

# Acoustic Testing of a High-Tip-Speed Fan With Bypass-Duct Liners—Overview

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### Acoustic Testing of a High-Tip-Speed Fan With Bypass-Duct Liners—Overview

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#### **Summary**

Under a pair of Space Act Agreements between NASA and Honeywell Aerospace, a model-scale (22-in.-diameter fan) acoustic wind tunnel test was carried out in the fall of 2014 in the NASA Glenn Research Center 9- by 15-Foot Low-Speed Wind Tunnel. The goal was to obtain far-field acoustic, inlet and exit rotating rake, and in-duct acoustic pressure measurements for a supersonic-tip-speed fan tested in three bypass duct configurations: hard-wall, traditional liner, and advanced multiple-degree-of-freedom. Limited aerodynamic data were acquired to verify the expected operating conditions. Preliminary analysis of the acoustic data finds it suitable for use in evaluating current NASA and Honeywell Aerospace acoustic tools and liner design practices.

#### **1.0** Introduction

The Predictive Tool Development (PTD) wind tunnel test was carried out as a combination of Space Act Agreement (SAA) activities with Honeywell Aerospace: a fully reimbursable company proprietary portion under SAA3–1334, and a nonreimbursable open, but time-restricted, release portion under SAA3–1372. The goal of the Honeywell fully reimbursable work is to collect data to be used in validating Honeywell's suite of aerodynamic and acoustic prediction tools. The goals of the NASA-funded nonreimbursable SAA were to collect data to validate the performance of an advanced multiple-degree-of-freedom (MDOF) liner as well as to assess NASA's design and analysis tool capability for this type of liner. The NASA portion of the test also included configurations of the rotating rake in order to assess improvements to the rotating rake processing. The data first produced under SAA3–1372 are being protected for 5 years after development and will become available to the public after December 9, 2019. Those data are reported in Miller, Stephens, and Sutliff, 2018. Honeywell data and designs shared with NASA but produced outside of SAA3–1372 remain Honeywell proprietary and are excluded from this report. These excluded details can be found in the government-only version of this report (Miller, Stephens, and Sutliff, 2017).

The Honeywell PTD model nacelle geometry and bypass flow-path are basically the same as those for the 2004 Quiet High Speed Fan II (QHSFII a.k.a. QHSF2) test (Woodward, Gazzaniga, and Hughes, 2004), also carried out in the NASA 9- by 15-Foot Low-Speed Wind Tunnel (9×15 LSWT) (Arrington and Gonsalez, 1995). For the PTD test, Honeywell used a fan developed under an internal Fan Module Demonstrator (FMD) project. The differences from the QHSF2 test include a modified core path, new blading for the fan and stator system, an active core booster, and a new strut and bifurcation. The nacelle lip, outer skin shape (skins were remanufactured), and nozzles were reused. The core plug, for adjusting bypass ratio, is a new shape, but it uses the same design and actuation system as used during the QHSF2 test. Design and test information on the QHSF2 fan are in Repp et al. (2003), Weir (2003), and Kontos, Weir, and Ross (2012). Figure 1 compares the previous QHSF2 with the current PTD test hardware, illustrating the similarities and differences.

#### 2.0 Model Specific Parameters

The FMD system is an improvement over the QHSF2—with a higher bypass ratio, lower fan pressure ratio, and a lower fan-tip speed. These changes are intended to improve efficiency and reduce noise. The blade counts for the present test hardware are given in Table I. Some comparisons between the present test and QHSF2 are given in Table II.



Figure 1.—Conceptual layout of the Predictive Tool Development (PTD) test, bottom, compared with the previously tested Quiet High Speed Fan 2 (QHSF2), top. The QHSF2 had a passive core; the PTD model has a boosted core. The PTD fan geometry is Honeywell proprietary (Miller, Stephens, and Sutliff, 2017), and the booster geometry is Space Act Agreement Limited Rights restricted (Miller, Stephens, and Sutliff, 2018).

TABLE I.—FAN MODULE DEMONSTRATOR (FMD) BLADE COUNTS [Bypass and core flow path split occurs downstream of fan and upstream of core inlet guide vane (IGV).] re has avit guide yong (ECV) unstream of corry through strute ]

I owered core has exit guide vale (EOV) upstream of carry-through struts.								
Path		Component: number of blades						
Bypass	Ean: 10		Vanes: 64		Strut: 8			
Core	ган. 18	IGV: 61	Booster rotor: 47	EGV: 80	Strut: 8			

#### TABLE II.—FAN PARAMETERS FOR THE FAN MODULE DEMONSTRATOR (FMD) USED IN CURRENT PREDICTIVE TOOL DEVELOPMENT (PTD) TEST AND QUIET HIGH SPEED FAN II (QHSF2)

Parameter	FMD fan <sup>b</sup>	QHSF2 fan <sup>c</sup>
Fan rotor diameter nominal size, in.	22	22
Fan rotor diameter at leading edge, in. (cm)	21.53556 (54.70032)	21.78714 (55.33934)
Aerodynamic design point, percent speed <sup>a</sup>	100	100
Aerodynamic design point, <sup>a</sup> N <sub>c</sub> , rpm	14 367	15 621
Test maximum physical speed, N, rpm	16 503	16 402
Corrected tip speed at aerodynamic design point, leading edge, ft/s (m/s)	1350 (411.5)	1485 (452.6)
Fan pressure ratio,		
Bypass	(Proprietary)	1.858
Core	(Proprietary)	1.762
Overall	1.690	1.840
Overall polytropic efficiency, percent	(Proprietary)	90.2
Bypass ratio	5.39	4.19

<sup>a</sup>Corrected revolutions per minute  $N_c = N / \sqrt{T_0 / T_{ref}}$ , where  $T_0$  is the tunnel temperature at stagnation condition and  $T_{ref}$  is standard day reference temperature.

<sup>b</sup>Pressure ratios, stage efficiency, and bypass ratio of FMD fan are Honeywell proprietary.

<sup>c</sup>Kontos, Weir, and Ross (2012).

#### 3.0 Facility

#### 3.1 The 9- by 15-Foot Low-Speed Wind Tunnel

The LSWT at the NASA Glenn Research Center has been used for acoustic and performance testing of aircraft propulsion systems for decades. The tunnel walls are acoustically treated, and a large muffler eliminates noise from the drive motors and compressor. A number of reports overview the facility including aerodynamic test capabilities and acoustic quality Arrington and Gonsalez (1995), Soeder (1993), Rentz (1976), Arrington and Gonsalez (1997), Dahl and Woodward (1992), Dahl and Woodward 1990), and Woodward et al. (1995). Testing has included model turbofans and propellers for both NASA research projects and external customers (Woodward, 1987; Woodward et al., 1992; Woodward et al., 2002; Woodward and Hughes, 2012; and Hughes et al., 2005). For all PTD testing, the test section free-stream Mach number  $M_0 = 0.1$ .

#### 3.2 The Ultra-High Bypass Drive Rig

The Honeywell fan was powered by Glenn's Ultra-High Bypass (UHB) drive rig described in Balan and Hoff (1993). This drive rig has a four-stage air turbine driven by compressed air generated by Glenn's 450-psig (3100-kPa) central air system. The UHB rig was refurbished in 2010 as part of the American Recovery and Reinvestment Act (ARRA) activities. A discussion of the rig's ability to hold a constant rpm is presented in Section 6.0, "Types of Data Acquired."

#### 4.0 Test Configurations

The model nacelle geometry and bypass flow path can be configured as either acoustic hard wall, with liner bay covers in place, or with acoustic liners in place. Figure 2 further illustrates the main features of the model.

In addition to the existing bypass duct outer wall liner bay, an additional liner bay was added to the new internal core-bypass nozzle (Figure 3).





#### 4.1 Hard-Wall Bypass Duct

The reference state for all aerodynamic and acoustic data is with the bypass liner bays, located downstream of the support struts, in a hard-wall configuration. The liner bay sections of the aft bypass duct are shown in Figure 3 and again in Figure 4 with the hard-wall surface in place. Note that Figure 4 shows the unsteady pressure sensors mounted in the hardwall liner covers. These sensors will be discussed in Section 6.2.4, "In-Duct Unsteady Static Pressure Measurements."

#### 4.2 Acoustic Barrier Wall

During a portion of the hard-wall far-field noise testing, an acoustic barrier wall was inserted in the test section (Figure 5) between the model and the far-field microphone traverse (Figure 6) to remove aft noise and provide far-field measurements of the inlet noise. The inlet noise contribution at aft far-field angles could then be estimated and used in the analysis of liner attenuation. The wall was placed approximately 24 in. (61 cm) offset from and parallel to the fan axis, and it extended axially from about 14 in. (36 cm) downstream from the plane of the inlet lip to past the aft end of the acoustically treated test section.



Figure 3.—Aft bypass duct acoustic liner bay locations. The inner and outer bypass duct liners have different designs, constrained by the shape of the installation bays. The available liner volume is shown with red hashing. The outer bay hard-wall surface is shown as a cyan overlay.



Figure 4.—Locations of four Endevco<sup>®</sup> model 8507C-5 (Meggitt PLC) unsteady pressure sensors mounted internally in the model. In the bypass duct, they are only present in the hard-wall configuration. The core path sensors are present in all liner configurations.



Figure 5.—Acoustic barrier wall placement in the 9- by 15-Foot Low-Speed Wind Tunnel test section. (a) View from the side of the model showing the barrier wall set back 14 in. (36 cm) from the inlet lip. (b) Forward-looking-aft view of the model with the barrier wall parallel to and offset 24 in. (61 cm) from the model rotation axis. Fan geometry is intentionally obscured.



Figure 6.—Acoustic barrier wall installed next to fan model in the 9- by 15-Foot Low-Speed Wind Tunnel test section. Microphones on the ceiling and floor are on model centerline, approximately 40° forward of the fan stacking axis. The three-element translating microphone and track are on the left, parallel to the model centerline, offset 89 in. (226 cm) from the model centerline. Fan geometry is Honeywell proprietary and is intentionally obscured.

#### 4.3 Traditional Liner

The Honeywell "traditional" liner is a set of inner and outer single-degree-of-freedom (SDOF) liners using a perforated face sheet over aluminum honeycomb, built using flight hardware techniques. The design points are different for the three liner sections—the outer section and the two depths of the inner liner, in effect creating an MDOF liner. In comparison to in-service liners, this liner has a face sheet porosity similar to in-service liners, and differing backing depths on the inner and outer liners, which provides differing tuning frequencies. Honeywell's intent was to assess the ability to achieve more broadband attenuation, similar to the design of the NASA MDOF liner, but implemented with a simpler manufacturing process.

#### 4.4 Multiple-Degree-of-Freedom Liner

A fabrication process developed and patented by Hexcel Corp. was use to design an advanced MDOF liner at the NASA Langley Research Center. Details of the liner design process are in Nark, Jones, and Sutliff (2016). This liner has a perforated metal face sheet over a polymer honeycomb, with porous mesh "caps" bonded into the honeycomb cells to split the depth. Because the mesh caps can be inserted to specified depths on a cell-by-cell basis, the technology can be used to fabricate SDOF (no mesh caps), double-DOF (DDOF—one mesh cap at the same depth in every cell) liners, as well as liners with

combinations of variable depth and multiple mesh caps—arbitrary-DOF. For this test, inner and outer MDOF liners were created using different cell types, and although the inner and outer design characteristics were different, the cell type within a set was the same. These included variable-depth SDOF cells and variable-depth, variable-resistance DDOF cells. The MDOF liner discussed in this report is expected to provide a wide broadband attenuation, as well as more attenuation than a SDOF liner. Design and implementation details for the MDOF liner have been included in a separate report on liner performance (Nark, Jones, and Sutliff, 2016).

#### 5.0 Instrumentation

During the pretest planning, instrumentation was defined and the associated critical minimum number of functioning sensors were identified. The following list summarizes the data collected, with sensor quantities in parentheses. Sensors used on a particular run configuration varied.

#### 5.1 Ultra-High-Bypass Drive Rig Health and Safety Instrumentation

A list of the health and safety instrumentation for the UHB drive rig follows:

- Thirteen bearing accelerometers (four related to shutdown)
- Fourteen bearing temperatures
- Two telemetry temperatures
- Two once-per-revolution (1/rev) and four 60/rev drive turbine speed pickups
- Ten turbine exit temperatures
- Nine lubrication oil flow meters
- Twelve lubrication system pressures
- Four lubrication system temperatures
- Seven 450-psig (3100-kPa) air system pressures
- Three turbine inlet and nine turbine exit air system temperatures, type K thermocouple

#### 5.2 Model Instrumentation

A list of the model instrumentation follows:

- Two-hundred thirty-three electronically scanning pressure (ESP) measurements—static and total pressure,  $P_s$  and  $P_t$ 
  - Two-hundred fifty-seven in the original plan
  - Twenty-four Ps lines removed from the front frame assembly because of fit and/or clearance problems,
- Rakes (Pt and total temperature Tt) behind the core path struts, and within the bypass strut region (see Figure 7)
- Forty-eight thermocouples
- Twelve tip-clearance cap probes
  - Eight in fan rub-strip
  - Four in booster rotor assembly
- One core plug position linear variable differential transformer (LVDT) sensor
- Four Endevco® model 8507C-5 (Meggitt PLC) in-duct unsteady pressure sensors
  - Two in bypass duct
  - Two in core duct
- Three nacelle accelerometers



Figure 7.—Aerodynamic instrumentation locations in Fan Module Demonstrator (FMD) model, where  $P_s$  is static pressure and  $P_t$  and  $T_t$  are total pressure and temperature, respectively. The FMD fan geometry is Honeywell proprietary, and booster geometry is Space Act Agreement Limited Rights restricted.

#### 5.3 Research Instrumentation

A list of the research instrumentation follows:

- Eight acoustic microphones: a single probe with three traversing and five fixed microphones
- Twenty-two Kulite Semiconductor Products, Inc., rotating-rake unsteady pressure sensors
  - Fourteen inlet rakes
  - Eight exhaust rakes
- Four rotating rake load cells between the drum and supports
- One shaft speed pickup, 144/rev, created from  $2 \times 72$ /rev; changed during the test to  $1 \times 90$ /rev

#### 6.0 Types of Data Acquired

#### 6.1 Aerodynamic Data

Real-time data acquisition and display was provided by Escort D+ (Fronek, 1987), the standard data system used in the large test facilities at Glenn. This system accommodates the ESP inputs, plus all steady-state analog and digital signals used, including survey rake and tunnel facility thermocouples and pertinent tunnel control parameters such as compressor speed, shock door positions, and positions of flow control doors. The Escort D+ facility microcomputer acquires these data, converts them to engineering units, executes performance calculations, checks limits on selected channels, and displays the information in alpha-numeric and graphical form at an update rate of 1/s. For this test, each collected data reading was the average of 13 scans (i.e., 13 s) of data. This provided a 3-s buffer on top of the 10-s acoustic reading acquired using the DataMAX, ensuring that the DataMAX finished recording before the microphone probe moved to the next position.

Steady-state pressure data were acquired with an ESP system. The ESP system uses plug-in modules, each containing 32 individual transducers, which can be addressed and scanned at a rate of 10 000 ports/s. Online calibration of all ESP transducers can be performed automatically every 20 min or at the discretion of the test engineer. Calibration is carried out by the operation of a pneumatic valve in each module, which allows the application of three pressures that have been measured with precision digital quartz transducers. Throughout this calibration program, the ESP transducers were calibrated roughly every 20 min. For this test,  $\pm 15$  psid ( $\pm 103$  kPa) modules were used.

Data in this test were collected under Escort Program D082.

#### 6.2 Acoustic Data

#### 6.2.1 Equipment

Standard acoustic instrumentation consists of Brüel & Kjær (B&K) type 4939 1/4-in. free-field microphones. A modified B&K UA–0385 nose cone windscreen was used for each sensor. Falcon Range type 2670, 1/4-in. microphone preamplifiers were used for some of the microphones, and Larson-Davis PRM902 0240 1/2-in. preamplifiers with B&K UA–0035 1/4- and 1/2-in. adapters were used for the remaining microphones. The microphones were powered by B&K Nexus condition amplifiers, and the data were recorded on an RC Electronics DataMAX DTX–9R 16-bit simultaneous sampling data acquisition system. Data were acquired at a sampling rate of 200 kHz and with a built-in anti-aliasing filter, resulting in a usable bandwidth of 80 kHz. The fan shaft 1/rev signal and the 144/rev (or 90/rev) signals were digitized simultaneously with the acoustic data.

#### 6.2.2 Microphone Layout

The primary microphone instrumentation is a three-microphone traversing probe on a sideline 89 in. (226 cm) from the fan model axis. A photograph and schematic of typical instrumentation are shown in Figure 8 and Figure 9. Here the three-microphone traverse measures 0° and  $\pm 22.5^{\circ}$  azimuthally from horizontal through the axis of the model when positioned at the 89-in. (226-cm) sideline. Additional fixed aft microphones are positioned along the 0° azimuthal position (horizontal center line) at approximately 140°, 150°, and 160° from upstream to fill in aft angles. Fixed floor and ceiling microphones are positioned  $\pm 40^{\circ}$  from the upstream fan axis.

For the discrete stops, the traversing microphone made recordings at 48 locations with roughly 2.3° arc spacing (in emitted angle) from 137.3° to 28.6° from upstream. These measurement locations are given in Table III. Continuously traversing microphone measurements were also acquired, with postprocessing used to produce measurements at any arbitrary angle within the range of traverse measurements.

After the test, it was found that, although the turntable was locked at the 0° position, the angle-ofattack sensor was not zeroed and was noisy, returning  $-0.39^{\circ}\pm0.05^{\circ}$  across the acoustic data runs. This angle of attack was collected, used in processing the data, and is reflected in the sideline directivity angles shown in Table III. Because the impact of this angle error is very small, the data were not reprocessed.



Figure 8.—View looking downstream in 9- by 15-Foot Low-Speed Wind Tunnel during Honeywell Predictive Tool Development (PTD) test. Fan geometry intentionally obscured.



Figure 9.—Select dimensions of standard acoustic measurement locations in 9- by 15-Foot Low-Speed Wind Tunnel. Flow from left to right. Not to scale; locations are approximate. All dimensions are in inches (centimeters).

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Stop	Angle	Stop	Angle	Stop	Angle	Stop	Angle	Stop	Angle	Stop	Angle
1	160.8	10	124.9	19	105.8	28	85.4	37	63.6	46	40.9
2	151.8	11	122.8	20	103.6	29	83.0	38	61.1	47	38.4
3	142.4	12	120.7	21	101.4	30	80.7	39	58.6	48	35.8
4	137.3	13	118.6	22	99.1	31	78.3	40	56.1	49	33.3
5	135.3	14	116.5	23	96.9	32	75.9	41	53.6	50	30.8
6	133.2	15	114.4	24	94.6	33	73.5	42	51.0	51	28.6
7	131.1	16	112.2	25	92.4	34	71.0	43	48.5		
8	129.1	17	110.1	26	90.1	35	68.6	44	46.0		
9	127.0	18	107.9	27	87.7	36	66.1	45	43.4		

TABLE III.—MICROPHONE STOP NUMBERS AND CORRESPONDING GEOMETRIC ANGLES IN DEGREES [Stops 1 to 3 are the aft fixed microphones. The data were processed with the angles listed in this table, but the true angles are about 0 39° lower ]

#### 6.2.3 Acoustic Signal Processing

The Digital Acoustics Data System (DADS) software package developed by Glenn's Acoustics Branch was used for data processing. DADS converts the proprietary DataMAX files into individual files for each instrument, stored in a simple binary format. Once the microphone gains were applied, calibrated time records of pressure in Pascals were obtained.

DADS also was used for postprocessing. The time records were used to calculate the narrowband pressure spectral density (PSD) functions, typically with 8192 data points, a 50 percent ensemble overlap, and a Kaiser window. The processing resulted in a bin width (frequency resolution) of 12.2 Hz. These PSD functions are called "as measured."

Next, the as-measured spectral density curves were corrected for the microphone and windscreen frequency response, giving "instrument corrected" spectra. Subsequently, the spectra were projected to a 1.000-ft (30.48-cm) arc and adjusted for atmospheric absorption to generate "1-ft lossless spectra."

Finally, each of the three (as-measured, instrument corrected, and 1-ft lossless) types of spectra were converted to the one-third octave band by summing the narrowband values in each one-third octave band. All records (one-third octave, narrowband, and time series) were saved. The accuracy of the data system is on the order of  $\pm 1$  dB (Dahl, 2012).

For a subset of the test conditions, measurements were made with the microphone moving continuously from one end of the traverse track to the other. This was typically done at a traverse speed of 1 in./s, corresponding to a time record of roughly 280 s. The traverse position was recorded simultaneously with the microphone signal and was used to calculate the geometric angle of the microphone from the center of the fan, for each point in the time series. To calculate acoustic spectra for an angle of interest, one needs to choose a segment of the time series that spans that angle. For the data presented in this report, a segment 0.5° wide was used. This resulted in record lengths that varied from 0.8 to 3 s. Because this is a new method (Shah et al., 2015) for recording data, only duplicate test conditions were recorded so that the method could be evaluated.

#### 6.2.4 In-Duct Unsteady Static Pressure Measurements

In-duct unsteady pressures were acquired with four Endevco<sup>®</sup> model 8507C-5 sensors mounted inside the aft ducts of the model during the test. Two transducers were flush-mounted on the outer fan bypass duct in the hard-wall liner bay cover, and the other two were mounted flush with the inner surface of the core flow path just before the exit of this flow path, as shown in Figure 4. The core path sensors were present for all liner configurations. The signals from these transducers were routed through a Precision Filters, Inc., model 28000 Signal Conditioner chassis with 28104A Quad Bridge Conditioner

cards and were again acquired by the DataMAX. After the test, the authors determined that the signal conditioner had mistakenly been set to low-pass filter the signals at 6000 Hz. It may be possible to use the published characteristics of the LP4F filter to recover a significant portion of the signal above 6000 Hz.

#### 6.2.5 Model Reference Signals

Model reference signals (1/rev, 90/rev, and the  $2 \times 72$ /rev rings described in Sec. 6.2.6, "Rotating Rake") as well as the microphone traverse position are simultaneously sampled and stored with the in-duct and far-field acoustic data.

#### 6.2.6 Rotating Rake

The rotating rake measurement system was developed and implemented by NASA Glenn in the 1990s to measure turbofan duct acoustic modes. The system is a continuously rotating radial microphone rake, synchronized to the fan shaft, which is inserted into the duct. The rotating rake provides a complete map of the acoustic duct modes (magnitude and phase) present in a ducted fan and has been used on a variety of test articles: from a low-speed, concept test rig (Loew et al., 2006) to a full-scale production turbofan engine (Sutliff, Konno, and Heidelberg, 2002). The rotating rake has been critical in developing and evaluating a number of noise reduction concepts as well as in providing experimental databases for verifying several aeroacoustic codes. More detailed descriptions of the unique rotating rake theory and application are in the references Cicon, Sofrin, and Mathews (1982) and Sutliff (2005).

For previous rotating rake entries, the typical configurations had a single inlet rake located with the acoustic measurement probe tips nominally aligned with the aerodynamic inlet plane (minimum inlet radius) and a single exhaust rake located at the exit plane (nozzle lip) of the bypass flow. Unique to this test entry was the addition of a second inlet rake mounted  $180^{\circ}$  circumferentially opposite and axially offset relative to the first. The intent was to separate upstream and downstream propagating modes. Traditional single-rake measurement and processing assumes that the modal energy propagates in one direction only; that is, there is no reflection off the inlet or exit impedance discontinuity. This "dual rake" concept was tested at two axial offsets. Table IV presents the rake configurations tested in this program. Figure 10 shows a photo of typical inlet rake setup in the 9×15 test section, Figure 11 illustrates the single and dual inlet configurations, and Figure 12 illustrates the exhaust rake configuration.

Designation	Туре	Rake 1 <sup>a</sup>	Rake 2 <sup>a</sup>		
		Model number	Position,	Model number	Position,
		(name)	Θ/δΖ,		$\Theta/\delta z$ ,
			deg/in. (cm)		deg/in. (cm)
I–A	Single inlet	59491M40A008 (QHSF-IN)	0/1.5765 (4.0043)	N/A	N/A
I–B	Single inlet	T–107684 (WI)	0/1.149 (2.919)	N/A	N/A
II–A	Dual inlet	59491M40A008 (QHSF-IN)	0/1.5765 (4.0043)	T-107684 (WI)	180/0.5 (1.3)
II–B	Dual inlet	59491M40A008 (QHSF-IN)	0/1.5765 (4.0043)	T-107684 (WI)	180/1.0 (2.5)
III	Single exhaust	59491M40A009 (QHSF-EX)	0/-0.3381 (-0.8588)	N/A	N/A

#### TABLE IV.—DESCRIPTION OF RAKE CONFIGURATIONS

<sup>a</sup>For inlet configurations, using either NASA QHSF-IN or Williams International WI rake,  $\delta Z$  is distance from inlet wall static ports (at aerodynamic inlet plane) to rake sensor plane,  $\delta z$  is axial offset of second rake. For exhaust configuration, QHSF-EX,  $\delta Z$  is distance from exit plane to rake sensor plane.  $\Theta$  is rake circumferential position relative to rake 1 (where  $\Theta = 0$ ).



Figure 10.—Typical inlet rotating rake setup.



Figure 11.—Dual rotating rake inlet configuration. As shown, upper (or single or standard) rake is positioned with sensors at aerodynamic interface plane (throat), and lower rake is positioned upstream of throat.



Figure 12.—Exhaust rotating rake configuration with rake sensors positioned at nozzle exit plane.

Rake model	Number of	Sensor locations	Hub-to-tip	Outer-wall radius,
	sensors	(normalized radius)	radius ratio	in. (cm)
59491M40A008	14	0.961, 0.936, 0.861, 0.783, 0.711, 0.632, 0.558, 0.482,	0	10.16 (25.81)
		0.405, 0.330, 0.253, 0.177, 0.097, 0.019		
T-107684	14	0.924, 0.888, 0.817, 0.735, 0.661, 0.587, 0.513, 0.438, 0.368, 0.293, 0.216, 0.146, 0.010, 0.019	0	10.17 (25.83)
		0.508, 0.275, 0.210, 0.140, 0.010, 0.017		
59491M40A009	8	0.960, 0.935, 0.904, 0.874, 0.836, 0.804, 0.773, 0.745	0.710	11.3 (28.7)

TABLE V.—RAKE GEOMETRIC DIMENSIONS

Certain geometric dimensions were required for the rotating rake processing. Because of imperfections and differences between the drawings and as-installed configuration, some estimation was required. Table V presents the relevant rake geometric dimensions used for the processing based on measurements and averaging.

During the inlet and nozzle testing with the rotating rake microphone, data were acquired on a Genesis High Speed GEN2i data system. To enable the synchronous sampling required by the rotating rake processing, a multiple-per-revolution shaft signal was used as the sample clock for the GEN2i (external sampling). A 144/rev magnetic encoder plate, using two 72/rev disks, was developed for this test. The guideline for selecting the *n*/rev signal was 8 times the number of fan blades (i.e.,  $8 \times 18 = 144$ ), to allow proper Nyquist criteria analysis up to and including the third fan harmonic, 3 times the blade passing frequency (BPF) of the fan  $(3 \times BPF)$ . Rotating rake testing performed early on during the test indicated that the 144/rev encoder had manufacturing defects. The 144/rev signal was generated by the electronic superposition of the transistor-transistor logic (TTL) signals generated from the two 72/rev disks. These two signal trains were designed to be 180° apart so that the electronic circuitry could distinguish the pulses and combine them into a single 144/rev TTL pulse train. However, because of a manufacturing defect, a single pulse from one of the 72/rev plates was too close to the prior pulse. The electronic "gate" was not yet open to detect and combine the next pulse, and therefore the pulse was not "seen." This resulted in a nonuniform 143/rev signal. It has been demonstrated that the rotating rake technique requires a precise, uniform, synchronous signal to operate. This effect can be seen in Figure 13 and Figure 14.



Figure 13.—Encoder signal details showing offset sensor pulse and resulting missing gated pulse. This offset is result of one magnet placement being outside of required manufacturing tolerance.



Figure 14.—Encoder signals showing entire encoder time history and effect of one misplaced magnet.

The remainder of the testing was accomplished with the previously used 90/rev encoder. However, the lower external sampling rate limits the upper frequency analysis limit to twice the blade passing frequency ( $2 \times BPF$ ). In addition, because of the on-the-fly-change in external sampling rate, the antialiasing filters were not adjusted. Normally, because of the harmonic fall-off of fan tones and the physics of Tyler-Sofrin (Tyler and Sofrin, 1962) mode generation, aliasing has not been a strong issue in rotating rake processing; however, because of the unique aspect of this test program, aliasing did have an effect.

The rotating rake speed is synchronized off the encoder signal. In this case, dynamic limitations caused the speed ratio to be 1:250 = (rake rpm):(fan rpm). The 250/rev rake signal was obtained with an electronic phase-locked multiplier for a ratio of 5:4 on the 200/rev signal generated from the physical card mounted on the rotating rake.

#### 7.0 Test Matrix

For all runs, the tunnel was operated with the test section free-stream flow at a Mach number of 0.1. In general the fan was operated at nine different corrected speeds varying from 27 to 93 percent. The intent was to go to 100 percent speed, but problems with the core plug position (described in Secs. 8.3, "Fan Operating-Line Comparison to Honeywell Rig Data" and 8.4, "Issues With Core-Plug Positioning") and rig bearing temperatures limited the maximum speed to 93 percent speed. When speeds were changed, the standard rate of 25 rpm/s was used.

Table VI provides an overview of the hardware configurations, type of data acquired, and the data owner; and Table VII lists in detail the readings where far-field acoustic data were taken.

#### 8.0 Data Analysis

This section contains a preliminary assessment of the model operation, an aerodynamic performance comparison with previous data, and a preliminary assessment of the acoustic data.

#### 8.1 **Revolutions-Per-Minute Stability**

The shaft speed in revolutions per minute (rpm) was set for each run and was held by a feedback control system, but there was some low-frequency drift from the set-point. Figure 15 shows both low-frequency oscillations with periods of 1.5 to 4 s, and a higher frequency oscillation with a period of about 0.5 s. The rpm was recorded during each of the 27 far field acoustic runs at each of 48 fixed microphone stops, providing 1296 samples of rpm stability. Figure 16 presents the measured shaft speed drift observed in these samples. The mean and standard deviation of rpm are scaled by the fan blade count in order to present the mean and standard deviation in terms of the fan BPF frequency. The standard deviation of the BPF tone is usually less than 1 Hz for all but the highest rpm (where it is usually less than 1.5 Hz). The processing has a bin width of 12.2 Hz, so tone smearing due to rpm drift should only be evident on fan harmonics above 8, or booster harmonics above 3, or fan+booster interaction tone harmonics above 2 (i.e., shaft orders above 146).

Test description	Liner	Rotating rake (RR)	Nozzle	Run	Escort readings	Customer	Date (2014)	Intellectual property rights <sup>a</sup>
Hardware install						Honeywell	Sept. 30	
Rig checkout to 3000 rpm	Hard wall		Flight	1	17–27	Honeywell	Nov. 4	SAA3-1334
Operating line, running clearance verification	Hard wall		Flight	2	28–44	Honeywell	Nov. 5	SAA3-1334
Flight nozzle checkout	Hard wall		Flight	3	47-60	Honeywell	Nov. 6	SAA3-1334
Far-field acoustics	Hard wall		Flight	4	61–92	Honeywell	Nov. 7	SAA3-1334
Far-field acoustics— acoustic barrier wall	Hard wall		Flight	5	93–119	Honeywell	Nov. 12	SAA3-1334
Far-field acoustics— traditional liner	Traditional		Flight	6	120–146	Honeywell	Nov. 13	SAA3-1334
Far-field acoustics— advanced liner	Advanced		Flight	7	147–183	NASA	Nov. 14	SAA3-1372
RR inlet checkout	Hard wall	Inlet	Flight	8	184–189	Honeywell	Nov. 19	SAA3-1334
RR inlet hard-wall	Hard wall	Inlet	Flight	9	190–221	Honeywell	Nov. 20	SAA3-1334
Dual RR inlet hard-wall, configuration IIA	Hard wall	Dual inlet	Flight	10	222–237	NASA	Nov. 21	SAA3-1372
Dual RR inlet hard-wall, configuration IIB	Hard wall	Dual inlet	Flight	11	238–253	NASA	Nov. 21	SAA3-1372
RR inlet, Williams International rake only	Hard wall	Inlet	Flight	12	254–269	NASA	Nov. 21	SAA3-1372
RR nozzle sizing	Hard wall	Aft	RR	13	270-276	Honeywell	Dec. 1	SAA3-1334
RR nozzle checkout	Hard wall	Aft	RR	14	277-290	Honeywell	Dec. 1	SAA3-1334
RR aft hard-wall liner	Hard wall	Aft	RR	15	291-315	Honeywell	Dec. 2	SAA3-1334
RR aft advanced	Advanced	Aft	RR	16	316-330	NASA	Dec. 3	SAA3-1372
RR aft traditional liner	Traditional	Aft	RR	17	331–347	NASA	Dec. 4	SAA3-1372
RR inlet hard-wall	Hard wall	Inlet	Flight	18	348-371	Honeywell	Dec. 8	SAA3-1334
RR inlet, Williams International rake only	Hard wall	Inlet	Flight	19	372–388	NASA	Dec. 8	SAA3-1372
Dual RR inlet hard-wall, configuration IIA	Hard wall	Dual inlet	Flight	20	389–405	NASA	Dec. 9	SAA3-1372
Dual RR inlet hard-wall, configuration IIB	Hard wall	Dual inlet	Flight	21	406–418	NASA	Dec. 9	SAA3-1372
Hardware removed from 9×15 LSWT <sup>b</sup>							Dec. 18	

## TABLE VI.—OVERVIEW OF TEST, SHOWING HARDWARE ONFIGURATIONS, TYPE OF DATA ACQUIRED, AND ASSOCIATED INTELLECTUAL PROPERTY RIGHTS

<sup>a</sup>Data under SAA3–1334 are Honeywell proprietary. Data under SAA3–1372 were acquired and are owned by NASA, but release is delayed.

<sup>b</sup>9- by 15-Foot Low-Speed Wind Tunnel.

Corrected	Hard-wall	48-Stop	discrete tr	averses		Continuous traverse at				
speed, percent	bypass duct (HW)					1.00 (2.54	) in./s · cm/s)		2.00 in./s (5.08 cm/s)	0.50 in./s (1.27 cm/s)
		HW with barrier <sup>a</sup>	SDOF <sup>b</sup>	MDOF <sup>c</sup>	HW	HW with barrier <sup>a</sup>	SDOF <sup>b</sup>	MDOF <sup>c</sup>	MDOF <sup>c</sup>	MDOF <sup>c</sup>
27				150				153	155	152
50	66	97	124	157						
61	71	99	126	159	73	101	128	161		
70	75	103	130	163						
75	77	105	132	165	73	107	134	167		
80	81	109	136	169						
82	83	111	138	171						
85	85	113	140	173				176	177	175
93	87	115	142	179	89	117	144	181		

## TABLE VII.—ESCORT READING NUMBERS FOR FAR–FIELD ACOUSTIC DATA ACQUIRED DURING HONEYWELL PREDICTIVE TOOL DEVELOPMENT (PTD) TEST

<sup>a</sup>With external acoustic barrier wall.

<sup>b</sup>Single-degree-of-freedom Honeywell acoustic liner.

<sup>c</sup>Multiple-degree-of-freedom NASA acoustic liner.



Figure 15.—Representative revolutions-per-minute (rpm) drift during acoustic sampling: run 150, traverse stop 1.



Figure 16.—Standard deviation of fan blade passing frequency (BPF) tone as function of mean fan BPF tone frequency, in revolutions per second (rps). Mean and standard deviation of shaft speed for every 10-s data acquisition of every far-field acoustic run (48 sideline stops  $\times$  27 runs) is shown multiplied by fan blade count *F* to show changes in terms of fan BPF tone. Higher order tones would have proportionally more deviation from mean.

#### 8.2 Aerodynamic Performance

Detailed aerodynamic performance was previously obtained with the model fan and core booster tested separately in the Honeywell fan test rig. The current configuration tested the fan and booster as a coupled system. During this test only limited aerodynamic data were obtained. This stage data verified that the fan stage performance was usually within  $\pm 1$  percent of the aerodynamic performance previously measured at Honeywell.

#### 8.3 Fan Operating-Line Comparison to Honeywell Rig Data

Fan pressure ratio and efficiency closely followed the Honeywell rig test data when the bypass ratio (core flow) could be matched. Note that the flow was computed from correlations supplied by Honeywell, which were valid above about 15 lb/s (7 kg/s) total, comprising above 13 lb/s (6 kg/s) for the bypass and above 2 lb/s (1 kg/s) for the core. In this test the lowest flow rate tested was 13.4 lb/s (6.1 kg/s) total. For most of the data collected, the bypass duct stage pressure ratio was within 1 percent of the Honeywell measurements, with only a few outliers falling within 2 percent of the Honeywell data. Further details can be found in the proprietary version of this report (Miller, Stephens, and Sutliff, 2017).

#### 8.4 Issues With Core-Plug Positioning

As mentioned before, the active booster pressurized the core flow path. The adjustable position core plug was used to adjust the bypass ratio to match data acquired in an aerodynamic performance rig at Honeywell. This was the first application of the powered dual flow path with core plug for this fan, and because of mechanical issues, the core plug would bind at a corrected fan speed of about 75 percent speed. As a result, for runs above 75 percent speed, the core plug position was set at low power and the model was run back up to the desired speed. The core plug also was unable to control flow for the highest



Figure 17.—Bypass ratio achieved as a function of core plug position.

speed settings, so the 83 percent speed position was used for 83 percent and higher. In addition, there were issues with the core plug position sensor, adding to the uncertainty. Honeywell will retest these higher speeds in their fan rig with the appropriate core flow rates in order to obtain details of the fan aerodynamics for the acoustic cases tested in the  $9 \times 15$  wind tunnel.

The inability of the core plug to control bypass ratio is detailed in Figure 17. In the design process, the computational fluid dynamics analysis used a two-dimensional model for the core path, which did not include the core path rakes used in the test. Current thinking is that the losses and blockage from the rakes reduced the core plug control authority.

#### 8.5 Acoustic Data

Data collected during this test include far-field, in-duct, and rotating rake collected in the inlet and exhaust nozzle.

#### 8.5.1 In-Duct Unsteady Pressures

The reference condition for all aerodynamic and acoustic data is with the bypass liner bays in a hardwall configuration. Unsteady pressure sensors (Endevco<sup>®</sup> model 8507C-5) were located in the outer bypass hard-wall liner—one at the front and one at the rear of the liner. These sensors provided a broadband noise reference level. There were similar sensors in the core path to provide the broadband noise from the core, but because there was no change to the core path hardware, data from these sensors were available for all configurations.

The broadband noise levels measured in the bypass duct are noticeably higher than the in-duct levels measured in the fan aerodynamics rig at Honeywell. This discrepancy could be due to forward propagating booster noise reflecting off of the fan and then propagating aft through the bypass duct, but this has not been investigated.

#### 8.5.2 Far-Field and Sideline Data

The tunnel was operated at Mach 0.1 for all data acquired during this test. This velocity was selected as a balance between providing sufficient flow cleanup into the inlet and minimizing the background noise level in the test section—thereby providing sufficient acoustic signal-to-noise ratio. It had the added benefit of only requiring one of the three tunnel drive motors, which reduced electrical power consumption.

Far-field data were acquired at the same 48 discrete positions along the microphone traverse and with the same three aft fixed floor microphones (shown in Figure 8 and Figure 9) used in the QHSF2 testing. In addition, data were acquired using a continuous traverse mode, where the traversing microphone moved at a constant fixed speed for a number of model hardware configurations and operating speeds. Continuous-scan data acquisition provided fine details of the directivity pattern (Shah et al., 2015) while allowing for faster data acquisition.

The continuous-scan data were processed by taking windows of  $\pm 0.25^{\circ}$  around the geometric angle of interest. This resulted in a varying data record size, depending on the sideline position of the traverse. The smallest number of data points coincides with the traverse at 90° to the fan model, since the traverse was moving most quickly through directivity angles at this location. Figure 18 shows spectra computed for each method. The shortest continuous-scan record was 0.79 s long, compared with 10 s for the fixed record. The shorter scan resulted in an obviously less converged broadband spectra, along with some differences in the tone levels. The broadband level could be smoothed by converting to one-third-octave band levels or by otherwise averaging over directivity angle and frequency.

Quantifying the tone level and directivity was considered a major advantage of the continuous-scan method. The tones were calculated by integrating around the expected tone frequency and including  $\pm 35$  Hz, or about three bins at the 12.2-Hz bin width used for the data. An example result is given in Figure 19. It can be observed that the fixed-stop method provided adequate resolution of the most forward and most aft tone directivity angles, but the sideline angles between 60° and 120° featured a complicated sound field that was underresolved by the 2° spacing. This conclusion on the directivity of the radiated noise is specific to a particular frequency tone and fan speed.



Figure 18.—Example spectra comparing continuous and fixed measurement methods. Spectral levels were normalized to 100 dB.



Figure 19.—Example of continuous-scan microphone data compared with fixed-stop measurement. Both spectra were adjusted by same offset to that peak tone level was normalized to 100 dB.



Figure 20.—Signal-to-noise ratio illustration: the background noise in the 9- by 15-Foot Low-Speed Wind Tunnel (9×15 LSWT) at Mach 0.1 is 7 to 30 dB below the broadband level for the Honeywell fan operating at 27 percent power with the multiple-degree-of-freedom (MDOF) liner installed.

The acoustic barrier wall was used to isolate the inlet-radiated noise by shielding the sideline microphone from aft-radiated noise. The barrier wall was expected to eliminate the interference pattern created by a tone propagating from the inlet and exhaust ends of the nacelle, and although this does seem to be the case at about 90°, the effect is rather small. Use of the barrier wall provides guidance on which directivity angles should be included in forward- and aft-radiated sound, and these angle ranges can be applied to model configurations where the barrier wall was not used, for example with the aft acoustic liners installed. These angle ranges are dependent on the fan speed and the tone being considered.

#### 8.5.2.1 Far-Field Directivity Levels

The signal-to-noise ratio for this test was quite good, ranging from 7 to 30 dB for broadband and 20 to 30 dB for all tones, as seen in Figure 20.

The directivity of the 1-ft (30.48-cm) lossless measurements was considered. Three tones were evaluated at each of the 51 sideline locations, along with the Overall Sound Pressure Level (OASPL) divided into tone and broadband components. OASPL was calculated by integrating the spectra between 750 Hz and 20 kHz. This integration was performed using the "trapz" function in MATLAB<sup>®</sup> (MathWorks<sup>®</sup>) to perform trapezoidal integration of the pressure spectral density over frequency. The tone and broadband separation was calculated with the use of a modified moving median filter, as described in Section 3 of Stephens and Vold (2014). The method identifies the "broadband" portion of the spectra, which is then subtracted from the total spectra to get the "tonal" portion of the spectra.

#### 8.5.2.2 Integrated Sound Power Level

Sound power levels in watts were computed from the 1-ft (30.48-cm) lossless spectra using the following expression to integrate over a 1-ft radius sphere:

$$\Pi = \frac{2\pi r^2}{\rho_0 c_0} \int_0^{\pi} p'^2 \left(\theta_e\right) \left(1 - M_0 \cos \theta_e\right)^2 \sin \theta_e \, \mathrm{d}\theta_e \tag{1}$$

where *r* is the integration radius,  $\rho_0$  is the tunnel free-stream air density,  $c_0$  is the free-stream speed of sound, and *p'* is the root-mean-squared amplitude of the sound pressure. The integration is limited to the range of emitted angles  $\theta_e$ , calculated from the microphone geometric angles  $\theta_g$  (28.6° to 160.8°; Table III) using  $\theta_e = \theta_g - \sin^{-1}(M_0 \sin \theta_g)$ , where  $M_0$  is the free-stream Mach number of the tunnel.

Free-stream density and speed of sound were calculated from tunnel steady-state measurements, using

$$\rho_0 = \frac{P_0}{RT_0} \tag{2}$$

where  $P_0$  is the tunnel free-stream pressure, R is the gas constant, and  $T_0$  is the tunnel free-stream temperature in degrees Rankine (Kelvins), and

$$c_0(\mathrm{m/s}) = 331.3 + 0.606T_0 \tag{3}$$

where  $T_0$  is now the tunnel free-stream temperature in degrees Celsius. Typically for the present test,  $\rho_0$  was 0.0724 lb/ft<sup>3</sup> (1.16 kg/m<sup>3</sup>) and  $c_0$  was 1132 ft/s (345 m/s). Sound power in decibels was computed using the usual  $10^{-12}$  W reference power:

$$PWL(dB) = 10\log_{10}\left(\frac{\Pi}{10^{-12} \text{ W}}\right)$$
(4)

Sound power was evaluated for individual tones, as well as for the overall tone and broadband portions of the spectra. For tones, the ideal frequency of the tone was identified, and three frequency bins on either side were included in the integration. For the overall (total, broadband, and tone) portions of the signal, the same 750 Hz to 20 kHz limits were used as previously discussed. These calculations were done for all four configurations and eight speeds listed in Table VII. The configuration with the acoustic barrier (barrier) serves to coarsely quantify noise radiated from the inlet and can be compared with the isolated hard-wall configuration. For example, the fan BPF tone typically radiates aft because the barrier and both acoustic liners attenuate it significantly. However, at 85 percent speed, the tone is much stronger and radiates out the inlet. This is reasonable to expect because the fan tip is sonic and produces strong multiple-pure tones.

Figure 21 shows the liner performance as a reduction in total sound power level from the hard-wall configuration.



Figure 21.—Liner performance expressed as reductions from hard-wall total sound power level.

#### 8.5.2.3 Representative Effective Perceived Noise Level

The noise metric of importance to the certification of a commercial aircraft is the Effective Perceived Noise Level (EPNL). Publications describing this analysis and the results include Berton (2012) and Guynn et al. (2011). This process is sometimes used to estimate the noise from a concept aircraft by including multiple noise sources, specific flight trajectories, throttle settings, and other realistic features to make a sophisticated noise prediction. For the present report, a simple EPNL calculation provides a way to "roll-up" the detailed sideline noise measurements into a single value. A straight and level flyover at an altitude of 1500 ft (457.2 m) and Mach 0.1 was used, with one engine at a scale factor of 1 for the wind tunnel data. A Doppler shift was included in the calculation, and the EPNL number includes the tone correction penalty.

The calculation was performed with two different codes, a simple MATLAB<sup>®</sup> script and the NASA software program ANOPP2 (v1.1.1.10643) (Lopes and Burley, 2011), to confirm that the application of the new ANOPP2 tool was done correctly. Both methods gave similar results, as seen in Figure 22. Tool verification was also carried out with data from the QHSF2 test data of 2004, and the MATLAB<sup>®</sup> calculations compared favorably with the previous analysis performed using DADS (see Figure 23). ANOPP2 and DADS EPNL calculations use 1/3-octave-band data as inputs at the sound source, whereas the MATLAB<sup>®</sup> tool used narrowband spectra at the sound source that were converted to 1/3 octave band after calculating the noise at the observer location. This may account for some of the differences observed in Figure 22.



Figure 22.—Effective perceived noise level calculated for 1500-ft (457.2-m) flyover with single engine, scale factor = 1, and Mach = 0.1, with tone correction, Doppler, and no ground effects. MATLAB<sup>®</sup> script was used to verify application of ANOPP2. Decibel values are Honeywell proprietary data.



Figure 23.—Effective perceived noise level calculated for 1500-ft (457.2-m) flyover with single engine, scale factor = 1, and Mach = 0.1, with tone correction, Doppler, and no ground effects. Digital Acoustics Data System (DADS) was used for Quiet High Speed Fan II (QHSF2) 2006 calculation. MATLAB<sup>®</sup> was used for QHSF2 2015 calculation. PTD, Predictive Tool Development; MDOF, multiple degrees of freedom. Decibel values are Honeywell proprietary data.



Figure 24.—Effective perceived noise level reduction due to liner attenuation, showing the increased attenuation from the NASA multiple degree of freedom (MDOF) liner at lower fan speeds.

As a means to evaluate liner performance, the EPNL calculation shows a larger range of results than the sound power. Figure 24 has a comparison of the liner attenuation as a function of percent speed for both the Honeywell and NASA MDOF liners. Attenuation provided by the NASA liner decreased from 3.9 dB at 50 percent speed to 1.1 dB for 93 percent speed. When measured by sound power (Figure 21), the attenuation values were as much as 2.5 dB at 50 percent speed, dropping to 1.9 dB at 93 percent speed.

#### 8.5.3 Rotating Rake Data

Table VIII summarizes the run logs. The individual run logs, time histories, and processed data are archived in digital storage. Data were acquired over the fan speed ranges of 50, 61, 70, 75, 80, 82, 85, and 93 percent of full-speed, 14 316  $N_c$  (corrected rpm). The three rating points (approach, cutback, and takeoff) are 61, 75, and 93 percent  $N_c$ ; generally, these points were repeated for all configurations. The daily run logs provide additional information including the corresponding Escort number.

Date	Designation	Location	Rake descriptor <sup>a</sup>	Data file	Runs	Encoder
Nov. 20, 2014	I–A	Inlet	QHSF–IN	HW14_IN1_	001–011	$72/\text{rev} \times 2$
Nov. 21, 2014	I–B	Inlet	WI	HW14_IN1	012-017	$72/rev \times 2$
Nov. 21, 2014	II–A	Inlet	QHSF–IN+WI $\delta z = 0.5$ in. (1.3 cm)	HW14_IN2_	001–006	$72/rev \times 2$
Nov. 21, 2014	II–B	Inlet	QHSF–IN+WI $\delta z = 1.0$ in. (2.5 cm)	HW14_IN2	007–012	72/rev × 2
Dec. 2, 2014	III–HW	Exhaust	QHSF-EX	HW14_EX	001-012	90/rev
Dec. 3, 2014	III–AL	Exhaust	QHSF-EX	HW14_EX	013-019	90/rev
Dec. 4, 2014	III–TL	Exhaust	QHSF-EX	HW14_EX	020-027	90/rev
Dec. 8, 2014	I-A-90	Inlet	QHSF–IN	HW14_IN1_	018-029	90/rev
Dec. 8, 2014	I-B-90	Inlet	WI	HW14_IN1	030-038	90/rev
Dec. 9, 2014	II-A-90	Inlet	QHSF-IN+WI	HW14_IN2_	013-020	90/rev
			$\delta z = 0.5$ in. (1.3 cm)			
Dec. 9, 2014	II-B-90	Inlet	QHSF–IN+WI $\delta z = 1.0$ in. (2.5 cm)	HW14_IN2	021-024	90/rev

TABLE VIII.—OVERALL ROTATING RAKE RUN LOG

 $a\delta z$  is axial offset between the two rakes.

The rotating rake processing involved two main results amenable to analysis: Fourier processing of the time histories and modal reduction. The first step of Fourier processing is the ensemble averaging of the time histories and subsequent fast Fourier transform (FFT) processing. This is considered an intermediate step used primarily for verification. The FFT processing was performed on a shaft-order analysis, and the results were stored in a MATLAB® file with a file name of the form "spec DATA FILE ###.mat". The file contains the spectra of the sensors followed by the three timing signals. The primary verification was examining the spectra of the fan 1/rev and the rake 250/rev to make sure that the fan and rake were synchronized. Because the rake was running at 1/250th of the fan speed, both of these spectra should have peaked exactly in the SO bin corresponding to SO = 1. Figure 25 shows that for a typical run the rake and fan were synchronized. Generally, the rake was shown to be synchronized throughout the rotating rake portion of this test. The spectra of the sensors can be analyzed quickly for verification purposes by verifying that the primary tones are synchronized about the fan harmonics in terms of  $h \times F$  normalized to SOs, where F is the number of blades in the fan rotor. Unique to this test were the interaction tones between the fan and the booster (Sutliff and Marotta, 2016), which should show up at integer combinations of fan and booster SOs:  $h \times F \pm k \times B$ , where h and k are integer multipliers, and B is the number of blades in the booster rotor. Figure 26 identifies the traditional fan harmonic tones and the unique fan and booster interaction tones. Table IX shows the expected harmonic and interaction tones in terms of SOs.



Figure 25.—Fast Fourier transform (FFT) of fan 1/rev and rake 250/rev signals showing synchronization at shaft order 1.



Figure 26.—Fast Fourier transform (FFT) of typical sensor (run 12, mic 3, with 18 fan rotor blades *F* and 47 booster rotor blades *B*) showing exhaust primary tones at fan harmonics and the fan/booster interaction tones unique to this test program. Decibel values are Honeywell proprietary data.

	$\mathcal{O}$	intuit	01110	1010		(LIU)	1101			
Multiplier on fan blade passing frequency, $h$	+1	+2	+1	+3	+1	+4	-1	+2	+5	0
Multiplier on booster blade passing frequency, $k$	0	0	0	0	+1	0	+2	+1	0	+2
SO	18	36	47	54	65	72	76	83	90	94

TABLE IX.-SHAFT-ORDER (SO) HARMONIC TONE GENERATION

The second verification step was to identify the dominant circumferential modes present by examining the quick plots produced by the batch modal processing of the data. The expected circumferential *m*-order modes are based on the well-known Tyler-Sofrin fan-stator interaction and fanstrut interactions (Sutliff, 2005). Currently, this quick analysis is available for the fan harmonics only. Table X presents the expected *m*-order interactions. Figure 27 shows the circumferential-mode-order distribution in the exhaust at 93 percent fan  $N_c$  for the 1 × BPF fan tone. Results for the hard-wall, Honeywell traditional, and advanced NASA MDOF liner configurations are in Miller et al. (2018).

Additional data validation can be accomplished by comparing points acquired at two different times within the same run, which can be considered an informal repeatability. Figure 28 shows that the repeated levels are within 1 dB, as has been the case historically.

TABLE X.—EXPECTED TYLER-SOFRIN INTERACTION CIRCUMFERENTIAL MODES, BASED ON THE FIRST FAN HARMONIC

[1  an rotor blade count  T = 16, 0  ypass duct buildt guide value count  T = 04, and support struct count $S = 6.]$									
		Tyler-Sofrin interaction circumferential modes							
		Fan harmonic interaction							
	$1 \times F$	$1 \times F$ $2 \times F$ $3 \times F$							
Fan-stator interaction	+18	-28, +36	-10, 54						
Fan-strut interaction	-14, -6, +2, +10, +18	-36, -28, -20, -12, -4, +4, +12, +20, +28, +36	-50, -42, -34, -26, -18, -10, -2, +6, +14, +22, +30, +38, +46, +54						



Figure 27.—Typical circumferential mode distribution (fan blade passing frequency at 93 percent speed with interaction modes measured by rotating rake in the exhaust). Decibel values are Honeywell proprietary data.





Figure 29 shows the FFT of a single microphone from the inlet rake at the takeoff fan rpm. The fan harmonics and multiple pure tones (MPTs) can be seen. The MPTs are generated at shaft-orders (SO) below and above the first fan harmonic (F = SO = 18) and with a circumferential *m* order equal to the SO. These MPTs can be analyzed in the same manner as the fan harmonics and are plotted on Figure 30. As a result of the eigenvalues, at the lower shaft-orders, which equal *m* order, the cutoff ratio actually decreased—to the point that for 5 and below the mode was cut off classically. The pressure was still measured by the rotating rake and is quite strong because of the nature of the shock; it is plotted at all SOs. The power also is plotted at each SO. Here the mode pressure is plotted along with the mode power level, because even if an MPT was cut off acoustically, there was still a significant pressure pulse because of the originally high levels from the fan. Although the mode was cut off classically, very high pressures were present at the rotating rake measurement plane (i.e., the release point), so it is likely that some of the decaying pressure radiated to the far field. Hence power was computed as if the mode were cut on as in Sutliff and Dahl (2016). This is also reported in Figure 30.

The measurements in the inlets of modern fans tend to be less "interesting" because of the design practices. Typically the vane count is chosen such that the fan-vane interaction mode is contrarotating (negative *m* order) and therefore more susceptible to blockage by the fan. Figure 31 and Figure 32 show the circumferential mode power level distribution at the fan BPF for two speeds: cutback and takeoff, respectively. At cutback (Figure 31), the strut interaction modes can be seen, and at takeoff fan  $N_c$  (Figure 32), the rotor-locked mode (where *m* order = blade count) can be seen. Figure 33 shows the modal power level distribution at 2 × fan BPF, again for the takeoff  $N_c$ .



Figure 29.—Fast Fourier transform (FFT) of typical inlet sensor (rotating rake run 029, mic 3) showing primary tones at fan harmonics and multiple pure tones (MPTs). *F* is fan shaft order. Decibel values are Honeywell proprietary data.



Figure 30.—Circumferential modal content in the inlet at  $2 \times$  fan blade passing frequency for 93 percent fan rotational velocity (rpm)  $N_c$ . For this condition, shaft orders equal *m* orders. Decibel values are Honeywell proprietary data.



Figure 31.—Circumferential modal content in the inlet at the fan blade passing frequency for the cut-back *N<sub>c</sub>* (75 percent). Interaction modes were measured by the rotating rake. The decibel values are Honeywell proprietary data.







Figure 33.—Circumferential modal content in the inlet at the fan second harmonic (2  $\times$  fan BPF) for the takeoff  $N_c$  (93 percent). Interaction modes were measured by the rotating rake. The decibel values are Honeywell proprietary data.

The mode measurements from the inlet portion of the rotating rake data were found to be problematic. Preliminary analysis did not identify the expected modal content. The initial assumption was made that the fan rotor blockage reduced the mode content significantly. However during the test a serendipitous opportunity arose to perform diagnostic measurements on the rotating rake setup. Recall from Sutliff (2005) that the rakes are normally fitted with a windscreen to mitigate flow effects. In the inlet the primary beneficial aspect of the windscreen is to eliminate the Strouhal shedding from the rake body, which may fall in the frequency range of interest depending on the flow and geometry conditions. The addition of the windscreen was shown to eliminate the Strouhal shedding without changing the magnitude or phase of the interaction modes in back-to-back windscreen off and on measurements for low-speed fan rotating rake measurements based on experience by the author (Sutliff, 1997). Back-to-back measurements are not available for the high-speed installation of the windscreen (Heidelberg and Elliot, 2000). It was assumed that the windscreen behavior would be identical in higher frequency or higher speed flow.

During the test, a rub of the inlet rake in position 1 against the nacelle inner wall resulted in a small portion of the windscreen being released from the rake body, exposing three of the sensor probes near the base of the rake. Figure 34 shows the damage to the windscreen. Because a replacement windscreen could not be fashioned immediately, the authors decided to take advantage of the scheduled test time and run without the windscreen installed on rake 1 as shown in Figure 35. Figure 36 presents the spectrum from sensor 1 (closest to the nacelle wall) during a run with the windscreen fully intact and from a run at the same rpm with the windscreen removed. The results were surprising. The spectrum is attenuated nearly 20 dB across the frequency range because of the presence of the windscreen. This attenuation is confirmed in the time history seen in Figure 37.

The time history from sensor 1 on rake 1 during the "rub-run" was plotted in Figure 38 to investigate if this attenuation was due to a system gain setting change or to another possible "glitch" between the two runs. Although the exact time of the rub was not determined, it is reasonable to identify where the rub and breakup of the screen chunk occurred. Furthermore, the amplitude at the beginning of this time history matches the amplitude from the run with the windscreen fully intact, and likewise the amplitude at the end of this time history matches the amplitude from the run with the windscreen fully removed. Figure 39 provides further evidence that the windscreen had a significant effect on the measured levels. The time history from all 14 sensors is plotted as acquired during the "rub-run." The time histories for sensors 1 to 7 are plotted in part (a): sensors 1 and 2 are most affected by the loss of the screen, and sensors 3 and 4 are less affected. Sensors 5 to 7, along with sensors 8 to 14 (part (b)) are not affected. (Refer back to Figure 34 to correlate to the sensor location.)



Figure 34.—Close-up of inlet rake showing damage to the rake windscreen and rub mark on the nacelle lip.



Figure 35.—Dual rake mounting showing the windscreen removed from rake 1 (configuration QHSF–IN).



Figure 36.—Spectra of sensor 1 on rake 1 with and without the windscreen (separate runs). The decibel values are Honeywell proprietary data.



Figure 37.—Time history of sensor 1 on rake 1 with and without the windscreen (separate runs).



Figure 38.—Time history of sensor 1 on rake 1 during the rub event.



Figure 39.—Time history of rake 1 sensors during the rub event. (a) Sensors 1 to 7, near the casing and the loss of windscreen. (b) Sensors 8 to 14, far from the casing. The effect of the windscreen loss is maximum at sensor 1, nearest to the casing, and reduces to nearly zero difference by sensor 5.

The inlet data are considered to be unreliable because of the unanticipated attenuation caused by the windscreen. The authors strongly recommend further investigation into the effects of a foam metal windscreen in high-speed flow or an alternative method for flow-effect mitigation.

Analysis of the exhaust rotating rake measurements, identification of fan rotor-locked and interaction modes, and comparison with predicted liner performance can be found in Sutliff, Nark, and Jones (2016). The only significant mode is the fan rotor-locked mode, in this case  $2 \times \text{fan BPF}$ , or m = 36.

#### 9.0 Conclusion

Wind tunnel testing has obtained engine model inlet, exhaust, and far-field acoustic data with the bypass duct in a hard-wall configuration, as well as with two different acoustic liners. In general, the NASA-designed multiple-degree-of-freedom liner performed better than the multiple design point set of single-degree-of-freedom liners designed to be fabricated with current in-flight product techniques. Preliminary analysis of the acoustic data finds it suitable for use in evaluating current NASA and Honeywell Aerospace acoustic tools and liner design practices.

В	booster rotor blade count
C	speed of sound
F	fan rotor blade count
h	Tyler-Sofrin interaction multiplier for first blade count
n k	Tyler-Sofrin interaction multiplier on second blade or vane count
л М	Mash number
IVI	
т	Tyler-Sofrin interaction circumferential mode order
N	fan revolutions per minute
Р	pressure
р	sound pressure
PWL	rotating rake sound power level relative to $10^{-12}$ W, dB, Eq. (4)
R	gas constant
r	integration radius, Eq. (1)
S	support strut count
Т	temperature
V	bypass duct outlet guide vane count
W	fan mass flow
$\delta Z$	distance from inlet wall static ports at aerodynamic inlet plane to the rake sensor plane
$\delta z$	axial offset of second rake
Θ	circumferential position relative to the reference axis of the rotating rake
θ	angle
П	sound power level, W, Eq. (1)

## Appendix—Symbols

 $\rho$  air density, slugs/ft<sup>3</sup> (kg/m<sup>3</sup>)

## Subscripts

0	tunnel freestream condition
С	calculated and corrected using pressure and/or temperature ratios to standard day values
е	emitted, between forward axis of fan rotor and sound emission direction
g	geometric, between forward axis of fan rotor and sound propagation direction (microphone location)
ref	standard day reference condition, 59 °F (15 °C) and 14.6959 psia (101 325 Pa)
S	static
t	total

#### Superscripts

' root-mean-squared amplitude

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