24.00      24.00      24.00      24.00
               freq_amp_max:  0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
               freq_amp_2nd:  0.041667   0.041667   0.016667   0.041667   0.041667   0.041667   0.041667
              phase_amp_max:     30.21     -67.56     167.69     -91.98       2.96     -81.75     -87.68
              phase_amp_2nd:    123.59      96.17      60.78      48.73     123.49     124.24     124.17
                    average:  0.969542   0.284451   0.000372  -0.000000   2.435776   0.000011   0.020315
                    amp_max:  0.000398   0.000457   0.000024   0.000000   0.002070   0.000000   0.000013
                    amp_2nd:  0.000017   0.000001   0.000002   0.000000   0.000060   0.000000   0.000001
amp_2nd_percent_of_amp_max:   4.376908%  0.172759%  9.868753% 12.228102%  2.880953%  2.326156%  3.990991%
```

```
===================================================================================================================
Case: 3000HzAmpLoFlowLo

probe_Outlet.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                      rho       xmom       ymom        zmom        rhoe           k       omega
            period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:       24.00      24.00      60.00      24.00      24.00      60.00      60.00
              freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:    0.041667   0.041667   0.016667   0.041667   0.041667   0.016667   0.016667
             phase_amp_max:      -34.92     -67.74      96.65    -155.88     -38.88      45.63      26.59
             phase_amp_2nd:     -155.60     112.92      40.11      38.88    -175.41      15.67      14.48
                   average:    0.969429   0.284942   0.000434   0.000000   2.435537   0.000010   0.018426
                   amp_max:    0.000299   0.000921   0.000008   0.000000   0.000301   0.000000   0.000017
                   amp_2nd:    0.000001   0.000005   0.000001   0.000000   0.000004   0.000000   0.000000
amp_2nd_percent_of_amp_max:    0.389627%  0.523810%  7.411559% 22.241097%  1.375306%  0.747528%  0.681650%

===================================================================================================================
Case: 3000HzAmpLoFlowLo

probe_WithinUp.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                      rho       xmom       ymom        zmom        rhoe           k       omega
            period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:       60.00      60.00      40.00      60.00      60.00      60.00      60.00
              freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:    0.016667   0.016667   0.025000   0.016667   0.016667   0.016667   0.016667
             phase_amp_max:       16.48    -121.65    -140.77      62.29     111.35     133.16    -163.09
             phase_amp_2nd:     -159.25    -172.30     -44.06       5.87      67.28     -11.09     162.71
                   average:    0.963160   0.000589   0.019690  -0.000112   2.392156   0.000003   1.463586
                   amp_max:    0.000231   0.000466   0.005523   0.000063   0.000742   0.000001   0.084429
                   amp_2nd:    0.000041   0.000108   0.000167   0.000033   0.000157   0.000000   0.026296
amp_2nd_percent_of_amp_max:   17.925341% 23.289733%  3.022117% 52.970541% 21.156374% 24.224908% 31.145251%
```

```
===========================================================================================================
Case: 3000HzAmpLoFlowLo

probe_Within.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom         zmom       rhoe          k      omega
            period_amp_max:      120.00     120.00     120.00       60.00     120.00     120.00     120.00
            period_amp_2nd:       60.00      60.00      60.00       40.00      40.00      40.00      40.00
              freq_amp_max:    0.008333   0.008333   0.008333   0.016667   0.008333   0.008333   0.008333
              freq_amp_2nd:    0.016667   0.016667   0.016667   0.025000   0.025000   0.025000   0.025000
             phase_amp_max:       57.57    -178.00     166.32    -145.42      94.87     -66.10     -44.05
             phase_amp_2nd:      120.76     178.29      -9.55    -123.63     105.64     -69.05     -42.00
                   average:    0.961041   0.001169   0.000117   0.000429   2.391559   0.000008   0.215467
                   amp_max:    0.000312   0.006898   0.003413   0.000172   0.000963   0.000003   0.067939
                   amp_2nd:    0.000179   0.001461   0.001051   0.000072   0.000070   0.000001   0.016708
amp_2nd_percent_of_amp_max:   57.309726% 21.173793% 30.806410% 41.950322%  7.284617% 21.034118% 24.593151%

===========================================================================================================
Case: 3000HzAmpLoFlowLo

probe_WithinDn.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom         zmom       rhoe          k      omega
            period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:       60.00      60.00      60.00      60.00      60.00      60.00      60.00
              freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:    0.016667   0.016667   0.016667   0.016667   0.016667   0.016667   0.016667
             phase_amp_max:      111.14     147.93     121.12     -72.90     -28.56     -69.46     -39.43
             phase_amp_2nd:      -99.49     166.33      99.96     -53.47     -87.90     -73.30      15.30
                   average:    0.959948  -0.003193  -0.048398   0.000306   2.393519   0.000012   2.140840
                   amp_max:    0.000447   0.003260   0.035012   0.000442   0.001410   0.000009   0.405354
                   amp_2nd:    0.000104   0.000764   0.005105   0.000045   0.000386   0.000001   0.116618
amp_2nd_percent_of_amp_max:   23.212635% 23.439653% 14.579751% 10.104317% 27.403833% 14.377937% 28.769449%
```

==

Case: 3000HzAmpLoFlowLo

probe_NearWallUp.dat

Number of time steps per cycle: 600
Number of cycles in file : 5
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	120.00	120.00	120.00	120.00	120.00	120.00	120.00
period_amp_2nd:	24.00	60.00	24.00	60.00	24.00	60.00	60.00
freq_amp_max:	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333
freq_amp_2nd:	0.041667	0.016667	0.041667	0.016667	0.041667	0.016667	0.016667
phase_amp_max:	9.61	-46.35	-133.33	-30.33	6.48	-55.34	-157.15
phase_amp_2nd:	-54.77	-159.88	-140.67	-158.43	-53.24	112.49	-61.22
average:	0.959237	0.036098	0.000014	-0.000059	2.394625	0.000002	8.229490
amp_max:	0.000537	0.000770	0.000004	0.000088	0.001840	0.000000	0.030308
amp_2nd:	0.000014	0.000011	0.000001	0.000003	0.000048	0.000000	0.000357
amp_2nd_percent_of_amp_max:	2.650334%	1.388858%	18.182984%	2.990157%	2.583855%	5.322082%	1.178153%

==

Case: 3000HzAmpLoFlowLo

probe_NearWallDn.dat

Number of time steps per cycle: 600
Number of cycles in file : 5
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	120.00	120.00	120.00	120.00	120.00	120.00	120.00
period_amp_2nd:	24.00	60.00	60.00	60.00	24.00	60.00	60.00
freq_amp_max:	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333	0.008333
freq_amp_2nd:	0.041667	0.016667	0.016667	0.016667	0.041667	0.016667	0.016667
phase_amp_max:	-8.92	-74.94	-29.80	135.57	-11.22	-62.21	177.44
phase_amp_2nd:	-47.05	-153.87	-110.63	-122.32	-42.38	-140.17	-135.26
average:	0.959537	0.032542	-0.000004	0.000426	2.394282	0.000006	8.010273
amp_max:	0.000725	0.004569	0.000029	0.002416	0.002481	0.000000	0.161697
amp_2nd:	0.000015	0.000292	0.000001	0.000202	0.000049	0.000000	0.008987
amp_2nd_percent_of_amp_max:	2.106535%	6.399526%	4.691776%	8.376438%	1.962509%	19.963329%	5.558116%

```
==============================================================================================================
Case: 3000HzAmpLoFlowLo

probe_Below.dat

Number of time steps per cycle: 600
Number of cycles in file      : 5
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:      120.00     120.00     120.00     120.00     120.00     120.00     120.00
            period_amp_2nd:       60.00      60.00      13.33      60.00      13.33      60.00      60.00
              freq_amp_max:    0.008333   0.008333   0.008333   0.008333   0.008333   0.008333   0.008333
              freq_amp_2nd:    0.016667   0.016667   0.075000   0.016667   0.075000   0.016667   0.016667
             phase_amp_max:     -101.93     177.73     165.47     154.14    -103.13     -94.34      95.64
             phase_amp_2nd:      153.48      77.32    -159.66      33.27     111.34     -88.50      90.62
                   average:    0.969336   0.000240   0.000339  -0.000003   2.393034   0.000001   0.001967
                   amp_max:    0.000189   0.000008   0.000087   0.000001   0.000649   0.000000   0.000005
                   amp_2nd:    0.000005   0.000005   0.000012   0.000000   0.000016   0.000000   0.000003
amp_2nd_percent_of_amp_max:    2.579099% 62.920245% 14.078332%  8.401882%  2.416712% 34.115776% 59.851590%
```

Case: 400HzAmpHiFlowHi

```
==============================================================================================================
Case: 400HzAmpHiFlowHi

probe_Inlet.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:       31.95     -21.55     -87.61     118.00      24.88     -27.41     -22.00
             phase_amp_2nd:      148.18      99.80      62.47    -143.68     144.98      15.18      83.27
                   average:    0.886362   0.508962   0.000026  -0.000000   2.257658   0.000044   0.049331
                   amp_max:    0.002128   0.005447   0.000001   0.000000   0.005792   0.000001   0.000693
                   amp_2nd:    0.000003   0.000012   0.000000   0.000000   0.000006   0.000000   0.000001
amp_2nd_percent_of_amp_max:    0.125785%  0.218012%  2.671361%  1.400794%  0.108774%  0.064408%  0.161533%
```

```
=====================================================================================================
Case: 400HzAmpHiFlowHi

probe_Above.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:       15.04     -23.55    -101.31      38.27       9.74     -44.42     -39.31
             phase_amp_2nd:      107.66      95.28      67.89      91.16     108.46      10.39      47.23
                   average:    0.885886   0.509790   0.000793  -0.000000   2.256628   0.000038   0.043125
                   amp_max:    0.001393   0.005634   0.000030   0.000000   0.004021   0.000001   0.000565
                   amp_2nd:    0.000002   0.000013   0.000001   0.000000   0.000004   0.000000   0.000001
amp_2nd_percent_of_amp_max:    0.158912%  0.231532%  2.994201%  0.371979%  0.096074%  0.129815%  0.232856%

=====================================================================================================
Case: 400HzAmpHiFlowHi

probe_Outlet.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:      -24.81     -25.11     -89.13     -26.29     -22.30     -59.96     -55.20
             phase_amp_2nd:       40.35      91.65     -24.89     128.52      26.38     -10.66      16.00
                   average:    0.885212   0.510964   0.000943  -0.000000   2.255170   0.000033   0.038423
                   amp_max:    0.001012   0.005700   0.000010   0.000000   0.003129   0.000001   0.000498
                   amp_2nd:    0.000002   0.000013   0.000000   0.000000   0.000004   0.000000   0.000001
amp_2nd_percent_of_amp_max:    0.222308%  0.232842%  1.938128%  1.350517%  0.139327%  0.201373%  0.295653%
```

```
============================================================================================================
Case: 400HzAmpHiFlowHi

probe_WithinUp.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     450.00
           period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     300.00
             freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.002222
             freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.003333
            phase_amp_max:       87.83    -177.56      41.54      64.77    -127.44      39.29    -121.99
            phase_amp_2nd:     -163.52    -106.65    -112.56     106.67      77.71    -117.47      88.91
                  average:    0.817837   0.001017   0.040911   0.000073   2.099939   0.000276   1.868117
                  amp_max:    0.000803   0.000058   0.001214   0.000102   0.000759   0.000040   0.009140
                  amp_2nd:    0.000191   0.000045   0.000456   0.000018   0.000099   0.000003   0.001330
amp_2nd_percent_of_amp_max:   23.745238% 76.486621% 37.562183% 17.379090% 13.010094%  8.759085% 14.553329%


============================================================================================================
Case: 400HzAmpHiFlowHi

probe_Within.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:      172.99     -13.06     -86.19    -123.30    -131.01      49.95      48.28
            phase_amp_2nd:      116.23    -107.53      83.59     -27.04      73.98    -105.30    -100.01
                  average:    0.819953   0.002747   0.003477  -0.000134   2.097406   0.000490   0.461163
                  amp_max:    0.001830   0.000154   0.000470   0.000311   0.000927   0.000051   0.033697
                  amp_2nd:    0.000124   0.000116   0.000065   0.000007   0.000125   0.000004   0.001815
amp_2nd_percent_of_amp_max:    6.797950% 75.231569% 13.854759%  2.119959% 13.468792%  8.258456%  5.386070%
```

==

Case: 400HzAmpHiFlowHi

probe_WithinDn.dat

Number of time steps per cycle: 4500
Number of cycles in file   : 3
Number of cycles used in fft : 1
Timestep size   : 0.2
Nyquist criterion   : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	900.00	900.00	900.00	900.00	900.00	900.00	900.00
period_amp_2nd:	450.00	450.00	450.00	450.00	450.00	450.00	450.00
freq_amp_max:	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111
freq_amp_2nd:	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222
phase_amp_max:	73.39	-122.79	-125.48	42.05	56.25	50.14	47.01
phase_amp_2nd:	162.98	92.56	80.27	-108.40	125.00	-81.51	-88.98
average:	0.833410	-0.007874	-0.140998	0.002196	2.111129	0.001651	3.857818
amp_max:	0.001804	0.000685	0.021574	0.000593	0.003086	0.000184	0.170713
amp_2nd:	0.000052	0.000037	0.000989	0.000034	0.000090	0.000012	0.012966
amp_2nd_percent_of_amp_max:	2.890270%	5.461924%	4.584191%	5.676621%	2.903783%	6.713839%	7.595183%

==

Case: 400HzAmpHiFlowHi

probe_NearWallUp.dat

Number of time steps per cycle: 4500
Number of cycles in file   : 3
Number of cycles used in fft : 1
Timestep size   : 0.2
Nyquist criterion   : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	900.00	900.00	900.00	900.00	900.00	900.00	900.00
period_amp_2nd:	450.00	300.00	450.00	450.00	450.00	450.00	450.00
freq_amp_max:	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111
freq_amp_2nd:	0.002222	0.003333	0.002222	0.002222	0.002222	0.002222	0.002222
phase_amp_max:	34.78	-16.30	-82.16	-121.32	44.15	-20.38	-27.69
phase_amp_2nd:	89.18	-89.54	70.30	72.25	99.78	68.45	63.91
average:	0.853183	0.185153	0.000023	0.000055	2.131507	0.003045	14.615655
amp_max:	0.000771	0.002956	0.000005	0.000025	0.002427	0.000083	0.102526
amp_2nd:	0.000006	0.000004	0.000000	0.000001	0.000016	0.000000	0.000278
amp_2nd_percent_of_amp_max:	0.782934%	0.150374%	3.002403%	4.316950%	0.673080%	0.153702%	0.271183%

```
====================================================================================================
Case: 400HzAmpHiFlowHi

probe_NearWallDn.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:       45.17      23.33      52.27      61.43      51.39       7.45      13.58
            phase_amp_2nd:     -124.32    -110.69     -85.08     -91.57    -104.68    -105.66    -117.93
                  average:    0.849870   0.170750  -0.000016  -0.000821   2.127138   0.002720  14.009068
                  amp_max:    0.001320   0.004291   0.000008   0.000786   0.003387   0.000083   0.145333
                  amp_2nd:    0.000014   0.000104   0.000001   0.000041   0.000035   0.000001   0.003026
amp_2nd_percent_of_amp_max:    1.060060%  2.419254%  6.300015%  5.156512%  1.037039%  1.336861%  2.082096%
```



```
====================================================================================================
Case: 400HzAmpHiFlowHi

probe_Below.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:      -75.14      72.58    -126.36    -144.70      56.14     -93.67     -87.47
            phase_amp_2nd:      -70.71     109.30    -139.19    -106.37      91.51     -93.44     -80.13
                  average:    0.811868  -0.001270   0.000482  -0.000013   2.104417   0.000001   0.001302
                  amp_max:    0.000105   0.000128   0.000092   0.000017   0.000077   0.000000   0.000103
                  amp_2nd:    0.000030   0.000023   0.000005   0.000001   0.000043   0.000000   0.000023
amp_2nd_percent_of_amp_max:   28.492617% 18.230033%  5.656395%  5.466888% 55.783800% 14.305673% 21.831701%
```

Case: 400HzAmpHiFlowLo

```
===============================================================================
Case: 400HzAmpHiFlowLo

probe_Inlet.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00      900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00      450.00     450.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111    0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222    0.002222   0.002222   0.002222   0.002222
             phase_amp_max:      27.98     -40.89    -139.64       73.71      22.54     -43.89     -41.43
             phase_amp_2nd:     120.27      39.79     -83.10      177.44     120.38     -55.59       5.74
                   average:   0.969659   0.283852   0.000015   -0.000000   2.436024   0.000012   0.022714
                   amp_max:   0.002873   0.009288   0.000001    0.000000   0.007455   0.000001   0.000992
                   amp_2nd:   0.000013   0.000043   0.000000    0.000000   0.000028   0.000000   0.000004
amp_2nd_percent_of_amp_max:   0.460091%  0.459353%  4.360821%  1.999974%  0.377536%  0.614330%  0.401815%

===============================================================================
Case: 400HzAmpHiFlowLo

probe_Above.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00      900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00      450.00     450.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111    0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222    0.002222   0.002222   0.002222   0.002222
             phase_amp_max:       6.54     -42.38    -147.96      -60.73       7.27     -71.95     -69.34
             phase_amp_2nd:      53.98      33.08    -101.25        6.87     114.42     -68.55     -41.08
                   average:   0.969535   0.284373   0.000372   -0.000000   2.435770   0.000011   0.020312
                   amp_max:   0.001701   0.009545   0.000070    0.000000   0.004490   0.000001   0.000844
                   amp_2nd:   0.000008   0.000044   0.000004    0.000000   0.000005   0.000000   0.000009
amp_2nd_percent_of_amp_max:   0.496663%  0.461648%  5.912327% 10.590817%  0.108112%  1.046085%  1.072685%
```

```
===========================================================================================================
Case: 400HzAmpHiFlowLo

probe_Outlet.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     450.00     900.00     900.00     900.00     900.00
           period_amp_2nd:      450.00     450.00     300.00     300.00     180.00     300.00     300.00
             freq_amp_max:    0.001111   0.001111   0.002222   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.002222   0.002222   0.003333   0.003333   0.005556   0.003333   0.003333
            phase_amp_max:      -50.70     -43.38     177.46     -40.24     -38.90     -97.86     -94.46
            phase_amp_2nd:      -31.44      27.98    -178.50     111.90     -24.47      -7.06      -6.07
                  average:    0.969423   0.284860   0.000426   0.000000   2.435534   0.000010   0.018424
                  amp_max:    0.001099   0.009612   0.000004   0.000000   0.002788   0.000001   0.000747
                  amp_2nd:    0.000016   0.000036   0.000002   0.000000   0.000000   0.000000   0.000000
amp_2nd_percent_of_amp_max:    1.424465%  0.376587% 42.767733%  0.798354%  0.011932%  0.027466%  0.041101%

===========================================================================================================
Case: 400HzAmpHiFlowLo

probe_WithinUp.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:      300.00     300.00     300.00     450.00     450.00     300.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.003333   0.003333   0.003333   0.002222   0.002222   0.003333   0.002222
            phase_amp_max:      152.48      44.09       7.25      43.97    -150.59      -8.85      -5.82
            phase_amp_2nd:      -17.98    -133.86    -138.46      30.51    -105.06     163.45     158.12
                  average:    0.964501   0.000349   0.012933  -0.000016   2.392337   0.000002   1.187619
                  amp_max:    0.001157   0.000308   0.013163   0.000133   0.000917   0.000002   0.587142
                  amp_2nd:    0.000243   0.000132   0.002643   0.000106   0.000364   0.000000   0.215272
amp_2nd_percent_of_amp_max:   21.011883% 42.872176% 20.080011% 79.881093% 39.713213% 16.244846% 36.664438%
```

```
======================================================================================================
Case: 400HzAmpHiFlowLo

probe_Within.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:       900.00     900.00     900.00     450.00     900.00     900.00     900.00
           period_amp_2nd:       450.00     300.00     450.00     225.00     300.00     180.00     300.00
             freq_amp_max:     0.001111   0.001111   0.001111   0.002222   0.001111   0.001111   0.001111
             freq_amp_2nd:     0.002222   0.003333   0.002222   0.004444   0.003333   0.005556   0.003333
            phase_amp_max:       178.18     -49.21    -153.32    -124.67    -157.66      23.44      35.71
            phase_amp_2nd:         5.45    -167.41      41.76      54.85      55.28    -164.42     -26.40
                  average:     0.964060   0.000362   0.004548   0.000124   2.391958   0.000004   0.134052
                  amp_max:     0.002992   0.001954   0.007420   0.000385   0.001402   0.000003   0.068163
                  amp_2nd:     0.001412   0.001854   0.003886   0.000139   0.000222   0.000001   0.028711
amp_2nd_percent_of_amp_max:   47.180690% 94.880350% 52.372925% 36.226442% 15.838870% 32.870394% 42.120278%
```



```
======================================================================================================
Case: 400HzAmpHiFlowLo

probe_WithinDn.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:       900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:       450.00     300.00     450.00     450.00     450.00     300.00     450.00
             freq_amp_max:     0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:     0.002222   0.003333   0.002222   0.002222   0.002222   0.003333   0.002222
            phase_amp_max:       172.95    -142.34    -147.09       3.15      43.81      26.14      18.79
            phase_amp_2nd:       -25.60     106.87     -95.14      27.24      80.33     -95.61    -149.23
                  average:     0.961196  -0.002628  -0.045529   0.000571   2.394444   0.000010   1.737467
                  amp_max:     0.001956   0.003316   0.063115   0.000828   0.002520   0.000013   1.116763
                  amp_2nd:     0.000710   0.000628   0.011424   0.000325   0.000996   0.000002   0.232581
amp_2nd_percent_of_amp_max:   36.315022% 18.934911% 18.100891% 39.231284% 39.505736% 14.476941% 20.826329%
```

```
==========================================================================================
Case: 400HzAmpHiFlowLo

probe_NearWallUp.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:      300.00     300.00     300.00     450.00     300.00     450.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.003333   0.003333   0.003333   0.002222   0.003333   0.002222   0.002222
            phase_amp_max:       39.54       0.18    -132.11    -137.62      44.04     -82.49     -18.76
            phase_amp_2nd:       77.55    -127.18      51.73     -92.01      83.23    -158.69     131.01
                  average:    0.959246   0.035735   0.000008   0.000049   2.394730   0.000002   8.340451
                  amp_max:    0.000802   0.002970   0.000009   0.000135   0.003246   0.000000   0.188100
                  amp_2nd:    0.000006   0.000044   0.000000   0.000006   0.000021   0.000000   0.004818
amp_2nd_percent_of_amp_max:    0.799537%  1.490403%  3.510667%  4.444581%  0.631959%  4.803725%  2.561226%
```



```
==========================================================================================
Case: 400HzAmpHiFlowLo

probe_NearWallDn.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:      450.00     450.00     300.00     450.00     300.00     450.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.002222   0.002222   0.003333   0.002222   0.003333   0.002222   0.002222
            phase_amp_max:       50.34      25.02      46.64      40.92      42.61     -85.73       4.52
            phase_amp_2nd:     -106.16      88.23     -84.38     -96.66    -124.98      97.08     178.26
                  average:    0.959684   0.032061   0.000001  -0.000706   2.394130   0.000005   8.022517
                  amp_max:    0.001212   0.011293   0.000024   0.002796   0.004654   0.000001   0.793731
                  amp_2nd:    0.000060   0.000713   0.000002   0.000179   0.000042   0.000000   0.040052
amp_2nd_percent_of_amp_max:    4.919082%  6.317719%  6.473615%  6.398305%  0.907854% 20.335871%  5.046092%
```

```
=====================================================================================================
Case: 400HzAmpHiFlowLo

probe_Below.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:     450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:     -16.01     -29.22    -119.00    -162.91     -44.06     -61.11     -53.26
            phase_amp_2nd:      18.08     -10.35    -114.80    -160.66      22.69     -51.48     -34.58
                  average:   0.969640  -0.000166   0.000029  -0.000006   2.393269   0.000000   0.001131
                  amp_max:   0.000064   0.000094   0.000151   0.000012   0.000142   0.000000   0.000044
                  amp_2nd:   0.000016   0.000036   0.000026   0.000004   0.000006   0.000000   0.000009
amp_2nd_percent_of_amp_max:  25.739155% 38.346727% 17.376380% 35.990458%  3.953768% 21.455547% 19.439020%
```


Case: 400HzAmpLoFlowHi

```
=====================================================================================================
Case: 400HzAmpLoFlowHi

probe_Inlet.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:     450.00     300.00     450.00     450.00     450.00     450.00     300.00
             freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:   0.002222   0.003333   0.002222   0.002222   0.002222   0.002222   0.003333
            phase_amp_max:      32.00     -21.59     -87.46     118.01      24.93     -27.46     -22.04
            phase_amp_2nd:     107.17     -89.67      86.66    -143.35     107.33     -74.21     -89.67
                  average:   0.886361   0.508979   0.000026  -0.000000   2.257655   0.000044   0.049333
                  amp_max:   0.000532   0.001362   0.000000   0.000000   0.001449   0.000000   0.000173
                  amp_2nd:   0.000000   0.000000   0.000000   0.000000   0.000001   0.000000   0.000000
amp_2nd_percent_of_amp_max:   0.092847%  0.034902%  5.926849%  0.351285%  0.076462%  0.059353%  0.035228%
```

```
=====================================================================================================
Case: 400HzAmpLoFlowHi

probe_Above.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00      900.00     900.00     900.00     900.00
           period_amp_2nd:      450.00     450.00     450.00       20.45     450.00     450.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111    0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.002222   0.002222   0.002222    0.048889   0.002222   0.002222   0.002222
            phase_amp_max:       15.08     -23.56    -102.54       38.27       9.76     -44.46     -39.35
            phase_amp_2nd:       98.90      97.28      88.07      -33.99      98.27     -63.68     -25.94
                  average:    0.885887   0.509807   0.000793   -0.000000   2.256629   0.000038   0.043127
                  amp_max:    0.000348   0.001409   0.000007    0.000000   0.001005   0.000000   0.000141
                  amp_2nd:    0.000000   0.000001   0.000000    0.000000   0.000001   0.000000   0.000000
amp_2nd_percent_of_amp_max:    0.082107%  0.039087%  6.898265%  0.124483%  0.055714%  0.073961%  0.044843%
```



```
=====================================================================================================
Case: 400HzAmpLoFlowHi

probe_Outlet.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
           period_amp_max:      900.00     900.00     900.00      900.00     900.00     900.00     900.00
           period_amp_2nd:      450.00     450.00     450.00      450.00     450.00     450.00     450.00
             freq_amp_max:    0.001111   0.001111   0.001111    0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:    0.002222   0.002222   0.002222    0.002222   0.002222   0.002222   0.002222
            phase_amp_max:      -24.81     -25.11     -89.38      -27.02     -22.30     -59.99     -55.22
            phase_amp_2nd:       39.31      91.56      82.49     -109.33      24.30     -58.97     -31.67
                  average:    0.885214   0.510981   0.000943   -0.000000   2.255172   0.000033   0.038424
                  amp_max:    0.000253   0.001425   0.000002    0.000000   0.000782   0.000000   0.000125
                  amp_2nd:    0.000000   0.000001   0.000000    0.000000   0.000000   0.000000   0.000000
amp_2nd_percent_of_amp_max:    0.054721%  0.058179%  2.330817%  0.618585%  0.034381%  0.097967%  0.084573%
```

==
Case: 400HzAmpLoFlowHi

probe_WithinUp.dat

Number of time steps per cycle: 4500
Number of cycles in file : 3
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	900.00	900.00	900.00	900.00	900.00	900.00	900.00
period_amp_2nd:	450.00	450.00	450.00	300.00	450.00	450.00	450.00
freq_amp_max:	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111
freq_amp_2nd:	0.002222	0.002222	0.002222	0.003333	0.002222	0.002222	0.002222
phase_amp_max:	92.76	-178.15	38.31	63.97	-150.96	34.71	110.57
phase_amp_2nd:	97.48	-142.05	-114.01	-85.70	89.02	-98.26	-130.30
average:	0.818472	0.001073	0.041443	0.000062	2.099925	0.000278	1.880057
amp_max:	0.000378	0.000017	0.000271	0.000021	0.000135	0.000009	0.001451
amp_2nd:	0.000106	0.000002	0.000036	0.000001	0.000059	0.000001	0.000586
amp_2nd_percent_of_amp_max:	28.180665%	9.388755%	13.156891%	6.777237%	43.688009%	8.504106%	40.356653%

==
Case: 400HzAmpLoFlowHi

probe_Within.dat

Number of time steps per cycle: 4500
Number of cycles in file : 3
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	900.00	900.00	900.00	900.00	900.00	900.00	900.00
period_amp_2nd:	450.00	450.00	450.00	450.00	450.00	450.00	450.00
freq_amp_max:	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111
freq_amp_2nd:	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222
phase_amp_max:	149.93	-29.73	-84.71	-126.81	-151.31	46.21	44.34
phase_amp_2nd:	92.08	-117.81	83.33	86.05	88.15	-94.58	-92.29
average:	0.820277	0.002886	0.003413	-0.000128	2.097362	0.000493	0.462240
amp_max:	0.000569	0.000036	0.000109	0.000071	0.000176	0.000012	0.007772
amp_2nd:	0.000146	0.000007	0.000008	0.000005	0.000063	0.000001	0.000642
amp_2nd_percent_of_amp_max:	25.662889%	18.029539%	7.349179%	6.987272%	35.728483%	9.366968%	8.263299%

```
====================================================================================================
Case: 400HzAmpLoFlowHi

probe_WithinDn.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00     450.00     300.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.003333   0.002222   0.002222
             phase_amp_max:      77.36    -126.62    -129.46      36.35      55.34      45.87      42.29
             phase_amp_2nd:      94.12      89.70      88.47     -92.66     -86.54     -88.95     -90.78
                   average:   0.833610  -0.007898  -0.141421   0.002219   2.111027   0.001659   3.868323
                   amp_max:   0.000507   0.000157   0.004942   0.000139   0.000760   0.000042   0.039181
                   amp_2nd:   0.000039   0.000014   0.000411   0.000013   0.000009   0.000004   0.003619
amp_2nd_percent_of_amp_max:   7.669391%  8.641968%  8.324012%  9.275417%  1.216628%  8.645618%  9.237653%

====================================================================================================
Case: 400HzAmpLoFlowHi

probe_NearWallUp.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:      35.85     -17.06     -81.74    -124.66      44.85     -20.73     -28.19
             phase_amp_2nd:      90.06     -91.64      87.15      87.83      91.61     -87.77     -86.29
                   average:   0.853183   0.185174   0.000023   0.000055   2.131503   0.003045  14.616425
                   amp_max:   0.000195   0.000742   0.000001   0.000006   0.000614   0.000021   0.025756
                   amp_2nd:   0.000003   0.000006   0.000000   0.000000   0.000007   0.000000   0.000135
amp_2nd_percent_of_amp_max:   1.532602%  0.827924%  4.754219%  8.560662%  1.169304%  0.338817%  0.524590%
```

```
==========================================================================================================
Case: 400HzAmpLoFlowHi

probe_NearWallDn.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:      45.05      19.36      48.10      58.05      50.10       4.92       8.88
             phase_amp_2nd:     -97.78     -92.23     -90.02     -90.58     -91.50     -91.56     -92.18
                   average:   0.849911   0.170794  -0.000016  -0.000801   2.127147   0.002721  14.010491
                   amp_max:   0.000326   0.001046   0.000002   0.000178   0.000825   0.000021   0.035823
                   amp_2nd:   0.000003   0.000055   0.000000   0.000016   0.000020   0.000001   0.002023
amp_2nd_percent_of_amp_max:   0.934746%  5.224640%  9.007156%  8.752319%  2.451661%  3.125304%  5.647642%
```



```
==========================================================================================================
Case: 400HzAmpLoFlowHi

probe_Below.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00     300.00     450.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222   0.003333   0.002222   0.002222   0.002222
             phase_amp_max:     -84.74      78.33    -116.86    -148.56      83.35     -99.41    -100.47
             phase_amp_2nd:     -88.63      92.26     -93.32      93.24      90.76     -93.29     -92.13
                   average:   0.812001  -0.001222   0.000511  -0.000012   2.104443   0.000001   0.001108
                   amp_max:   0.000073   0.000052   0.000028   0.000004   0.000080   0.000000   0.000026
                   amp_2nd:   0.000031   0.000014   0.000003   0.000000   0.000042   0.000000   0.000007
amp_2nd_percent_of_amp_max:  41.925749% 27.304557% 12.561908%  2.867045% 52.976166% 17.783838% 25.893528%
```

Case: 400HzAmpLoFlowLo

```
==============================================================================================
Case: 400HzAmpLoFlowLo

probe_Inlet.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:      28.01     -40.84    -142.80      73.72      22.56     -43.83     -41.38
             phase_amp_2nd:     116.75      47.64     -35.28     178.94     116.87     -58.79      11.62
                   average:   0.969656   0.283936   0.000015  -0.000000   2.436019   0.000012   0.022721
                   amp_max:   0.000717   0.002324   0.000000   0.000000   0.001862   0.000000   0.000248
                   amp_2nd:   0.000001   0.000003   0.000000   0.000000   0.000002   0.000000   0.000000
amp_2nd_percent_of_amp_max:   0.105952%  0.109219%  2.840014%  0.507348%  0.087056%  0.139054%  0.087350%

==============================================================================================
Case: 400HzAmpLoFlowLo

probe_Above.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:     450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:       6.55     -42.38    -150.52     -60.44       7.25     -71.88     -69.26
             phase_amp_2nd:      58.55      30.93     -54.17       6.89     109.83     -67.56     -38.46
                   average:   0.969540   0.284452   0.000369  -0.000000   2.435773   0.000011   0.020317
                   amp_max:   0.000425   0.002387   0.000020   0.000000   0.001122   0.000000   0.000211
                   amp_2nd:   0.000001   0.000003   0.000001   0.000000   0.000000   0.000000   0.000001
amp_2nd_percent_of_amp_max:   0.128094%  0.124048%  2.564410%  2.621651%  0.038399%  0.243896%  0.254685%
```

==

Case: 400HzAmpLoFlowLo

probe_Outlet.dat

Number of time steps per cycle: 4500
Number of cycles in file : 3
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	900.00	900.00	900.00	900.00	900.00	900.00	900.00
period_amp_2nd:	450.00	450.00	450.00	450.00	450.00	450.00	450.00
freq_amp_max:	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111
freq_amp_2nd:	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222
phase_amp_max:	-50.66	-43.40	156.71	-39.41	-38.92	-97.78	-94.38
phase_amp_2nd:	-31.35	24.56	165.10	7.85	-58.91	-95.95	-79.75
average:	0.969429	0.284941	0.000430	0.000000	2.435537	0.000010	0.018426
amp_max:	0.000275	0.002403	0.000001	0.000000	0.000697	0.000000	0.000187
amp_2nd:	0.000001	0.000002	0.000001	0.000000	0.000001	0.000000	0.000001
amp_2nd_percent_of_amp_max:	0.352204%	0.092952%	74.109456%	1.967181%	0.164098%	0.377178%	0.405632%

==

Case: 400HzAmpLoFlowLo

probe_WithinUp.dat

Number of time steps per cycle: 4500
Number of cycles in file : 3
Number of cycles used in fft : 1
Timestep size : 0.2
Nyquist criterion : 2.5

	rho	xmom	ymom	zmom	rhoe	k	omega
period_amp_max:	900.00	900.00	900.00	900.00	900.00	900.00	900.00
period_amp_2nd:	450.00	450.00	450.00	450.00	450.00	450.00	450.00
freq_amp_max:	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111	0.001111
freq_amp_2nd:	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222	0.002222
phase_amp_max:	158.25	11.63	10.41	0.90	-154.92	-9.20	1.28
phase_amp_2nd:	-37.04	174.56	-173.15	101.26	-38.28	91.24	166.79
average:	0.962882	0.000247	0.016348	-0.000087	2.392398	0.000002	1.466357
amp_max:	0.000401	0.000447	0.005465	0.000038	0.000470	0.000001	0.157547
amp_2nd:	0.000077	0.000129	0.001064	0.000020	0.000049	0.000000	0.053959
amp_2nd_percent_of_amp_max:	19.271850%	28.940334%	19.463280%	52.631416%	10.509862%	8.100054%	34.249502%

```
==========================================================================================================
Case: 400HzAmpLoFlowLo

probe_Within.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:     450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:     -66.27       5.57     -23.01    -112.64    -157.39     179.13     172.27
            phase_amp_2nd:     167.08     179.17     120.16    -124.93      -7.89      -3.91     -10.79
                  average:   0.960382  -0.000893  -0.000237   0.000463   2.391926   0.000006   0.175083
                  amp_max:   0.000197   0.004059   0.000863   0.000117   0.000624   0.000002   0.053001
                  amp_2nd:   0.000071   0.001925   0.000391   0.000072   0.000050   0.000001   0.031058
amp_2nd_percent_of_amp_max:   36.058392% 47.427186% 45.250389% 61.145242%  8.050639% 66.085378% 58.598936%

==========================================================================================================
Case: 400HzAmpLoFlowLo

probe_WithinDn.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                  rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:     900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:     450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:    -159.90    -122.75    -149.08       2.33      45.97      28.70      24.63
            phase_amp_2nd:     104.30      97.14       1.71      80.63      66.93    -159.48    -142.23
                  average:   0.959536  -0.003456  -0.043162   0.000402   2.393389   0.000010   2.234043
                  amp_max:   0.000205   0.000837   0.024681   0.000406   0.000616   0.000005   0.308266
                  amp_2nd:   0.000010   0.000164   0.002222   0.000031   0.000101   0.000000   0.075305
amp_2nd_percent_of_amp_max:    4.950576% 19.592625%  9.002701%  7.624549% 16.479310%  6.988172% 24.428502%
```

```
=========================================================================================================
Case: 400HzAmpLoFlowLo

probe_NearWallUp.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:       900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:       450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:     0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:     0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:        40.28       1.45    -135.80    -140.29      44.54     -81.92     -17.78
            phase_amp_2nd:         3.81     160.91     -17.76     -16.51      17.99    -162.45     130.38
                  average:     0.959231   0.035837   0.000007   0.000045   2.394694   0.000002   8.350883
                  amp_max:     0.000193   0.000792   0.000002   0.000039   0.000789   0.000000   0.050029
                  amp_2nd:     0.000001   0.000012   0.000000   0.000001   0.000004   0.000000   0.000983
amp_2nd_percent_of_amp_max:    0.699139%  1.512300%  2.998550%  3.008755%  0.529671%  1.383339%  1.964808%

=========================================================================================================
Case: 400HzAmpLoFlowLo

probe_NearWallDn.dat

Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                    rho       xmom       ymom       zmom       rhoe          k      omega
           period_amp_max:       900.00     900.00     900.00     900.00     900.00     900.00     900.00
           period_amp_2nd:       450.00     450.00     450.00     450.00     450.00     450.00     450.00
             freq_amp_max:     0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
             freq_amp_2nd:     0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
            phase_amp_max:        41.70      24.75      45.13      38.22      41.91     -78.33       4.17
            phase_amp_2nd:       171.72     134.70    -172.72    -150.63     166.12      99.06     153.33
                  average:     0.959405   0.032297   0.000003  -0.000340   2.394220   0.000005   8.108580
                  amp_max:     0.000298   0.003262   0.000007   0.000785   0.001208   0.000000   0.222652
                  amp_2nd:     0.000004   0.000092   0.000000   0.000032   0.000010   0.000000   0.007232
amp_2nd_percent_of_amp_max:    1.207231%  2.826272%  2.832617%  4.043930%  0.869076%  7.997267%  3.248165%
```

```
==========================================================================================================
Case: 400HzAmpLoFlowLo

probe_Below.dat


Number of time steps per cycle: 4500
Number of cycles in file      : 3
Number of cycles used in fft  : 1
Timestep size                 : 0.2
Nyquist criterion             : 2.5
                                   rho       xmom       ymom        zmom       rhoe          k      omega
            period_amp_max:      900.00     900.00     900.00     900.00     900.00     900.00     900.00
            period_amp_2nd:      450.00     450.00     450.00     450.00     450.00     450.00     450.00
              freq_amp_max:    0.001111   0.001111   0.001111   0.001111   0.001111   0.001111   0.001111
              freq_amp_2nd:    0.002222   0.002222   0.002222   0.002222   0.002222   0.002222   0.002222
             phase_amp_max:      -42.66     -61.22    -116.54    -172.45     -46.97     -84.10     -56.50
             phase_amp_2nd:      -15.38     -26.91    -112.11     178.30      65.13     -85.71     -35.95
                   average:    0.969664  -0.000020   0.000012  -0.000002   2.393069   0.000000   0.000726
                   amp_max:    0.000029   0.000042   0.000043   0.000002   0.000042   0.000000   0.000004
                   amp_2nd:    0.000005   0.000008   0.000002   0.000000   0.000001   0.000000   0.000000
amp_2nd_percent_of_amp_max:   15.749383% 18.560486%  5.594506% 19.597120%  1.625661% 38.391542% 12.158492%
```

Appendix B.—Unforced Flow Properties at Probe Locations

The flow field for the two unforced cases, at freestream Mach numbers of 0.25 and 0.50, remained steady. Therefore, there was no need to perform the Fast Fourier Transform Analysis. The average values at the nine probe locations follows.

AmpNoFlowLo

	rho	xmom	ymom	zmom	rhoe	k	omega
probe_Inlet	0.969658E+00	0.283935E+00	0.154879E-04	-0.474731E-09	0.243602E+01	0.124489E-04	0.227199E-01
probe_Above	0.969539E+00	0.284455E+00	0.371635E-03	-0.101717E-08	0.243577E+01	0.113653E-04	0.203156E-01
probe_Outlet	0.969429E+00	0.284945E+00	0.434313E-03	0.170709E-08	0.243554E+01	0.104798E-04	0.184263E-01
probe_WithinUp	0.962452E+00	0.640076E-03	0.191285E-01	-0.548296E-04	0.239217E+01	0.267719E-05	0.148402E+01
probe_Within	0.960587E+00	0.140035E-02	0.912727E-05	0.403823E-03	0.239165E+01	0.474594E-05	0.143964E+00
probe_WithinDn	0.959457E+00	-0.364976E-02	-0.472027E-01	0.441015E-03	0.239316E+01	0.112174E-04	0.229931E+01
probe_NearWallUp	0.959210E+00	0.361262E-01	0.142228E-04	-0.567697E-04	0.239462E+01	0.204082E-05	0.823133E+01
probe_NearWallDn	0.959431E+00	0.324384E-01	-0.324604E-05	0.277435E-03	0.239431E+01	0.537631E-05	0.800765E+01
probe_Below	0.969415E+00	-0.329358E-04	-0.149483E-03	-0.723566E-05	0.239292E+01	0.889748E-06	0.237134E-02

AmpNoFlowHi

	rho	xmom	ymom	zmom	rhoe	k	omega
probe_Inlet	0.886389E+00	0.508930E+00	0.268117E-04	-0.800644E-09	0.225772E+01	0.437032E-04	0.493249E-01
probe_Above	0.885897E+00	0.509790E+00	0.823677E-03	-0.111450E-08	0.225665E+01	0.378005E-04	0.431184E-01
probe_Outlet	0.885214E+00	0.510981E+00	0.954187E-03	-0.212095E-08	0.225517E+01	0.333888E-04	0.384198E-01
probe_WithinUp	0.870266E+00	0.740993E-03	0.396226E-01	0.468319E-04	0.210213E+01	0.236597E-03	0.160907E+01
probe_Within	0.865477E+00	0.195006E-02	0.483125E-02	0.814695E-04	0.209977E+01	0.480041E-03	0.479480E+00
probe_WithinDn	0.857245E+00	-0.759270E-02	-0.124955E+00	0.196957E-02	0.211021E+01	0.148122E-02	0.368647E+01
probe_NearWallUp	0.853310E+00	0.185808E+00	0.247938E-04	-0.104832E-03	0.213189E+01	0.305898E-02	0.144484E+02
probe_NearWallDn	0.853112E+00	0.170312E+00	-0.133078E-04	0.160236E-02	0.212657E+01	0.273751E-02	0.137991E+02
probe_Below	0.881424E+00	0.184436E-03	0.226568E-02	-0.143407E-04	0.210564E+01	0.400014E-05	0.494452E-02

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This work studied the feasibility of using Helmholtz resonator cavities embedded in low-pressure-turbine (LPT) airfoils to (1) reduce core noise by damping acoustic modes; (2) use the synthetic jets produced by the liner hole acoustic oscillations to improve engine efficiency by maintaining turbulent attached flow in the LPT at low-Reynolds-number cruise conditions; and (3) reduce engine nitrogen oxide emissions by lining the internal cavities with materials capable of catalytic conversion. Flat plates with embedded Helmholtz resonators, designed to resonate at either 3000 or at 400 Hz, were simulated using computational fluid dynamics. The simulations were conducted for two inlet Mach numbers, 0.25 and 0.5, corresponding to Reynolds numbers of 90 000 and 164 000 based on the effective chordwise distance to the resonator orifice. The results of this study are (1) the region of acoustic treatment may be large enough to have a benefit; (2) the jets may not possess sufficient strength to reduce flow separation (based on prior work by researchers in the flow control area); and (3) the additional catalytic surface area is not exposed to a high velocity, so it probably does not have any benefit.

15. SUBJECT TERMS
Helmholtz resonators; Vortex generators; Separation; Boundary layer control; Turbine blades

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