Quiet High Speed Fan II (22-inch) Duct Mode Characteristics as Measured by the Rotating Rake Mode Measurement System while Operated in the NASA Glenn 9x15 Low Speed Wind Tunnel

Daniel L. Sutliff*

NASA Glenn Research Center, Cleveland, Ohio, 44135

A 22-inch scale model of the Honeywell Quiet High Speed Fan II was tested in the NASA Glenn 9- by 15-foot Low Speed Wind Tunnel at a tunnel Mach number of 0.10. This was an entry to investigate the effect of "stator clocking" on noise. The fan consisted of a moderately aft swept rotor, and an aft swept set of stator vanes. The fan stage consisted of 22 rotor blades, 50 stator vanes, and 10 downstream support struts. A set of stator vanes designed for lower noise was tested as well as a baseline stator vane set. The stator assembly could be rotated several degrees to adjust the clocking angle between the stator vane pack and the strut assembly. All configurations were with a hard wall duct (no acoustic treatment). The NASA Glenn Research Center's Rotating Rake Mode Measurement System was utilized to obtain a complete map of the acoustic duct modes present in the ducted fan. The system is a radial rake emersed into the duct that continuously rotates about the duct centerline. For the two stator configurations, data were acquired at several different fan speeds which included nominal, approach, cutback, and takeoff conditions. Analysis of the mode power level results at the fan fundamentals showed the improved designed set resulted in lower rotor-stator and rotor-strut interaction acoustic levels for the interaction modes. Varying the angle between the stators and struts was shown to be a viable method to achieve a minimum in rotor-strut interaction mode power level. Multiple-pure-tones generated by the Quiet High Speed Fan II in the inlet were also measured.

ABBREVIATIONS

BPF – Blade Passing Frequency
PWL – Power Level
QHSF – Quiet High Speed Fan
MPT – Multiple Pure Tones
SPL – Pressure Level
RPMc – Corrected RPM
RRMMS – Rotating Rake Mode Measurement System

I. Introduction

THE NASA Quiet Aircraft Technology program had a noise reduction element to provide the technology to meet increasingly restrictive airport noise regulations whose goals were reducing transport aircraft noise attributed to the engine. A component of engine noise is the fan tone noise caused by rotor-stator, and other interactions, coupled to duct propagation which radiate to the farfield and contribute to the community noise generated by turbofan engines[1]. In order to reduce engine tone noise, it is desirable to measure the level of and understand the generation of these interaction modes.

A high-speed scale model with a 22-inch diameter fan was tested in the NASA Glenn 9-by 15-foot Low Speed Wind Tunnel to investigate noise characteristics generated from interactions of the rotor wake on the downstream stator vanes and struts. As part of this effort, a forward-swept rotor fan was designed and constructed by Honeywell Engines and Systems to reduce the noise of supersonic tip speed fans. Honeywell provided a new design for the QHSF (which had a lower hub/tip ratio and higher specific flow than an earlier design. In addition to the baseline set of stator vanes, a stator vane set was designed to minimize the interaction of the newly designed rotor wake on that set and was tested. Uniquely, the clocking (static) angle between the stator vanes and struts was varied to investigate a potential noise reduction method. An additional goal of the test was to document the multiple-pure tones generated when the rotor tip speed exceeds sonic.

This paper presents measurements of both exhaust duct modes generated by the rotor-stator, and rotor-strut interactions for the first and second blade passing frequencies and their corresponding modal power levels. In addition, the effect of relative positioning between the stator vane pack and the downstream struts in the circumferential direction was studied for both sets of stator vanes. Finally, the multiple-pure-tines generated in the inlet by the Quiet High Speed Fan II rotor is presented.

*Research Engineer, Acoustics Branch, MS 54-3, AIAA Associate Fellow.

II. Test Apparatus

A. Honeywell QHSF II Fan Model

The Quiet High Speed Fan II (QHSF II) design[2] (Figure 1,Table I) was developed based on the experience of the earlier QHSF I[3,4] entry, and other recent Honeywell product fan design experiences. The design process relied on analytical Design of Experiments to define the optimum rotor and stator system to achieve all acoustic, aerodynamic, aeroelastic, and mechanical performance goals. These series of analyses included the selection of blade forward sweep, blade tangential lean, blade thickness distribution, rotor incidence, and stator sweep and lean optimization. The fan model has a passive core (as identified in Figure 1). A nozzle core plug can be adjusted to set the bypass ratio.

1. QHSF II Rotor

The QHSF II rotor is a forward-swept blade with a reduced sweep at the tip and additional sweep at lower spans when compared to the QHSF I. The QHSF II also has a full span stator with an optimized, non-linear sweep and lean (Figure 2). The rationale for the improved design was to (i) reduce noise at supersonic tip speeds, (ii) improve aeroelastic, and (iii) maintain aerodynamic performance – all relative to the previous entry[5,6,7].

2. QHSF II Stator Vane Sets

Two configurations of stator vanes packs were installed and tested during this entry – a baseline set of 50 stator vanes from the earlier QHSF I entry and an alternate set of stator vanes (also 50 count). The second set, which will be referred to as QHSF II, was specifically designed to reduce the effect of the rotor wake impinging on the stator vane and the strut to mitigate the acoustic interaction levels. The QHSF II stator vanes have a higher lean with a modified leading edge. The design modification to the stator vane was also intended to lower the effect of the stator vane shape on the rotor-strut interaction.

3. Stator-Strut Clocking Assembly

A repositionable stator disk assembly to allow the stator positions to circumferentially vary relative to the strut positions was incorporated into the 22" fan rig test article. A drawing of the dual-actuator system is provided in Figure 3a with a corresponding picture in Figure 3b. This design permits the mechanical rotation of the stator disk assembly relative to the strut assembly. The relative stator-strut spacing angle, ϕ, of 4.32°, is the nominal design position; ϕ=0° and ϕ=7.2° represent clocking across a full 1/50th of the circumference, or one complete stator vane passage. (Note that there are 10 struts.)

B. NASA Glenn 9x15 Wind Tunnel /UHB Rig

The 9x15 Foot Low Speed Wind Tunnel at GRC has been used for performance and acoustic testing of aircraft propulsion systems for decades. The tunnel walls are acoustically treated, and a large muffler reduces noise from the drive motors and compressor. Several reports[8,9,10] overview the facility including aerodynamic test capabilities and acoustic quality. For all data presented in this paper, the tunnel was operated at a test section free-stream flow of 0.1 Mach number. The research fan is powered by the NASA GRC Ultra-High Bypass drive rig[11] which has a four-stage air turbine. The UHB rig is driven by compressed air generated by the NASA Glenn 450 psi central air system. The power requirements for this fan were in the mid-range of the drive-rig capability.

C. Rotating Rake Mode Measurement System

An experimental measurement system[12] was developed and implemented at the NASA Glenn Research Center in the 1990s to measure fan duct acoustic modes. The Rotating Rake Mode Measurement System is an integrated hardware, instrumentation, data acquisition, reduction, and processing technique to obtain a complete modal map of acoustic duct modes present in a ducted fan for multiple fan harmonics. It has been used on a variety of test articles: from a low-speed concept test fan rig to a full-scale production turbofan engine. The RRMMS has been critical in developing and evaluating several noise reduction concepts and has made several advances in the understanding of turbofan mode generation. It has also provided experimental databases for verification and benchmarking of several aero-acoustic codes, or used as input to system analysis.

Tyler-Sofrin modes[13] are generated by the well-documented interaction of the rotor wakes impinging on stator vanes. Table II presents these expected potential modes based on Equation 1. It is worth repeating the concept that a given (m,n) mode will propagate only if the frequency is above the cut-off frequency. For frequencies only somewhat below cut-off (ζ<1.0), it can be shown that a 10-20 dB attenuation per duct diameter occurs, increasing significantly as the cut-off ratio decreases. The cut-off ratio with Mach number effects is given by Equation 2.

The primary hardware component of the RRMMS[14] is a rake with radially distributed microphones inserted into the duct, which continuously rotates about the duct centerline and is synchronized to the fan shaft. Instrumentation to acquire the microphone time histories and process the data with a unique algorithm provides the ability to obtain circumferential and radial modal amplitudes and phases for multiple fan harmonics in near-real-time.

The underlying principle of the RRMMS is the concept that every circumferential mode spins at a different, discrete rate at an exact integer multiple to the fan shaft. The rake, also rotating synchronously at an exact fraction of the fan shaft, imparts a Doppler shift from the fan fundamental and harmonics that is unique to each circumferential mode. This frequency separation is a linear function of the mode number and the rake rotation speed; the higher the mode number the greater the frequency shift with m=0 un-shifted (i.e., remaining at the fan harmonic frequency).

In addition, the rotor wakes will propagate downstream to generate rotor-strut interaction modes; These modes were 1st measured on the TFE-731[15].

Figure 4 is a photograph of the RRMS installed in exhaust duct (4a), and installed in the inlet duct (4b), of the QHSF II. The measurement for the exhaust rake is the exit plane and for the inlet is the throat, these are the acoustic release points. When the rake is installed in the exhaust duct, the nozzle outer radius is increased so that the exit area (which is reduced by the rake blockage) remains the same.

$$m = nB +/- kV \qquad \text{(Equation 1a)}$$
$$m = nB +/- kS \qquad \text{(Equation 1b)}$$

where *B = # of rotor blades*
V = # of stator vanes
S = # of struts
n = fan harmonic
k = integer

$$\zeta = \frac{\pi f D}{R\sqrt{(1-M^2)\cos(2\phi)}}; \quad k = R\,e^{i\phi} \qquad \text{(Equation 2)}$$

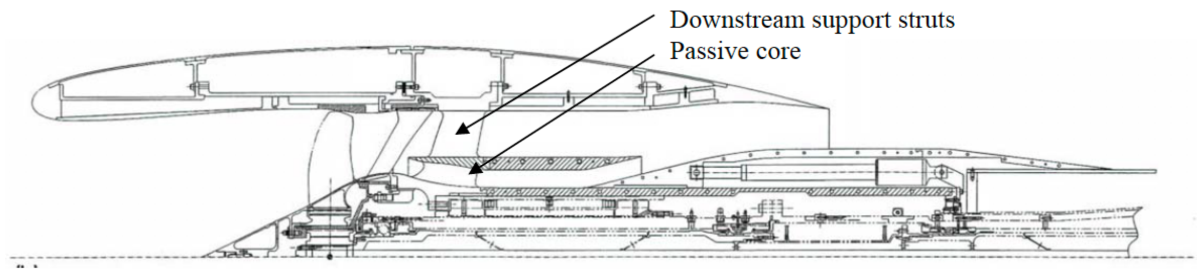
Table I: Honeywell QHSF II Design Parameters

PARAMETER	VALUE	UNITS
Rotor Inlet Diameter	21.772	inches
Hub/Tip Ratio	0.325	–
BPR	4.08	–
Corrected Speed	15,621	revolutions per minute
Corrected Tip Speed	1,484	feet/second
Corrected Weight Flow	99.454	pound-mass/second
Specific Flow	43	pound-mass/second/feet^2
Stage Pressure Ratio	1.83	–
Stage Efficiency	89	%
Rotor Pressure Ratio	1.87	–
Rotor Efficiency	91.1	%
Fan Stability Margin	>10	%

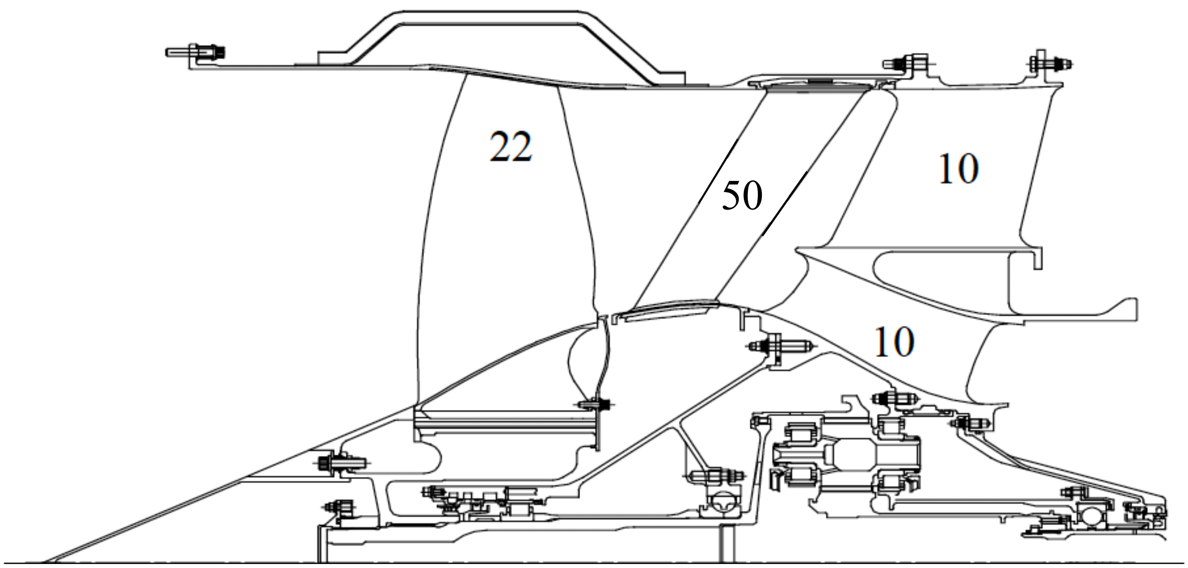
PARAMETER	VALUE
Rotor Count	22
Stator Count	50
Strut Count	10

Table II. Possible Generated Modes Due to Interactions

[B=22]	1xBPF	2xBPF	3xBPF
Vane Modes (V=50)	+22	-6,+44	-34,+16,+66
Rotor Locked Mode	+22	+44	+66
Strut Modes (S=10)	-28,-18,-8, +2,+12,+22	-46,-36,-26,-16,-6, +4,+14,+24,+34,+44	-64,-54,-44,-34,-24,-14,-4, +6,+16,+26,+36,+46,+56,+66



(a) Full Flow Path



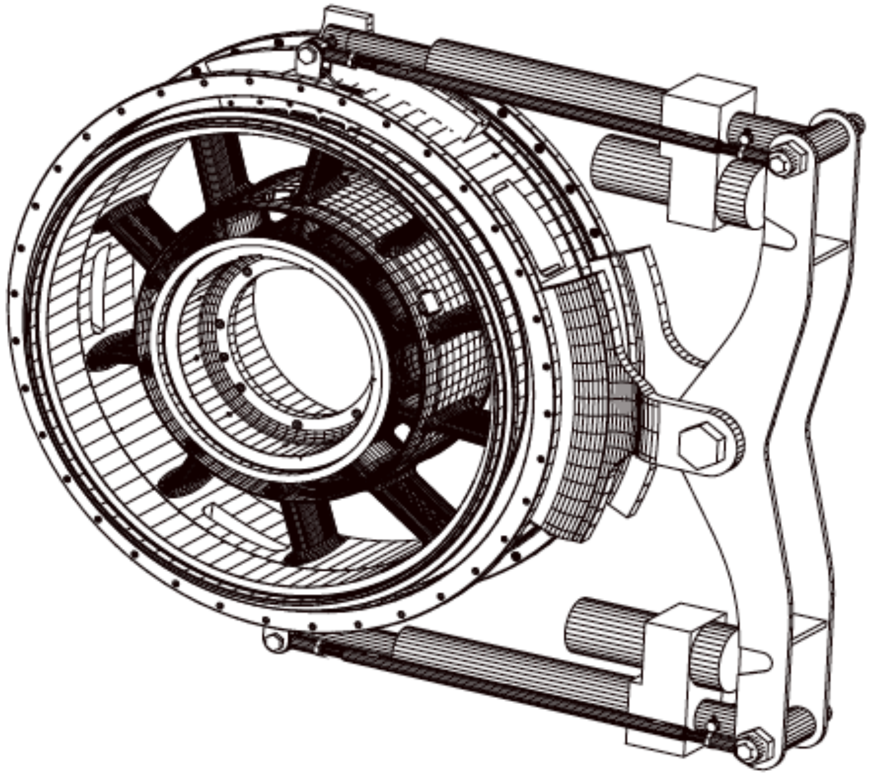
(b) Fan Stage

Figure 1: QHSF II Model Flow Path

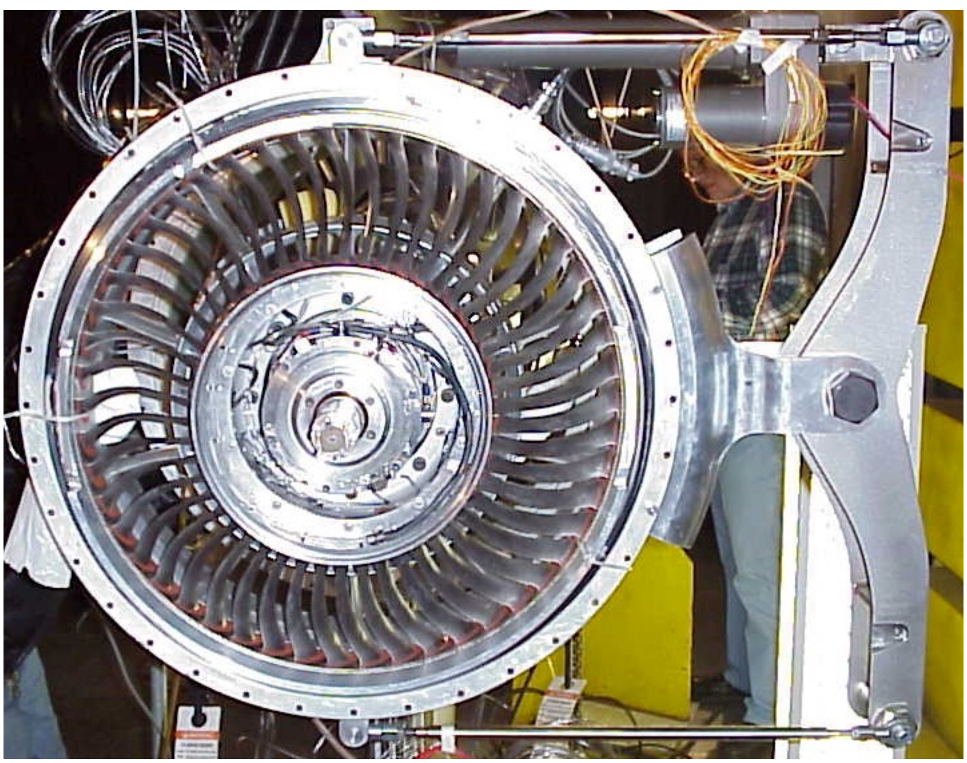
(a) Fan Frontal View

(b) Fan / Nacelle in 9x15 Test Section

Figure 2: QHSF II Rotor Photos (from NASA/CR—2012-217451 figure 183)

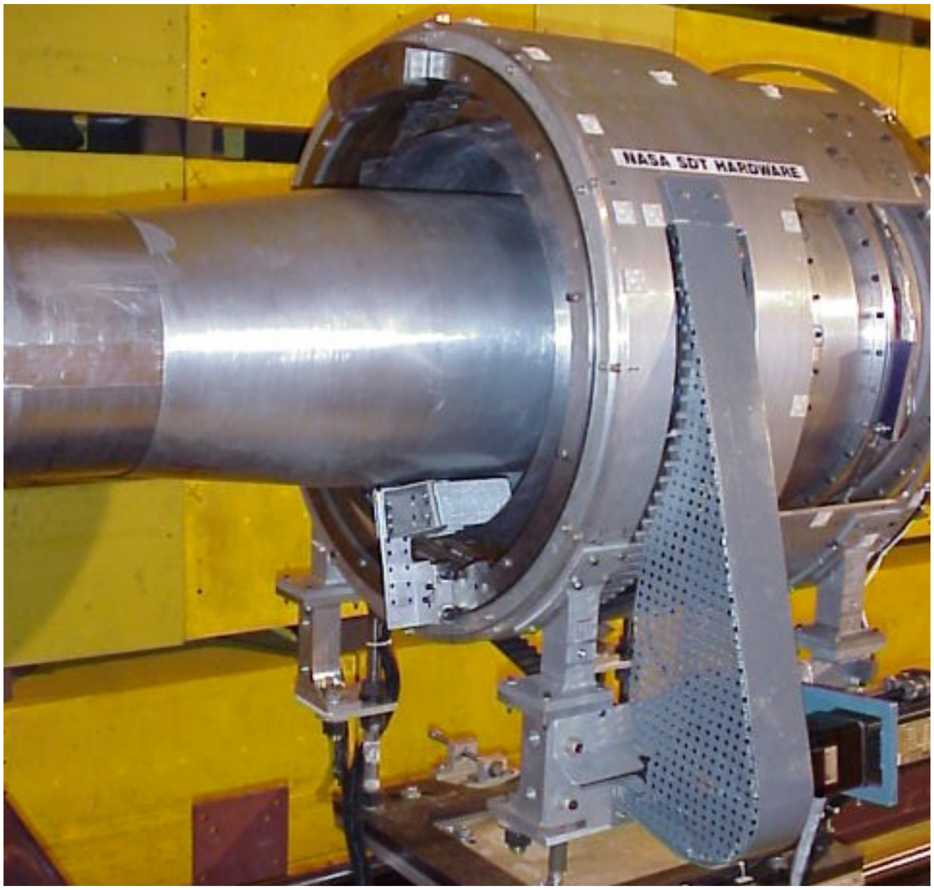


(a) Schematic of Stator Clocking Mechanism (from NASA/CR—2012-217451 figure 158)

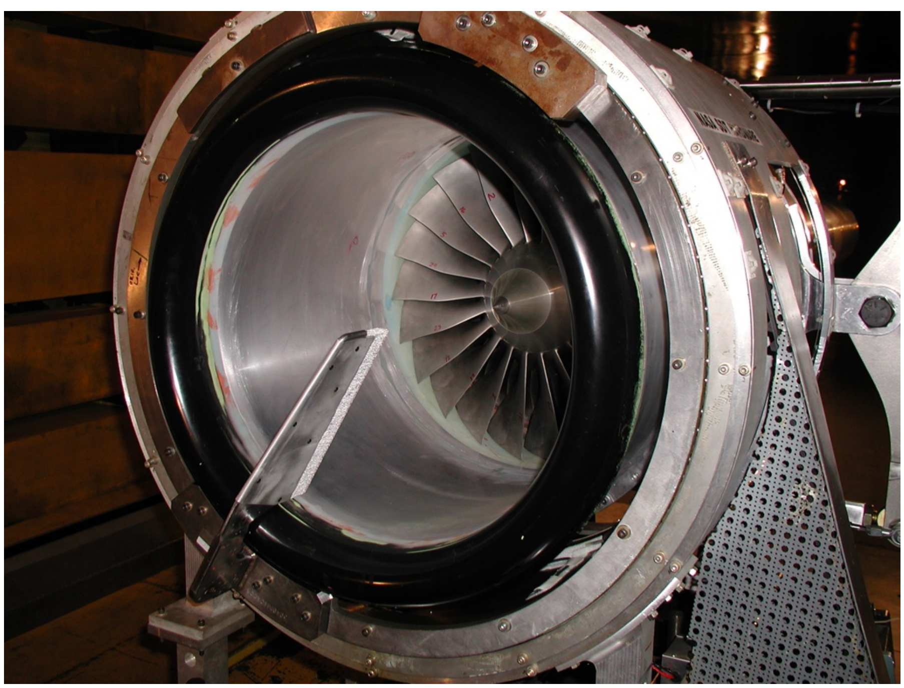


(a) Photograph of Stator Clocking Mechanism

Figure 3: Stator Disk Pack Clocking Mechanism



(a) Exhaust Duct Installation – Rake Measurement @ duct exit plane



(a) Inlet Duct Installation – Rake Measurement @ throat plane

Figure 4: Rotating Rake Installed in on QHSF II Model

III. Results and Discussion

The data processing routine calculates all the modes at the fan harmonics (or any shaft-order tone). They are typically plotted in a 3-D 'tombstone' plot shown in Figure 5. The base plane axes are circumferential (*m*) and radial (*n*) orders, and the vertical value axis is the acoustic power level (PWL in dB) in the specific (*m,n*) mode. Along the backwall of the *n*-order axis, the sum of all the radial modes provides the power in that circumferential mode. The lowest level of the *z*-axis is chosen to be based on the measurement noise floor. The sum of all the modes provides the PWL in the harmonic presented. A typical modal decomposition provides information as to the dominant modes present which are usually those from the rotor-stator interaction. Of secondary interest will be other modes, which may be due to inflow distortions or other geometric disturbances. Phase information, while tabulated, is generally not plotted. For clarity, only the total circumferential mode PWL will be presented in this paper.

The uncertainty in the mode PWL acquired and computed from the RRMMS arise from three basic components: (i) instrumentation/calibration, (ii) data reduction, and (iii) modeling error. These have been estimated[16] to be ±3.4 dB (Table III). Future RRMMS processing should use the basis functions computed using the actual (or predicted) shear flow in the least-squares curve fit solution for more accurate calculation of the mode PWL. Incorporating this (non-trivial) processing could reduce the mode PWL uncertainty to ±1.6 dB. Figure 6 shows examples of simple repeatability of the total PWL in circumferential modes. While not technically rigorous, historical observation has shown the level of repeatability to be approximately ±1 dB. Table IV shows the repeatability of the individual radial modes comprising dominant circumferential modes. A typical case (Baseline Vane Set : Inlet BPF @ 90% RPMc) shows that the radial decomposition repeatability is ±0.5 dB for strong modes, up to ±2 dB for weaker modes. The 1st two points were acquired back-to-back, the 3rd point was a repeat of the strut-stator angle after a complete cycle of angles.

Table III: Mode PWL Measurement Uncertainty

Inlet	ΔdB PWL	Linear Ratio	"Error"
Calibration	0.5	1.122	0.122
Telemetry	0.4	1.096	0.096
Data Reduction	1.5	1.413	0.413
Modeling	3.2	2.089	1.089
RMS of dB	3.6	2.175	1.175
	RMS	**3.4**	

Table IV. Dominant Circumferential Modes Mode-Radial Mode Breakdown Repeatability
(Typical: Exhaust Duct @ 90% RPMc, ϕ = 4.32° : Baseline Vane Set Installed)

Harm	Mode	Run #	TOT PWL	%error	n=0	n=1	n=2	n=3	n=4	n=5	n=6
1BPF	m=-18	68	126.1	6.6%	125.6	116.6	94.3	–	–	–	–
		69	126.1	6.2%	125.6	116.6	96.1	–	–	–	–
		75	126.2	6.3%	125.7	116.6	95.6	–	–	–	–
1BPF	m=-8	68	113.9	7.9%	105.5	111.4	108.3	93.3	–	–	–
		69	113.5	10.3%	106.3	110.5	108.3	91.4	–	–	–
		75	113.4	11.3%	105.7	110.5	108.2	92.3	–	–	–
1BPF	m=+2	68	114.2	7.4%	111.6	110.1	102.8	80.2	–	–	–
		69	113.9	8.9%	111.6	109.3	102.2	84.1	–	–	–
		75	114.0	2.6%	111.1	110.1	103.6	83.1	–	–	–
1BPF	m=+12	68	123.0	5.1%	122.7	98.5	110.7	93.4	–	–	–
		69	122.7	5.4%	122.3	98.0	111.2	95.6	–	–	–
		75	122.8	4.5%	122.5	97.0	110.1	96.4	–	–	–
2BPF	m=-8	68	131.2	0.0%	126.1	120.9	124.0	124.7	123.1	114.4	105.6
		69	131.2	0.0%	126.0	121.5	123.7	124.8	123.2	113.7	104.2
		75	131.2	0.0%	126.1	120.9	123.3	124.6	123.2	114.4	105.0

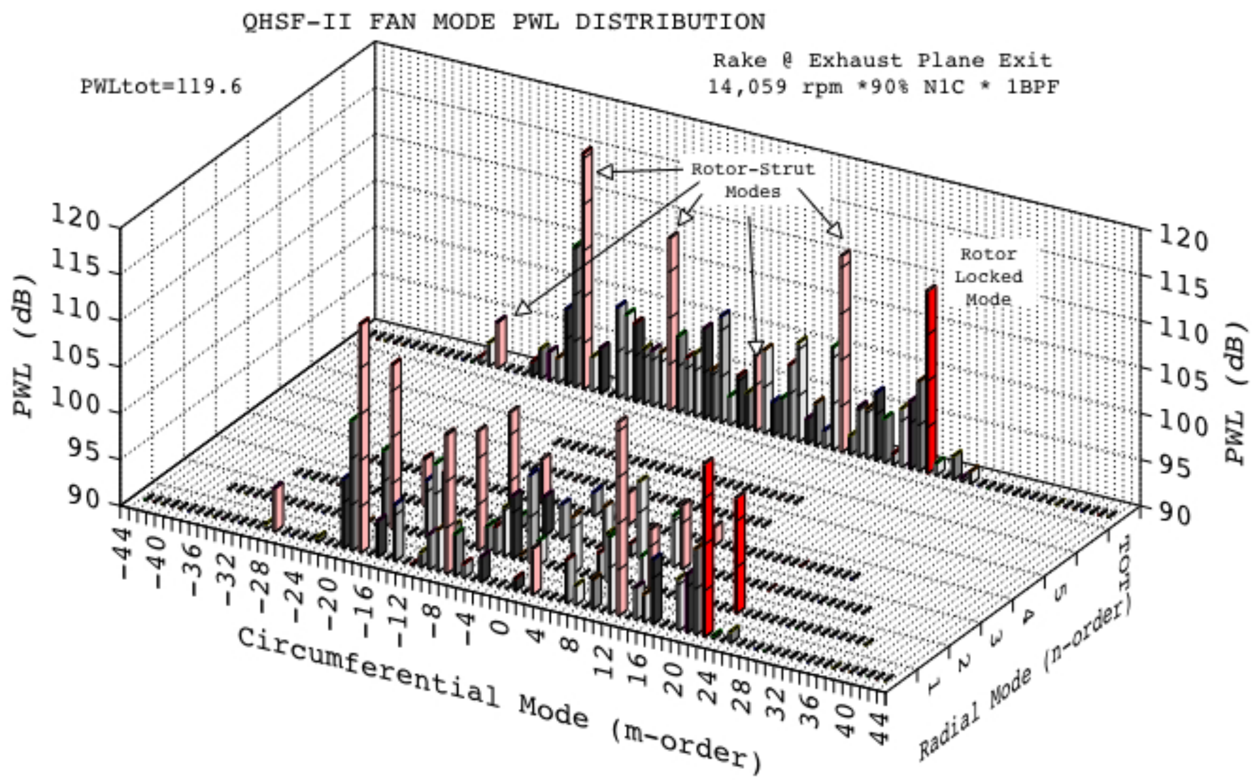


Figure 5. Typical Modal Decomposition 'Tombstone Plot'

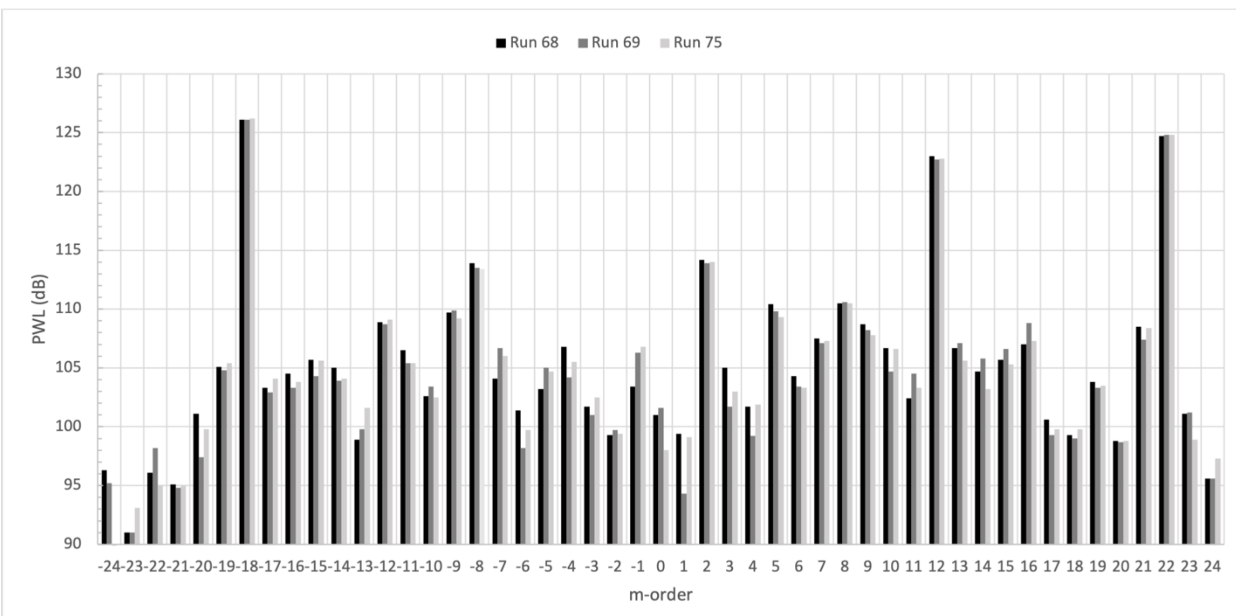


Figure 6: Circumferential Mode PWL Measurement Repeatability
(Typical: Exhaust Duct @ 90% RPMc, ϕ = 4.32° : Baseline Vane Set Installed)

A. Analysis of Interaction Mode PWLs in Exhaust Duct

The intent of this section is to present the effects of the relative clocking angle (ϕ) between the stator and strut disks as well as the more traditional rotor-stator interaction. Data were acquired from discrete ϕ set-points from both sets of stator vanes. RRMMS data from six discrete values of the angle (ϕ) were acquired at the rating points to provide a reasonable investigation. The first (ϕ=0°) and last (ϕ=7.2°) set points have nominally the same physical relationship between the stators and struts as discussed in section II.A.3 At other fan corrected revolutions-per-minute (RPMc) a smaller set of angles was tested to match cases evaluated by the CFD cases[2]. The nominal angle, ϕ=4.32°, was tested at additional RPMc. Table V shows the setpoint conditions for data acquired in the exhaust.

1. Effect of Stator-Strut Relative Position on PWL of Interaction Modes (1BPF and 2BPF)

The fundamental blade passing frequency is cut-off for both stator vane sets. However, the rotor-strut interaction modes are cut-on due to the lower count (10 vs 50). The possible modes are listed in Table II. The sum of the rotor-strut interaction modes is plotted vs. RPMc for both the Baseline and QHSF II set of stator vanes in Figure 7. The QHSF II stator vane set generates lower rotor-strut interaction mode PWL than the Baseline set (1.8 to 9.5 dB lower), except at 7,811 RPMc where the QHSF II is 0.5 dB higher – within the measurement uncertainty. At the takeoff condition (14,059 RPMc) the QHSF II vane set is 9.5 dB quieter than the Baseline set.

Figure 8 presents PWLs of the rotor-strut interaction modes as measured in the exhaust with the Baseline stator vane set installed generated at 1BPF for fan RPMc of 14,059 (90%). For the QHSF II stator vane set this is shown in Figure 9. The strongest interaction mode in both cases is m=*-18*, noticeably so for the Baseline set, slightly so for the QHSF II set. The sensitivity of this dominant mode PWL from the variation in ϕ, shows a greater range (max to min) with the QHSF II set compared to the Baseline set (6.9 vs 2.7 dB). The variations generated for individual interaction mode PWL for the Baseline set is 1.3 dB (m=+12) to a maximum of 5.7 dB (m=-8). The clocking angle resulting in the minimum PWL at 1BPF varies with mode and is not necessarily discernable. The QHSF II vane set generates a variation of 4.6 dB (m=+12) to a maximum of 7.0 dB (m=-8). The clocking angle resulting in the minimum PWL is ϕ=0° and generally consistent with the m-order.

The variation in the radial mode PWL decomposition of the dominant m=*-18* due to clocking angle for the takeoff fan speed (90%) is plotted in Figure 10 for the Baseline stator vane set and Figure 11 for the QHSF II set. The variation in the individual radials essentially follows the variation in the total circumferential mode, with the QHSF II set showing noticeably more variation as the clocking angle is changed.

The exhaust rotor-strut mode PWLs generated at 2BPF are shown for both the Baseline stator vane set (Figure 12) and the QHSF II stator set (Figure 13). The rotor-stator interaction mode at m=*-6* is dominant. Consider that the m=-*6* is the combination of two modes, one generated by the rotor-stator interaction and the second generated by the rotor-strut interaction. It is expected that the former component should be more prominent since the stator vanes are much closer to the rotor. Therefore, the rotor wakes were much stronger at that axial location. These combine into a single-mode which is measured in-toto by the RRMMS. For the Baseline stator vane set this mode is approximately 12 dB above the next higher interaction mode and ~7 dB greater than the sum of the other rotor-strut interaction modes, with a range of 0.3 dB. It is approximately 6 dB above the next higher interaction mode and ~3 dB stronger than the sum of the other rotor-strut interaction modes for the QHSF II set, with a range of 1.0 dB. The clocking angle resulting in the minimum PWL is not really discernable – which is not surprising as the design effort was for 1BPF.

For the various stator vane clocking angles (0° and 7.2° represent clocking across a complete stator vane passage) the Baseline set generates a range of 1.1 dB (m=+14) to a maximum of 9.6 dB (m=+34). The QHSF II set generates a variation of 1.4 dB (m=+4) to a maximum of 8.1 dB (m=+44).

2. Rotor-Stator Interaction Mode PWL (2BPF)

At 2BPF, the rotor-stator interaction mode is m=*-6*. It is cut-on at all speeds tested, though the number of radials that are cut-on increases with increasing speed, from 3 radials at 7,811 RPMc (50%) to 7 radials at 14,509 RPMc (90%). (see Figure 14). As a result, the PWL of this interaction mode for the QHSF II vane set is 1 to 8 dB quieter than the baseline set: 4.6 dB quieter at takeoff condition (90%).

The variation in the 2BPF rotor-stator interaction mode radials due to clocking angle for a representative speed (90%) is shown in (Figure 15) for both sets. The baseline set range in PWL is less than a fraction of a dB (0.3) – within the expected repeatability as discussed in the last section. On the other hand, the QHSF II stator vane set shows a little more range in the PWL (0.9 dB), barely greater than the repeatability. Recall that the m=*-6* is the combination of two modes combined into a single-mode which is measured by the RRMMS. As was seen in the previous section the m=-*6* mode was significantly higher than the other interaction modes and ~7 dB higher than the sum of the other interaction modes, while the QHSF II stator vane set was less so, ~3 dB above interaction modes sum. Therefore, any variation in in the portion of the measured *m=-6* mode due to the rotor-strut interaction modes will be more noticeable when the rotor-stator interaction mode is closer in level, as with the QHSF II vane set, assuming the portion off the measured *m=-6* mode due to rotor-stator interaction mode does not vary with clocking angle.

The radial mode decomposition of the interaction mode vs RPMc is shown for the baseline stator vane set (Figure 16) and for the QHSF II stator vane set (Figure 17). The comparison shows some variation in the distribution of the radials especially noted at 10,935 RPMc. This is not surprising since the difference in lean and sweep between the two sets was expected to result in lower acoustic levels from the QHSF II stator vane set as the rotor wake impingement on the stator leading edge.

Table V: QHSF II Test Points Acquired with RRMS in the Exhaust

Objective: Determine effect of vane clocking on mode levels.

CONDITION	FNC,%	FNC,RPM	STATOR CLOCKING (ϕ)
approach	50	7,811	0°,1.44°,2.88°,4.32°,5.76°,7.2°
	63	9,841	4.32°
cutback	70	10,935	0°,1.44°,2.88°,4.32°,5.76°,7.2°
	74	11,560	0°,1.8°,3.6°,5.4°
	80	12,497	4.32°
	85	13,278	0°,1.8°,3.6°,5.4°
takeoff	90	14,059	0°,1.44°,2.88°,4.32°,5.76°,7.2°
	100	15,621	0°,1.8°,3.6°,5.4°
*At 74,%85%,100% FNC, clocking increments of 1.8° were used to match what was used in the CFD evaluation.			

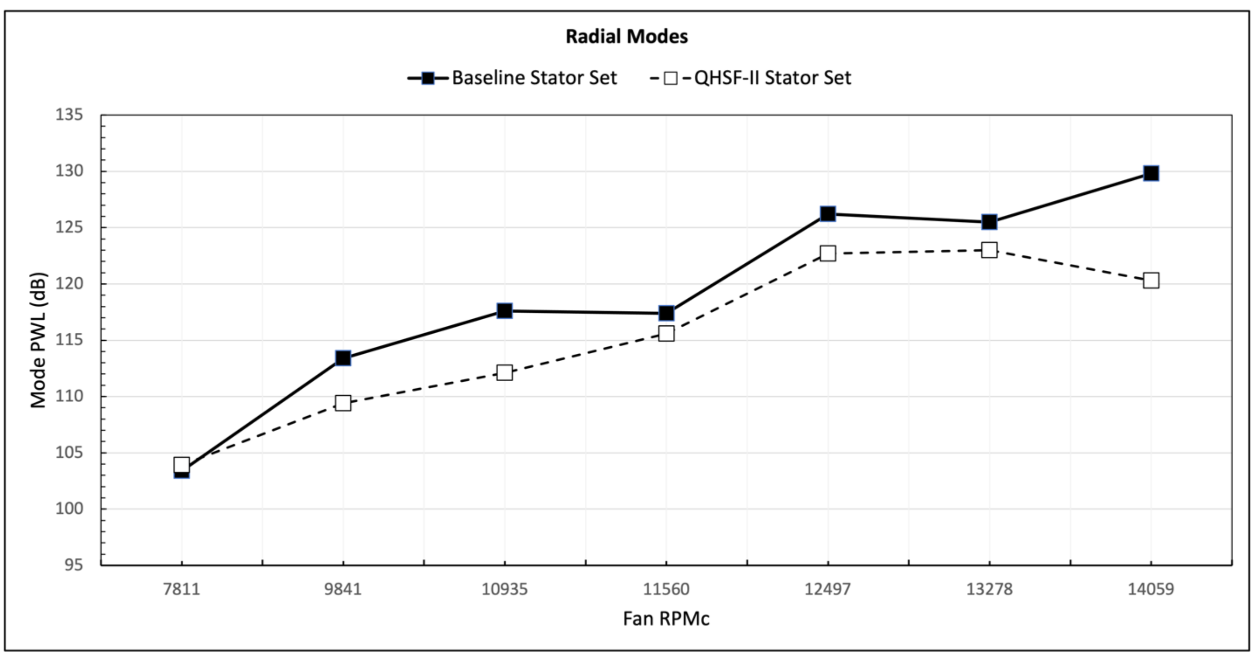


Figure 7: Sum of Rotor-Strut Interaction Mode PWLs at 1BPF vs RPMc for Baseline Stator and QHSF II Vane Sets

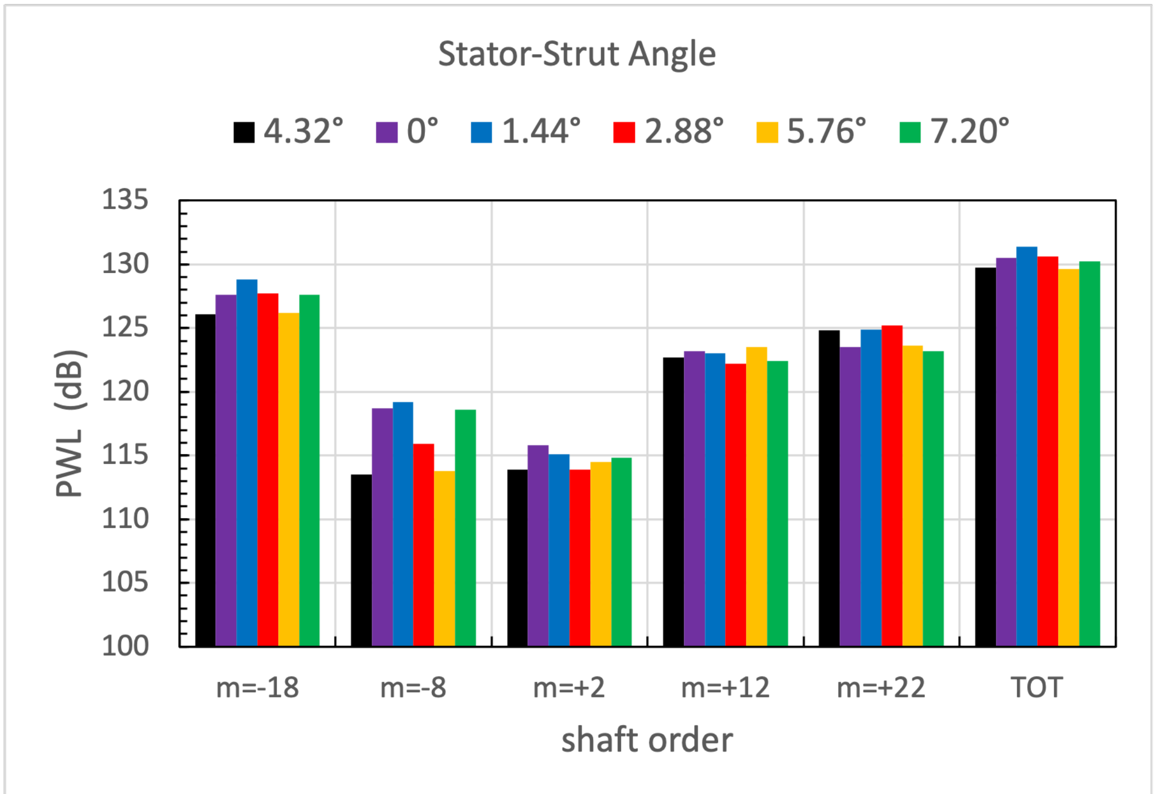


Figure 8: Rotor-Strut Interaction Modes vs ϕ : 90% RPMc, 1BPF with Baseline Stator Vanes Installed

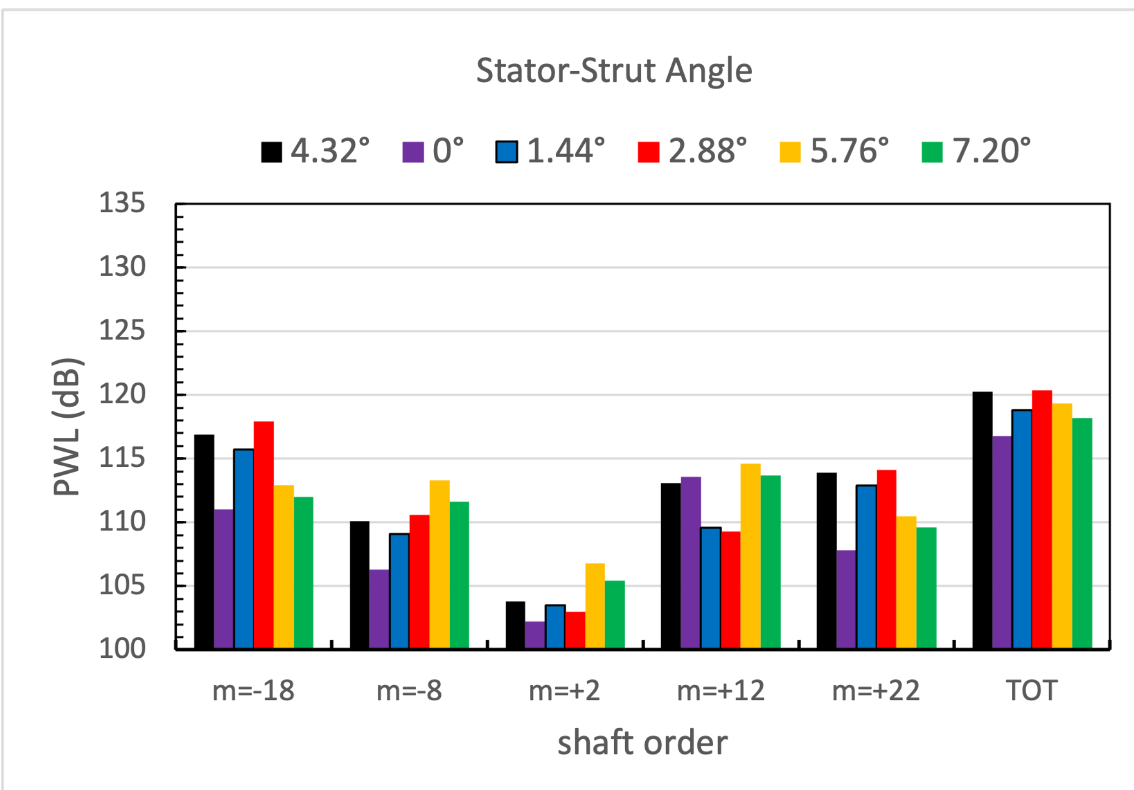


Figure 9: Rotor-Strut Interaction Modes vs ϕ : 90% RPMc, 1BPF with QHSF II Stator Vane Set Installed

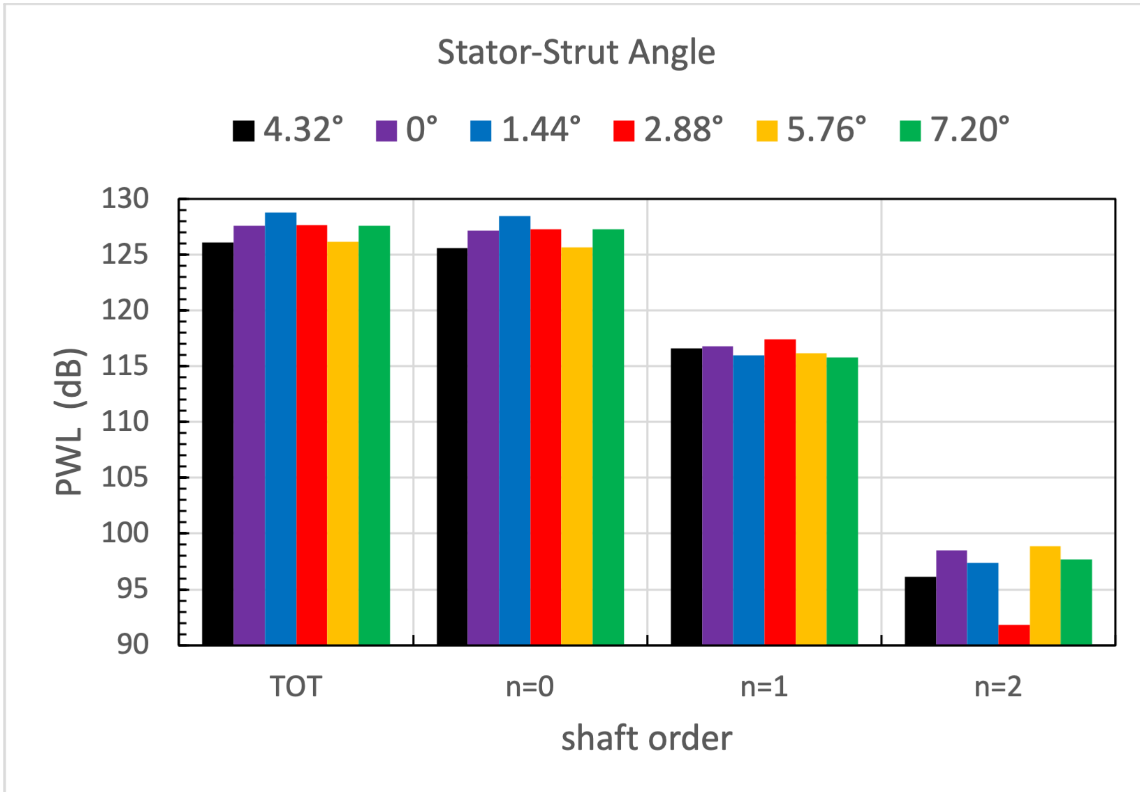


Figure 10: Radial mode variation in m=-18 with ϕ : 90% RPMc, 1BPF with Baseline Stator Vanes Installed

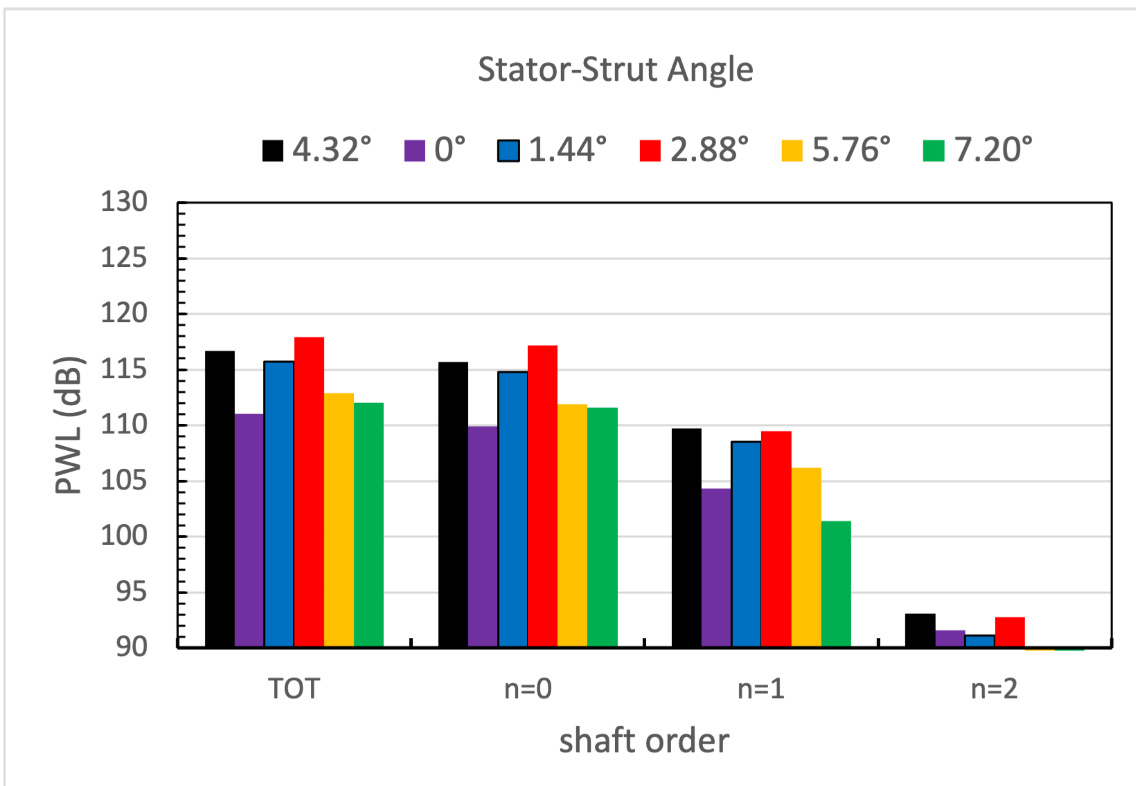


Figure 11: Radial mode variation in m=-18 with ϕ : 90% RPMc, 1BPF with QHSF II Stator Vanes Installed

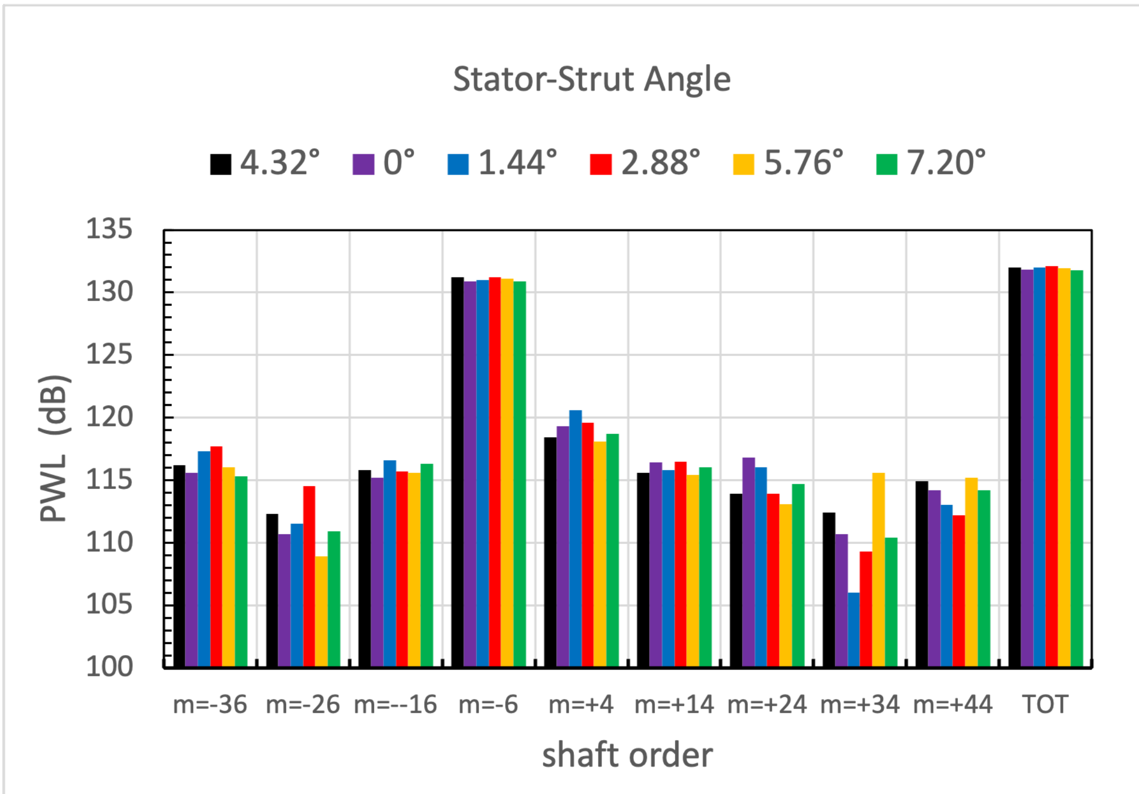


Figure 12: Rotor-Strut Interaction Modes vs ϕ : 90% RPMc, 2BPF with Baseline Stator Vanes Installed

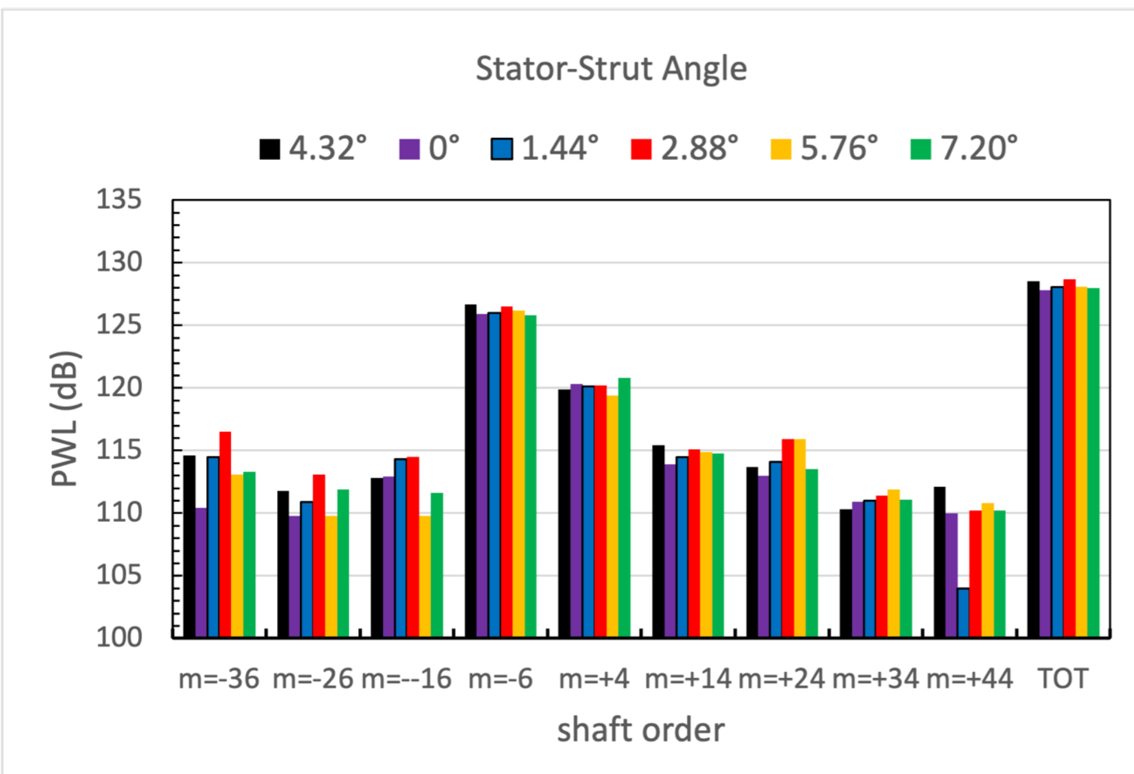


Figure 13: Rotor-Strut Interaction Modes vs ϕ : 90% RPMc, 2BPF with Stator Vanes QHSF II Installed

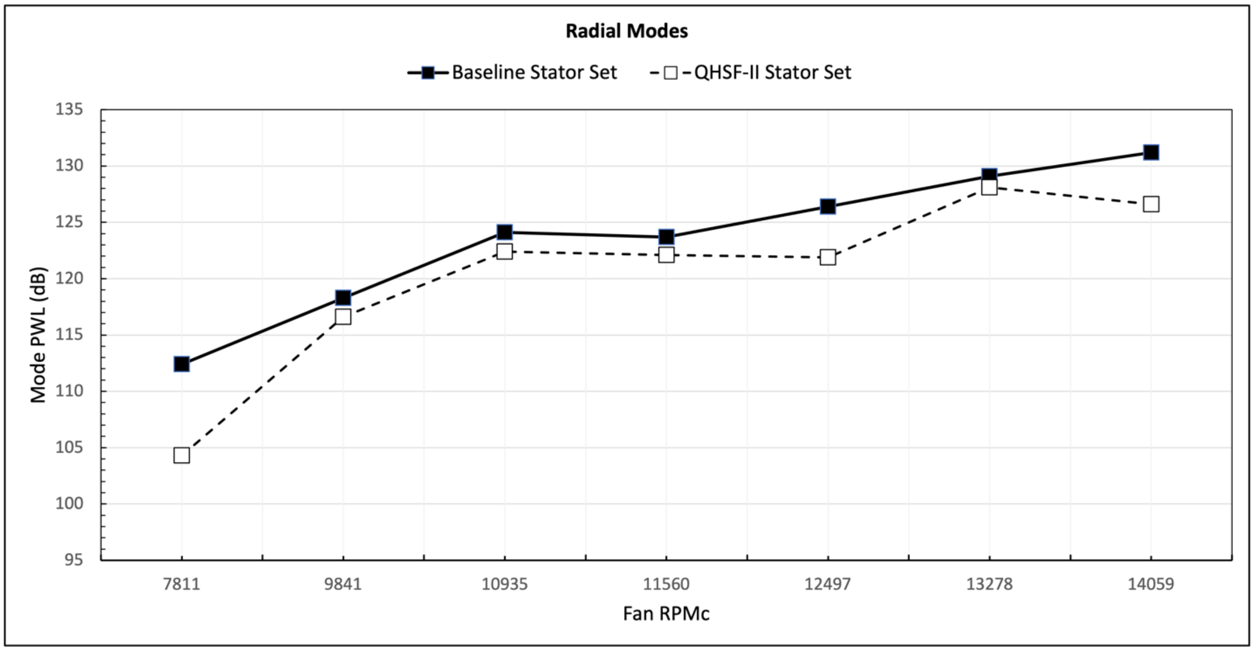


Figure 14: Rotor-Stator Interaction Mode PWL at 2BPF (m=-6) vs RPMc for Baseline Stator and QHSF II Vane Sets

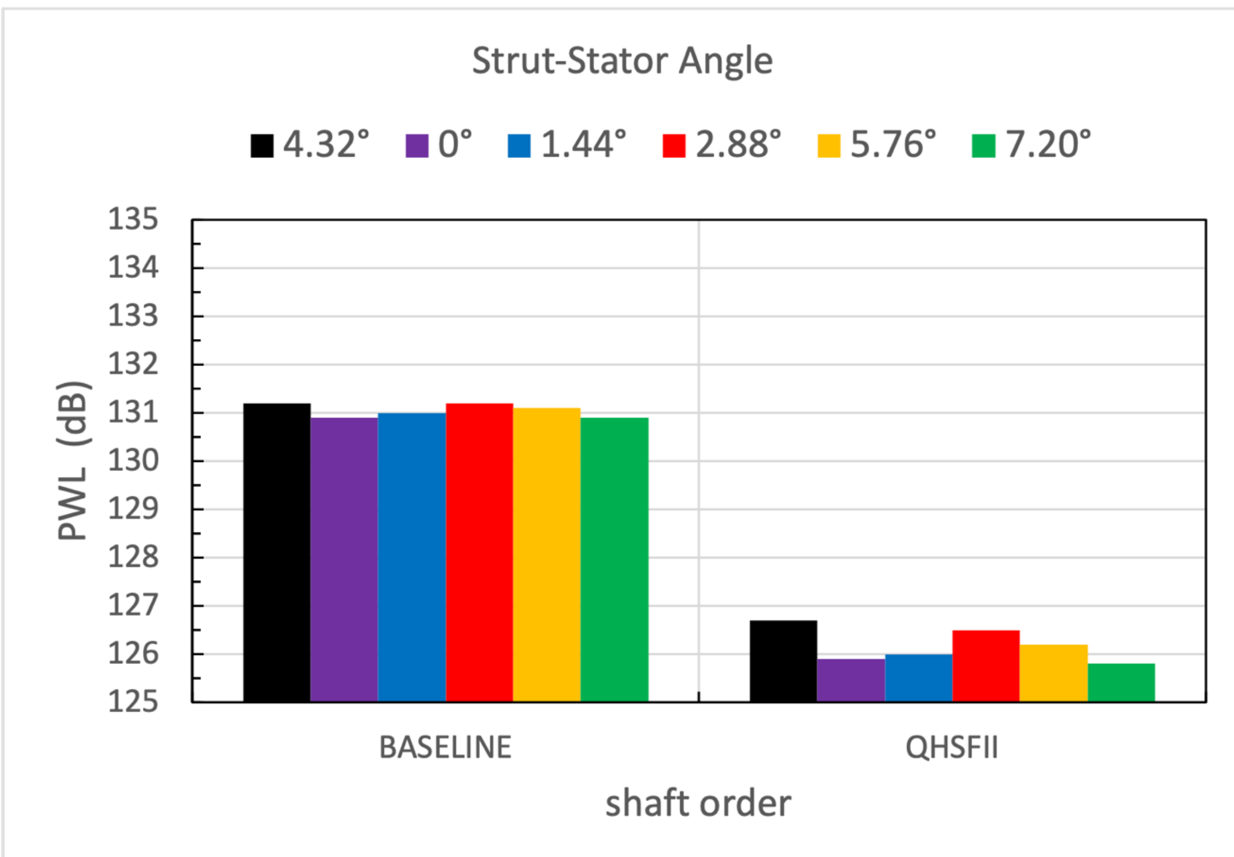


Figure 15: Radial Mode Variation with ϕ of Rotor-Stator Interaction Mode PWL : 90% RPMc, 2BPF (m=-6)

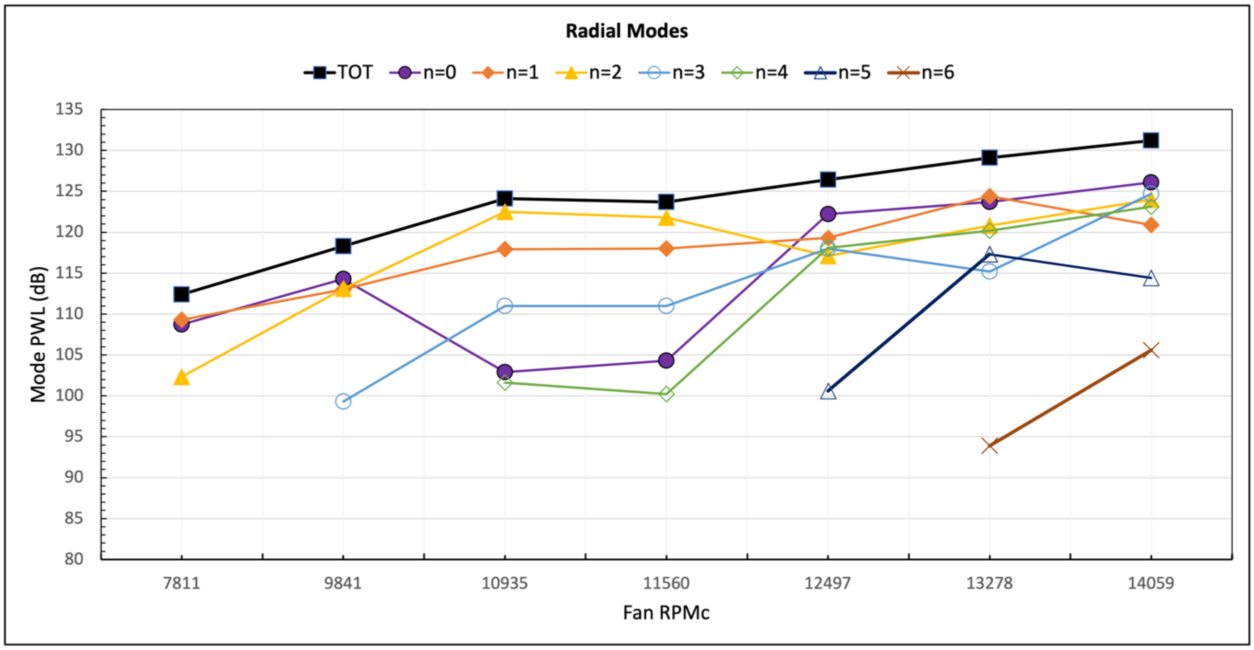


Figure 16: Rotor-Stator Interaction Mode PWL vs RPMc : 2BPF (m=-6) with Baseline Stator Vane Set Installed

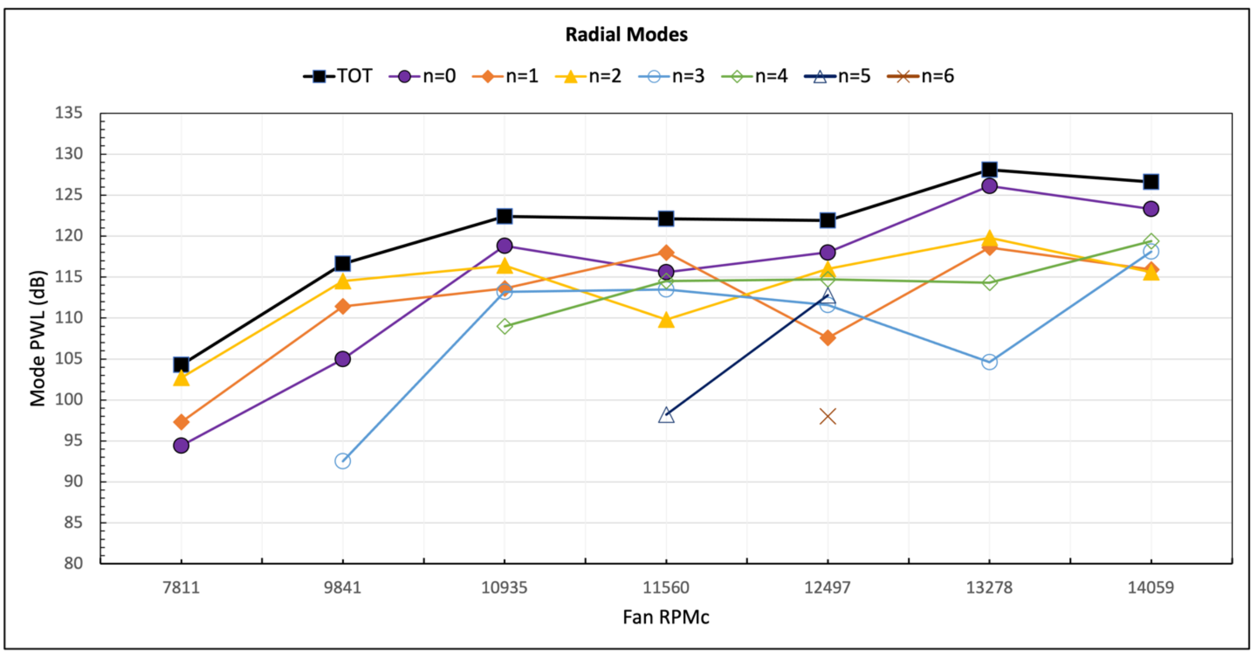


Figure 17: Rotor-Stator Interaction Mode PWL vs RPMc : 2BPF (m=-6) with QHSF II Stator Vane Set Installed

B. Analysis of Multiple-Pure-Tones in the Inlet Duct

The intent of this section is to describe the features of the rotor-locked modes or multiple-pure-tones (MPT) generated in the inlet when the rotor tip speed is above sonic (Ω_{fan} > 11,630 RPMc**)**. Data in the inlet were acquired only with the QHSF II stator vane disk set installed. Table VI shows the set point conditions for data acquired in the inlet.

Rotor-locked modes may be generated at the BPF and shaft orders below. A unique feature of rotor-locked modes is that the *m*-order (circumferential mode) is numerically equal to the shaft-order. That is, at a shaft-order of 22, the MPT mode generated is *m*=+22; at shaft-order of 21, the MPT mode generated is *m*=+21, decreasing numerically all the way down to *m*=+1; at shaft-order of 1. The non-linear mode Mach # / cut-off characteristic of the cylindrical wave equation solution results in the modes generated at the lower shaft order being cut-off before the rotor tip speed drops below sonic.

Figure 18 shows that at 85% RPMc, the rotor locked mode PWL does not vary with stator-strut vane clocking angle – with less than 0.5 dB range (max to min), which is less than the uncertainty. This result is not only phenomenon. Thus, in the following presentations, data from clocking angles of ϕ=3.6 or ϕ=4.32° are used complete data curves. The rotor-locked mode (*m*=+22) is plotted vs RPMc (both mode SPL and mode PWL) in Figure 19. A peak in rotor locked mode PWL at 12,497 RPMc fan is seen followed by decreasing strength as the RPMc increases.

Figures 20–23 show the PWL in rotor-locked shaft order modes at several corrected fan speeds. The PWL is set to 0 if the mode is mathematically cut-off (i.e cut-off ratio > 1.0). Mode sound pressure level amplitude (SPL) is also plotted – even below the cut-off frequency – since, while a cut-off mode does not propagate in an infinite duct, there is still a fixed decay rate. This pressure, while decaying exponentially, is still relevant as it will propagate into the far-field if not sufficiently decayed before encountering the duct release point. This can potentially impact duct nacelle wall structural fatigue. This condition occurs if the generated pressure level is very high and the mode is just below cut-on, or the duct length is short relative to the duct inner diameter.

Figure 20 presents the MPTs at 12,008 fan RPMc (77%) fan speed. At 1BPF (shaft-order 22) ζ = 1.000 for *m=+22,* and ζ = 0.997 for the MPT at shaft-order 21/*m*=+21. Therefore, MPTs for shaft-orders 21 and below are cut-off. The rotor-locked mode *m*=+22 is dominant. All others are 20 to 30 dB lower in mode SPL. At the shaft-order 1 (*m*=+1) there is significant mode SPL at the inlet release point (rake measurement plane) and could most likely propagate into the far-field. MPTs at 12,497 RPMc fan (80%) are shown in Figure 21. At this fan speed the cut-off ratio at BPF is ζ=1.061 with the lower shaft-orders cut-on down to 11. The rotor-locked mode PWL is very strong at 129.8 dB (144.7 dB SPL), with the other cut-on MPTs also notably stronger. Figure 22 presents the MPTs for 13,278 RPMc (85%) where ζ=1.240 and shaft-orders 4 and above are cut-on. The rotor-locked mode decreases, but the other MPTs are generally stronger, compared to the previous speed. Indeed, some of the mid-range MPTs are stronger than the rotor-locked mode. As seen in Figure 23 where the fan RPMc is 14,059 (90%) and ζ=1.296 the shaft orders are cut-on down to 3. The rotor locked mode is further reduced and lower order MPTs (8 and below) are even more noticeably above it. The strength of the rotor-locked mode and MPTs are significantly reduced at 15,821 RPMc (100%) ζ=1.653 and all MPTs are cut-on down to shaft-order 2 (Figure 24).

Table VI: QHSF II Test Points Acquired with RRMS in Inlet

Objective: Investigation of rotor-locked cut-on mode and MPTs

CONDITION	FNC,%	FNC,RPM	STATOR CLOCKING (ϕ)
approach	50	7,811	0°,1.44°,2.88°,4.32°,5.76°,7.2°
	63	9,841	4.32°
cutback	70	10,935	0°,1.44°,2.88°,4.32°,5.76°,7.2°
	74	11,578	4.32°
	77	12,008	4.32°
	80	12,497	4.32°
	85	13,278	0°, 1.8°, 3.6°, 5.4°
takeoff	90	14,059	0°,1.44°,2.88°,4.32°,5.76°,7.2°
	100	15,621	0°,1.8°,3.6°,5.4°
*At 85% & 100% FNC, clocking increments of 1.8 were used to match what was used in the CFD evaluation.			

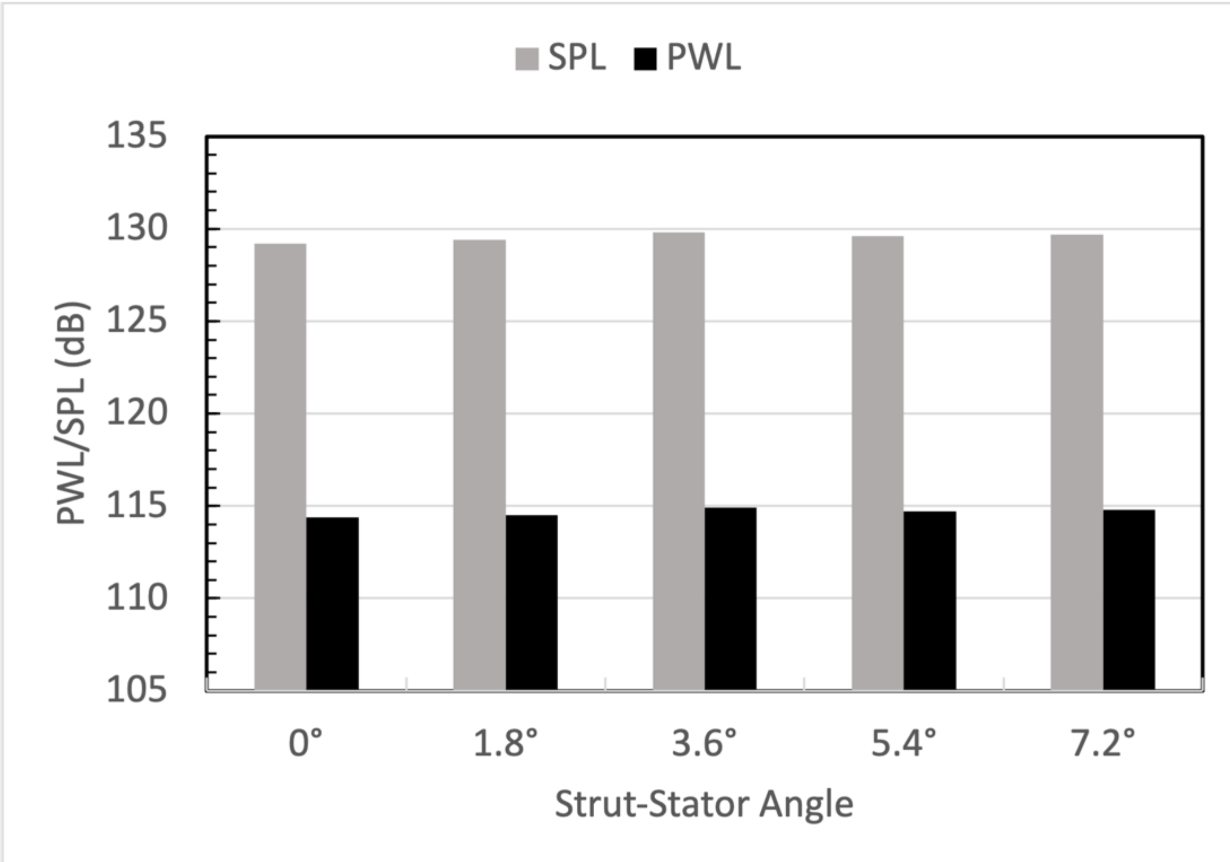


Figure 18: Rotor Locked Mode (Shaft Order/m-order=22) 85% RPMc : QHSF II Stator Vane Set

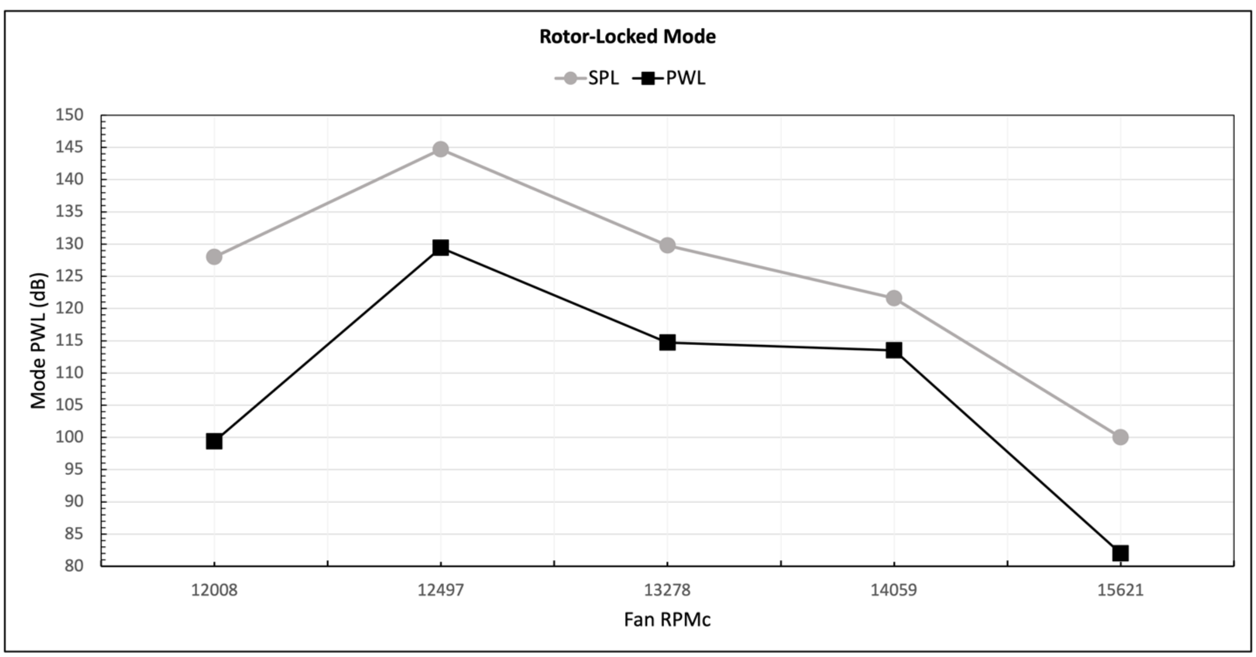


Figure 19: Rotor-Locked Mode (m=22) vs RPMc : QHSF II Stator Vane Set Installed

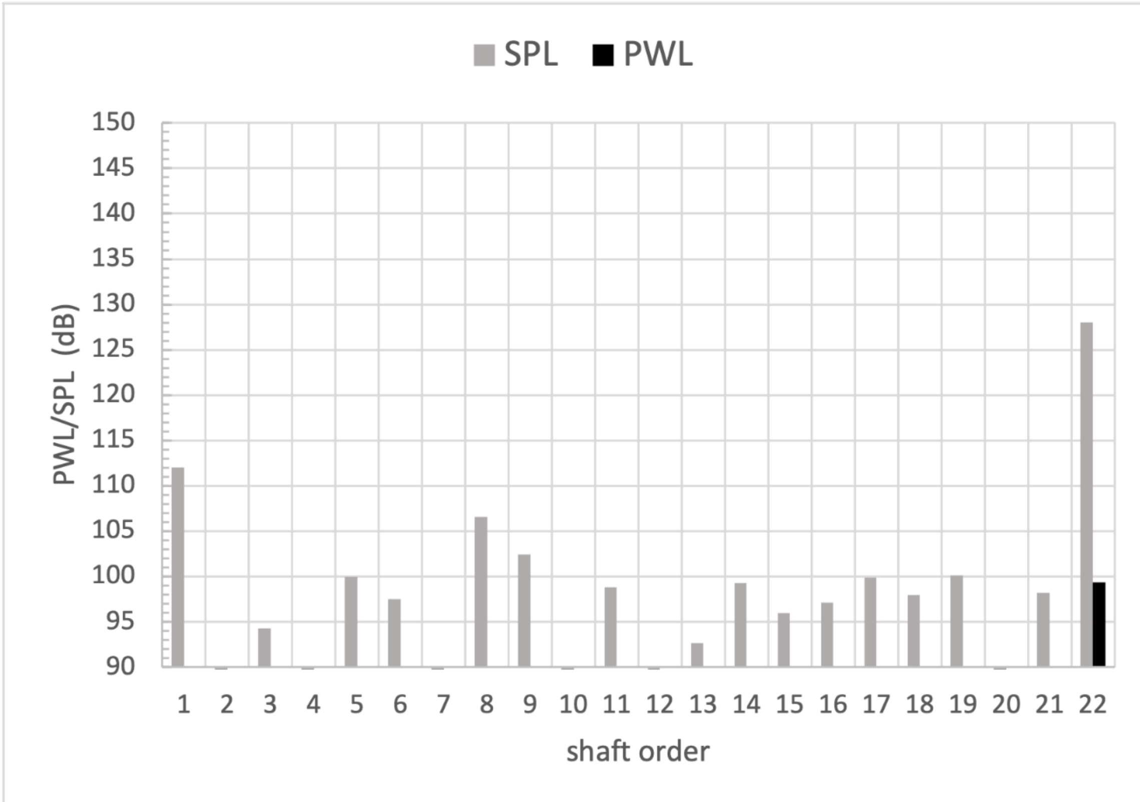


Figure 20: MPTs @ RPMc = 12,008 (77%) : QHSF II Stator Vane Set Installed / ϕ = 4.32°

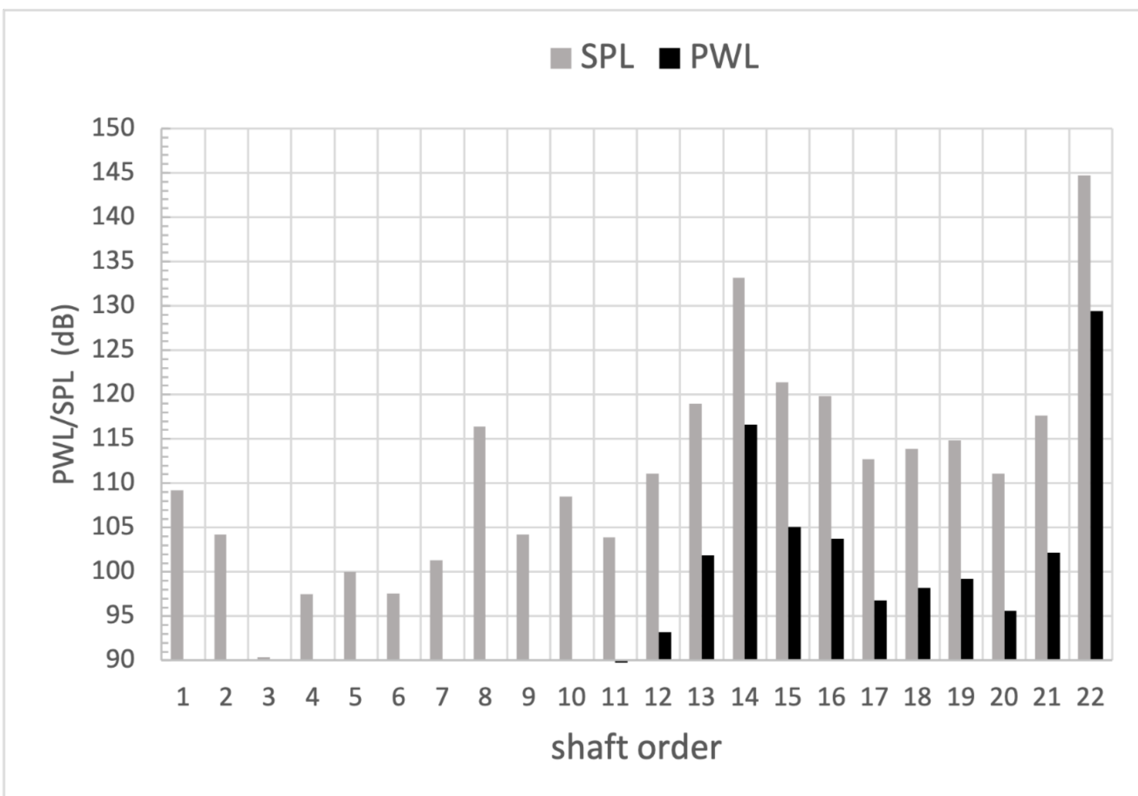


Figure 21: MPTs @ RPMc = 12,497 (80%) with QHSF II Stator Vane Set Installed / ϕ = 4.32

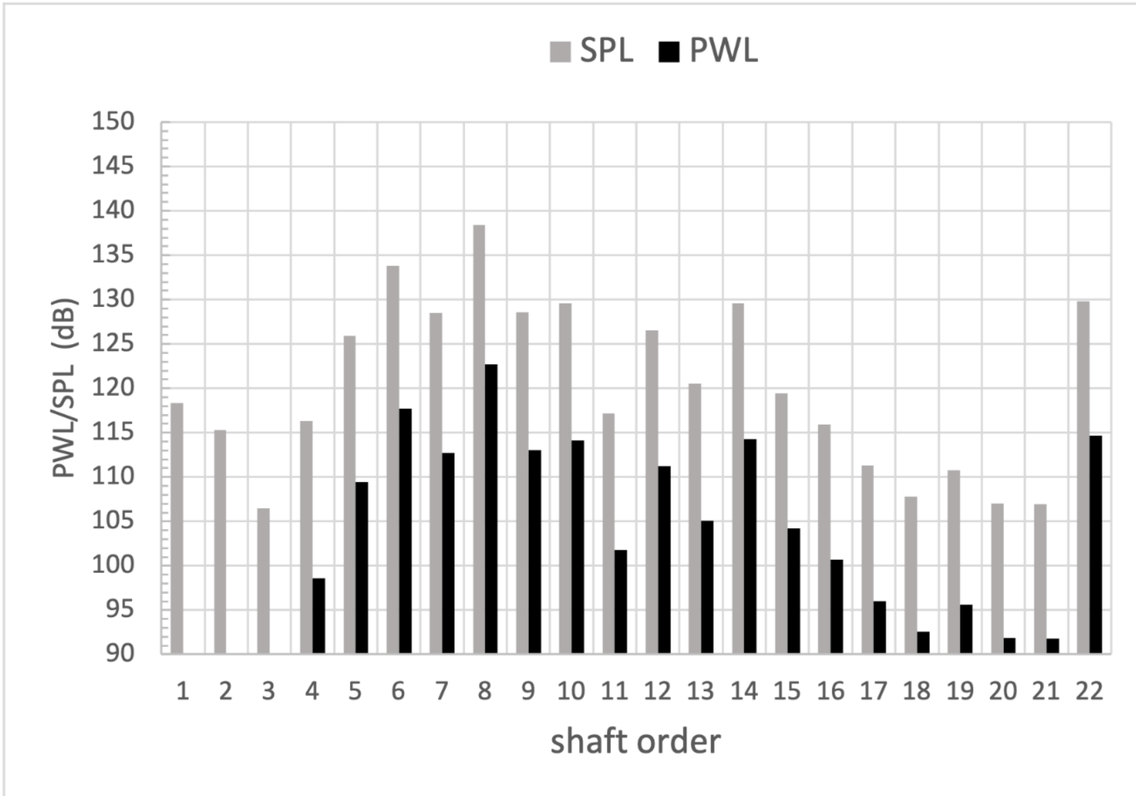


Figure 22: MPTs @ RPMc = 13,278 (85%) with QHSF II Stator Vane Set 77% / ϕ = 3.6°

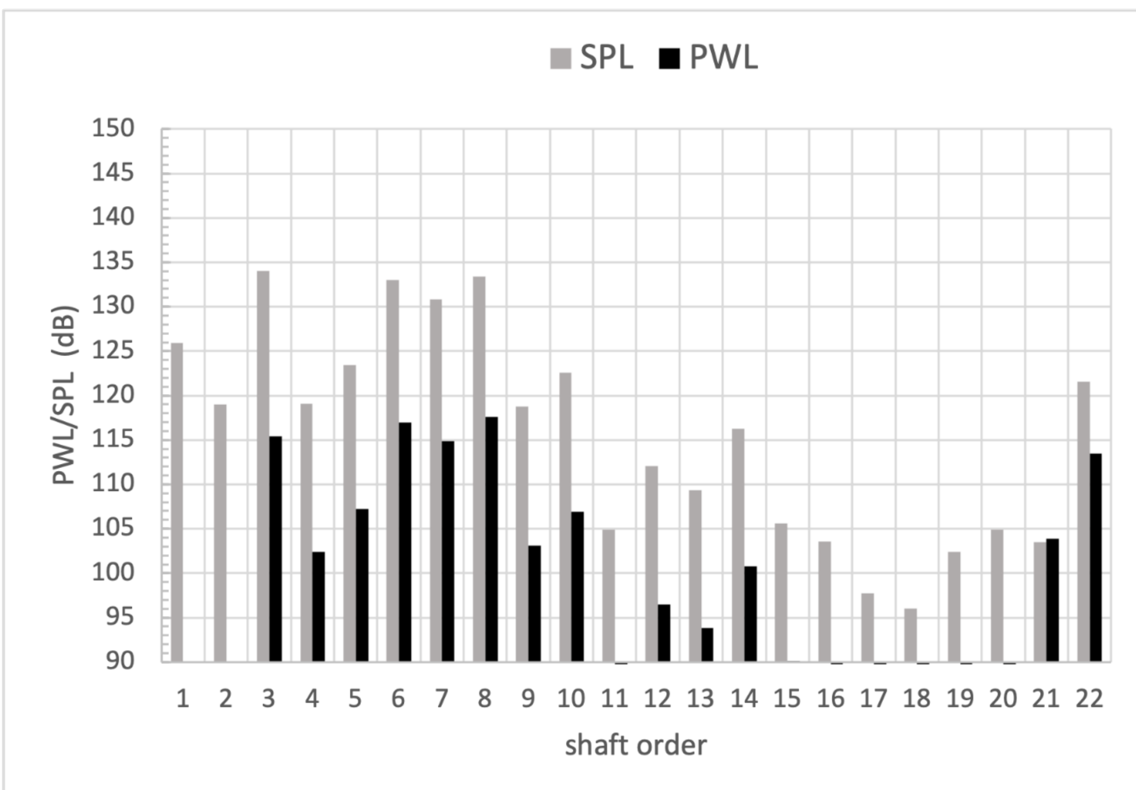


Figure 23: MPTs @ RPMc = 14,059 (90%) with QHSF II Stator Vane Set Installed % / ϕ = 4.32°

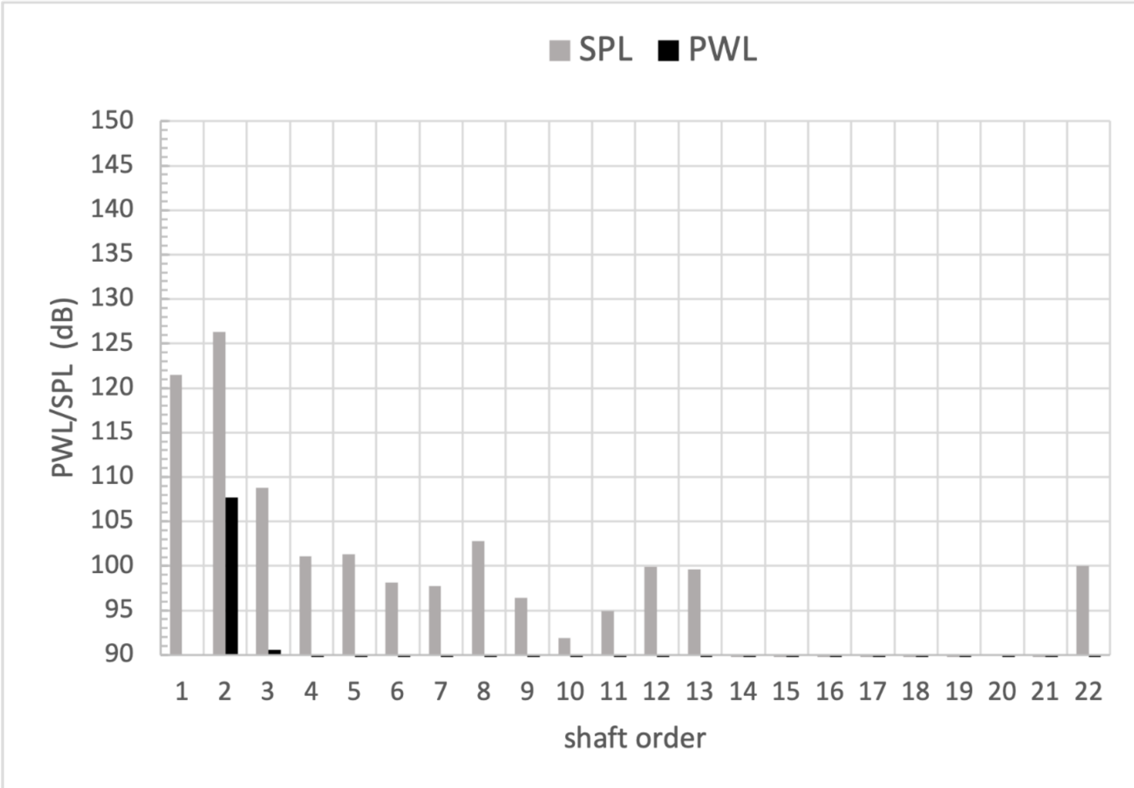


Figure 24: MPTs @ RPMc = 15,821 (100%) with QHSF II Stator Vane Set Installed / $\phi = 4.32°$

IV. Conclusion

Mode power levels (PWL) were measured by the NASA Glenn Research Center's Rotating Rake Mode Measurement System (RRMMS) in the exhaust and inlet ducts of a Honeywell Quiet High Speed Fan II (QHSF II) scale model that was tested in the NASA Glenn 9-by 15-foot Low Speed Wind Tunnel.

Two configurations of stator vane disk packs were tested along with the specifically designed rotor: A Baseline set of stator vanes and a set of stator vanes (also denoted QHSF II) designed to lower rotor-stator interaction noise and to mitigate the effect of the rotor wakes on the downstream support struts. Overall, the QHSF II stator vane set was determined to have significantly lower mode PWL than the Baseline set – up to 8 dB lower. This model had a stator clocking mechanism to change the relative circumferential position between the stators and support strut. Changes in the relative positioning between the stator vanes and support struts resulted in a ~7 dB variation in modal PWL at blade passing frequency, with the design clocking angle of ϕ=4.32° providing the minimum or near-minimum levels.

In the inlet, multiple pure tones were measured. The QHSF II rotor had lower rotor-locked mode PWLs than the earlier QHSF I, though the differences in data acquisition and processing over time make a direct numerical comparison difficult.

Significant enhancements to the RRMMS hardware and processing have been proposed for future duct mode measurements and analysis. These include a measurement technique to separate incident from reflected waves, processing to account for shear flow in the duct, with and without treatment. However, NASA has decided not to pursue these improvements and has instead elected to discontinue this unique capability.

Acknowledgments

The author would like to acknowledge the contributions of the Honeywell team for their design and manufacture of the Honeywell Quiet High Speed Fan II model. The staff of the NASA Glenn Research Center 9x15 Low Speed Wind Tunnel is commended for their professional job in the installation of the model and conduct of the test.

References

[1] Hubbard, H. Harvey, editor, Aeroacoustics of Flight Vehicles: Theory and Practice: Volume 1, NASA Reference Publication 1258, Vol 1, WRDC Technical Report 90-3052.

[2] Kontos, K., Weir, D., and Ross, D., "Quiet High Speed Fan II (QHSF II): Final Report", NASA/CR–2012-217451.

[3] Repp, R., Gentile, D., Hanson, D., and Chunduru, S., "Design and Test of Fan/Nacelle Models Quiet High-Speed Fan", NASA/CR—2003-212369

[4] Weir, D., "Design and Test of Fan/Nacelle Models Quiet High-Speed Fan", NASA/CR—2003-212370.

[5] Dittmar, J. H., Elliott, D.M., and Fite, E.B., "The Noise of a Forward Swept Fan," NASA TM-2003-212208.

[6] Heidelberg, L.J., "Comparison of Tone Mode Measurements for a Forward Swept and Baseline Rotor Fan", AIAA–2003-3292.

[7] Fite, E. B., "Overall Aerodynamic Performance Measurements for a Forward Swept Low Noise Fan", NASA/TM-2006-214413.

[8] Arrington, E.A. and Gonsalez, J.C, "Calibration of the NASA Lewis Research Center 9- by 15-Foot Low Speed Wind Tunnel", NASA CR–195438, 1994.

[9] Arrington. E.A. and J. C. Gonsalez J.C., "Flow Quality Improvements in the NASA Lewis Research Center 9- by 15-Foot Low Speed Wind Tunnel", NASA CR-195439, 1995.

[10] Dahl, M.D. and Woodward, R.P. "Acoustical Evaluation of the NASA Lewis 9- by 15-Foot Low Speed Wind Tunnel", NASA/TP–3274, 1992.

[11] Balan C. and Hoff, G.E., "Propulsion Simulator for High Bypass Turbofan Performance Evaluation," *SAE Technical Paper Series, 931410,* 1993.

[12] Sutliff, D.L. "Turbofan duct mode measurements using a continuously rotating microphone rake", *International Journal of Aeroacoustics*, vol 6, no 2, 2007, pps 147–170.

[13] Tyler, J.M., and Sofrin, T.G., "Axial Flow Compressor Studies", *SAE Transactions*, Vol. 70, 1962.

[14] Cicon, D.E., Sofrin, T.G., and Mathews. D.E., "Investigation of a Continuously Traversing Microphone System for Mode Measurement" NASA CR-168040, PWA-5846-26, November 1982.

[15] Sutliff, D.L., Konno, K.E., and Heidelberg, L.J., "Duct Mode Measurements on the TFE731-60 Full Scale Engine", NASA/TM–2002-211573, AIAA-2002-2564

[16] Dahl, M.D., "Assessment of NASA's Aircraft Noise Prediction Capability", NASA/TP–2012-215653.