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In reply please refer to:  
SSC:DTFAWA-10-C-00041/15

31 August 2017

FEDERAL AVIATION ADMINISTRATION  
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Room 402  
Washington, D.C. 20591

Subject: Revised Swedish Biofuel Performance Evaluation, **FR-27652-5**

Reference: Contract No. DTFAWA-10-C-00041, Item No. 15

In accordance with the applicable requirements under the referenced contract, Pratt & Whitney herewith submits one (1) copy of the Swedish Biofuel Performance Evaluation for the subject contract.

Sincerely,



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**CONTINUOUS LOWER ENERGY, EMISSIONS, AND NOISE  
(CLEEN)**

**PRATT & WHITNEY CLEEN TECHNOLOGIES**

**FINAL REPORT — PUBLICLY RELEASABLE VERSION**

Prepared for  
Federal Aviation Administration  
AJA-482 Exec & Manage Supp Team  
800 Independence Ave, SW  
Washington DC 20591

Prepared under  
Other Transaction Agreement (OTA) No. DTFAWA-10-C-00041

In Response to  
CDRL No. 15

Prepared by  
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**TERMS AND ACRONYMS**
**Numerics**

3-D Three-Dimensional

**B**

BOM Bill of Material

BPF Blade Passing Frequency

**C**

CFD Computational Fluid Dynamics

CIPT Component Integrated Product Team

CLEEN Continuous Lower Energy, Emissions, and Noise

**D**

DDR Detailed Design Review

**E**

ERA Environmentally Responsible Aviation

ESW Engineering Standard Work

**F**

FAA Federal Aviation Administration

FEGV Fan Exit Guide Vane

FPR Fan Pressure Ratio

FTB Flying Testbed

**G**

GTF Geared Turbofan

**L**

LPC Low-Pressure Compressor

LPT Low-Pressure Turbine

**O**

OEM Original Equipment Manufacturer

OTA Other Transaction Agreement

**P**

P&W Pratt & Whitney

PDR Preliminary Design Review

**T**

TRR Test Readiness Review

**U**

UHB Ultrahigh Bypass

## 1. EXECUTIVE SUMMARY

Pratt & Whitney (P&W) successfully concluded all activities included as part of the technology maturation efforts covered by the Federal Aviation Administration's (FAA's) Continuous Lower Energy, Emissions, and Noise (CLEEN) Program as outlined in Other Transaction Agreement (OTA) DTFAWA-10-C-00041. Key technologies matured included ultrahigh bypass (UHB) technologies through scaled fan rig and ground engine test, as well as support and development of strategies for drop-in replacement of alternative fuels. P&W led the alternative fuel evaluation original equipment manufacturer (OEM) team and characterized four fuels in support of the initiative. Ground engine test results were used to update a Vision engine performance assessment demonstrating that UHB technologies, when incorporated with other technologies into the Vision engine, result in projected performance that contributes significantly to meeting CLEEN program goals (**Table 1-1**). Note that CLEEN program goals are for the aircraft system, and the expectation was that engine-only technology would not be able to achieve the goals. The P&W goals for fuel burn and noise were -20 percent and -20 EPNdB, respectively. The technologies included in the CLEEN program were the majority contributor to achieving P&W goals.

**Table 1-1.** Vision Engine Incorporating UHB Technology Demonstrated in CLEEN Program and Other Technologies Under Development Contribute Significantly To Meeting CLEEN Program Goals

<i>Metric</i>	<i>Goal<sup>1</sup></i>	<i>Status-Vision Engine</i>
Fuel Burn	-33%	-20+%
Noise	-32 EPNdB (Stage 4)	-20+
Emissions	60% reduction in NOX	-60+%

<sup>1</sup> Relative to a Boeing 737-800/CFM56-7B

The three major demonstrators (**Figure 1-1**) evaluated as part of the CLEEN effort included a low-loss fan exit guide vane (FEGV) configurations in a simplified UHB fan rig, a scaled fan rig testing of the UHB system in collaboration with the NASA Environmentally Responsible Aviation (ERA) program, and ground testing of the UHB demonstrator engine with a combined test time in excess of 475 hours. In addition to comprehensive aerodynamic and acoustic performance and aeromechanical test programs, a complementary set of pretest predictions were made to validate advanced computational fluid dynamics (CFD) analysis tools. Comparison between engine ground demonstrator test results and the scaled UHB Demonstrator Fan Rig confirmed rig to engine scalability.

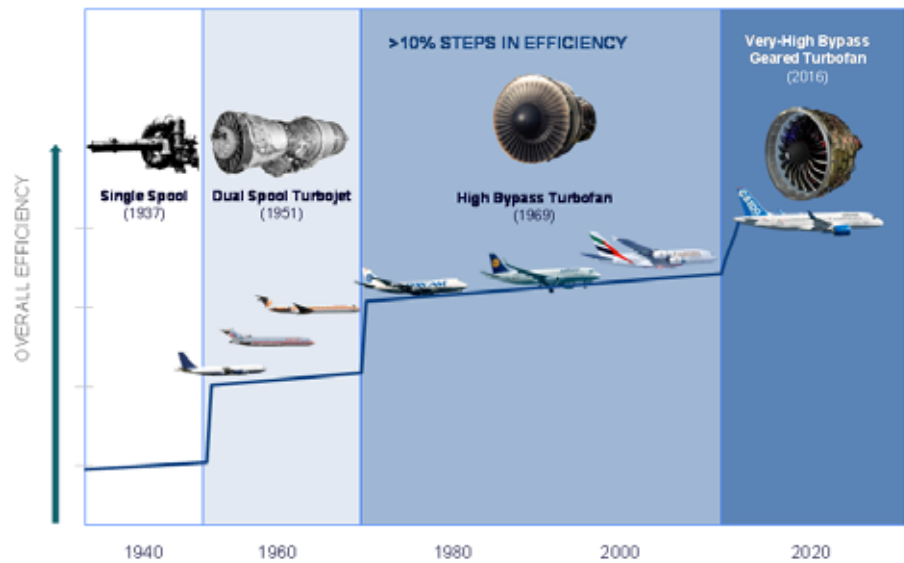


**Figure 1-1.** Major Technology Demonstrators From UHB Program

The combination of testing and analysis from these three demonstrations resulted in significant risk reduction and technology maturation preparing the UHB technology for product introduction. Results verified the aerodynamic and acoustic performance of the UHB technology in an engine environment, and no obstacles for product insertion were identified. Flight testing is the next step for technology maturation.

## 2. INTRODUCTION

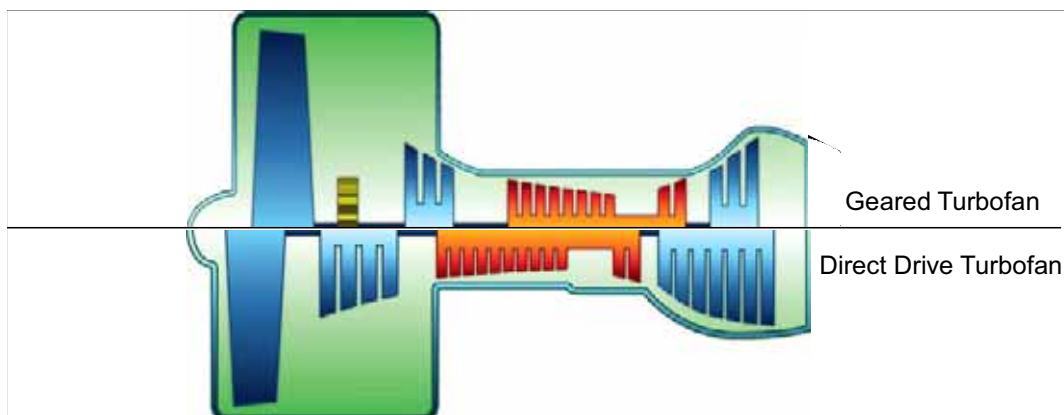
Step changes in overall engine efficiency (*Figure 2-1*) have been enabled by changes in the fundamental architecture of the engine. The majority of the current single-aisle and wide-body fleet is powered by the high bypass ratio engine first introduced into service in 1969. However, the development and maturation of the Geared Turbofan™ (GTF) engine by P&W marked the start of a new era of engine architecture, enabling the introduction of very high bypass engines. The very high bypass (12.5:1) GTF entered into service in 2016 on the Airbus A320neo aircraft, followed by the Bombardier CSeries aircraft in 2017. The



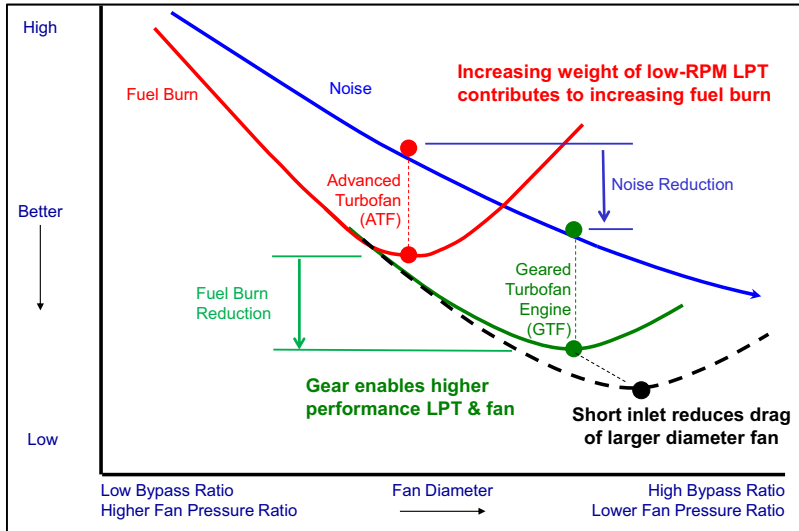
*Figure 2-1. Step Changes in Engine Efficiency are enabled by Changes in Engine Architecture*

GTF engine architecture leverages the introduction of a reduction gear between the fan and low-rotor spool that allows the fan and low spool to operate at optimum speeds. Relative to advanced dual-spool turbofans without a gear, this allows for increased fan diameter and lower fan pressure ratio (FPR; i.e., higher bypass), because the fan rotor can operate at a lower speed while the low rotor is allowed to operate at higher speeds, reducing the stage count and weight of the low-pressure compressor and turbine (LPC and LPT). In addition the lower speed, higher bypass ratio fan results in lower acoustic levels and overall improvement in performance. A general comparison between a geared turbofan and a direct drive turbofan is shown in *Figure 2-2*.

P&W recognized that continued progress into ultrahigh bypass ratios (>15:1) were achievable through the maturation of an integrated low pressure ratio fan/short inlet technology. This is illustrated in *Figure 2-3*. The shorter inlet results in reduced installation/nacelle losses, allowing for the implementation of a larger diameter, lower pressure ratio fan. A lower pressure ratio fan not only results in increased bypass ratio, it also provides an intrinsic efficiency benefit, resulting in overall fuel burn improvements. In addition, the lower pressure ratio fan lowers the overall acoustic response, which, when combined with the reduced acoustic treatment area available due to the

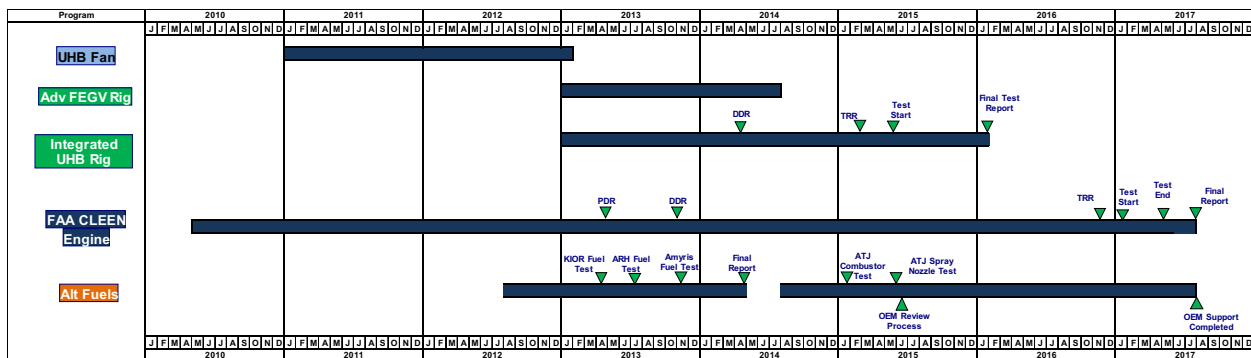


*Figure 2-2. Comparison Between GTF Engine (Top) and Direct Drive Engine (Bottom) Illustrating Key Differences: Larger Fan, Reduced Low-Spool Stage Count*



**Figure 2-3. Impact of GTF Configuration on Fuel Burn and Acoustic Performance — Reduction in Nacelle Drag Enabled by Short Inlet Allows Lower Pressure Ratio/Larger Diameter Fan**

presence of a short inlet, results in no impact to the overall acoustic levels of the GTF engine. The key technical risk was to verify that both the inlet and fan could meet operating requirements in the new design space. To address this risk, a multiyear program of both fan rig and ground engine tests was conducted (**Figure 2-4**). The items listed as Advanced FEGV Rig and Integrated UHB Rig were conducted in collaboration with NASA as part of the Environmentally Responsible Aviation Project. Also shown is a P&W/NASA project (called UHB Fan) where the initial testing of the low-FPR/short inlet configuration was conducted in support of the overall FAA CLEEN design effort. For completeness, **Figure 2-4** also shows the alternate fuels support provided by P&W as part of the CLEEN program. This report will not include any results related to the alternate fuel tests, as those results have been reported previously as public reports under this CLEEN program. This report will focus on the activities conducted as part of the FAA CLEEN engine program and also provide an assessment of rig to engine scalability by comparing the results from the engine demo with the results from the Integrated UHB rig which was approximately a 1/3 aerodynamically scaled version of the engine demo. The next phase in UHB technology maturation is to complete flight test demonstration. The combined fan rig, ground engine and flight test process is the same procedure that was used to develop the first generation GTF product (**Figure 2-5**).



**Figure 2-4. Multiyear Rig and Engine Demonstrator Plan Aimed at Maturing UHB Technology and Supporting CLEEN Initiative To Develop Drop-In Alternative Fuels**



*Figure 2-5. Fan Rig, Ground Engine, and Flight Tests Conducted in Late 2000s To Support 2016 GTF Entry Into Service; Same Process for UHB Technology, With Flight Testing To Be Conducted*

### 3. PROGRAM DETAILS

As shown in *Figure 2-4*, the P&W FAA CLEEN program was initiated in May 2010 and culminated in a ground engine test demonstration in 2017. A summary of the major program milestones and key changes/learning is presented in *Table 3-1* (not all milestones listed are shown in *Figure 2-4*).

*Table 3-1. Milestone Summary for UHB Program*

<i>Milestone</i>	<i>Date</i>	<i>Key Changes/Learning</i>
Concept Initiation	May 2011	Selected fan pressure ratio. Confirmed compatibility with expected donor engine.
Preliminary Design Review (PDR)	May 2013	Confirmed fan configuration. Identified rig as best test for FEGVs. Confirmed compatibility with identified donor engine.
Detailed Design Review (DDR)	Nov 2013	Released procurement for demonstrator finished parts.
Advanced FEGV Test	Nov 2014	Determined additional UHB FEGV optimization is required.
Integrated UHB Test	Nov 2015	Successfully tested three-dimensional (3-D) aero nacelle with pylon and bifurcations. Confirmed aero & acoustic predictions for UHB.
Engine Test Readiness Review (TRR)	Nov 2016	Engine cleared for ground test.
Engine Test	July 2017	Aero, acoustic, and mechanical performance confirmed. Demonstrated rig to engine scalability.

## 4. DESIGN SUMMARY

### 4.1 UHB ENGINE DESIGN SUMMARY

The key design challenge for the UHB engine demonstrator was to integrate the UHB propulsor module with an existing GTF engine, maintaining the ability to meet flying testbed capability for the engine and demonstrate compliance with current engine criteria for the UHB configuration. To achieve this, design activity focused on the fan module and select nacelle components. The donor engine selected for the demonstrator program was an existing development engine used in both the PW1500G and PW1900G development programs, along with experimental nacelle hardware used in prior ground and flight test programs. Fan diameter was maintained consistent with the donor engine at 73 inches. A summary highlighting the differences between the baseline and UHB engine modules is presented in **Table 4-1**. In addition to meeting engine design requirements, many of the parts were also subjected to instrumentation installation and egress design and evaluation. For acoustic testing, additional hardware was designed and procured without instrumentation installed to provide aerodynamically clean surfaces and minimize extraneous contributions to the noise response.

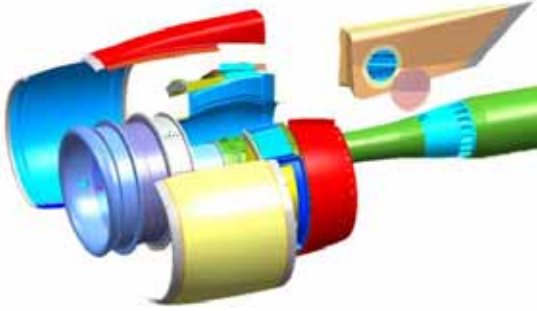
**Table 4-1. Summary of Design Differences Between Donor Engine and UHB Demonstrator**

<i>Module</i>	<i>Major Parts Changed</i>	<i>Summary Changes</i>	<i>Module Challenge</i>
Fan	Fan blade, fan hub, platforms, spinner, fan exit guide vanes, fan exit stator, fan case liners	Reduced count, lower pressure ratio fan blade. Fan hub, platform, spinner, fan exit guide vanes, case liners, fan exit stator to match new fan blade (aero and design)	Meet fan blade out load capability of baseline engine
Nacelle	Inlet, fan cowls	Reduced length inlet, fan cowls modified to integrate inlet with flying testbed (FTB) pylon	None
Nacelle	Acoustic Insert	New hardware required to meet fan operating line requirements for acoustic database	None

P&W Engineering Standard Work (ESW) practices and criteria were used in executing the new module designs. In general all criteria were achieved with minimal deviations approved. Existing P&W procedures managing component, module and system level reviews were executed at the required program phases (concept optimization, *preliminary design*, *detailed design*, *test readiness*, and *post-test assessment*). The **highlighted** items were also program deliverables, and additional reviews were held with the FAA and other Government representatives.

### 4.2 INTEGRATED UHB RIG DESIGN SUMMARY

As mentioned previously, a key element to successful demonstration of very high and ultrahigh bypass engines is execution of scaled fan rigs to provide learning on fan aero, acoustic, and mechanical behavior before engine demonstration. The CLEEN program provided a unique opportunity for NASA, the FAA and P&W to collaborate on demonstration of the UHB configuration on both a rig and engine scale. As part of the CLEEN and NASA ERA programs, the team designed a 1/3 aerodynamically scaled version of the CLEEN engine including the first ever implementation of 3-D aero nacelle and installation impacts such as a pylon integration and bifurcations. The key objective of this test was to provide more extensive characterization of the UHB performance and demonstrate rig to engine scalability for acoustic and aerodynamic performance. A schematic of the scaled UHB rig design is shown in **Figure 4-1** highlighting the modular design of the rig along with key installation relevant features. Several features in the engine fan duct were not included in the scaled rig and approaches to mitigate rig to engine acoustic scalability were established. A comparison of rig to engine aerodynamic and acoustic correlations is presented in a subsequent section of the report.



<b>Feature</b>	<b>Mitigation</b>
Air oil cooler inlet not included in rig	Plug inlet in engine test
Aft duct cooler inlets and bleeds not included in rig	Kulites installed in engine test to separate contribution

*Figure 4-1. Model of Integrated UHB Rig Showing Modular Design Concept and Listing of Mitigation Approaches for Acoustic Contribution of Engine Features not Included in the Rig Design*

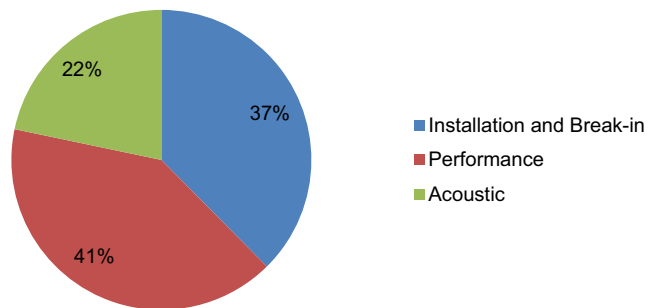
## 5. TEST READINESS

### 5.1 TEST READINESS — INTEGRATED UHB RIG

As shown in *Figure 2-4*, the scaled UHB rig detailed design activities were conducted after the CLEEN engine design was finalized facilitating the aerodynamic scaling process. Because the rig test was conducted as part of the NASA ERA program, it was subject to completing test consistent with the end of the ERA program in 2015. Considerable effort was made to prepare and deliver the rig for testing at the NASA Glenn Research Center Low-Speed Wind Tunnel. Installation of the rig initiated in January 2015 and was completed in March 2015, with initial facility checkout testing conducted on 1 April. Before the test, a safety review was conducted with NASA and approval for test was received. A comprehensive set of aero performance, aeroacoustic, and aeromechanical pretest predictions using advanced CFD methodologies was completed. *Figure 5-1* shows the integrated UHB rig installed in the tunnel, ready for initial testing. Note that there were over 800 individual pieces of instrumentation installed throughout the test program. *Figure 5-2* shows the distribution of applied instrumentation for the various test objectives.



*Figure 5-1. Integrated UHB Rig Installed in NASA Low-Speed Wind Tunnel Ready for Initial Break-In*



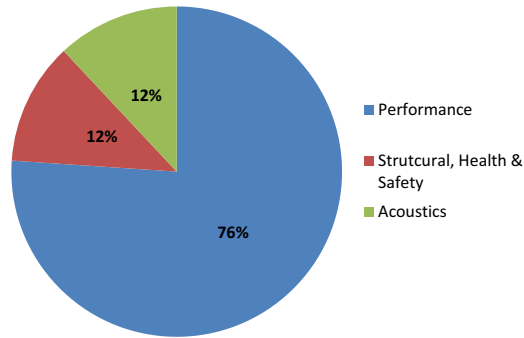
*Figure 5-2. Distribution of Instrumentation Installed in Integrated UHB Fan Rig*

### 5.2 TEST READINESS — FAA CLEEN ENGINE

Preparations for the CLEEN engine test ramped up in June 2016, when the engine was released from a prior flight test program and disassembly was initiated. A Pedigree Review of module hardware was conducted with the component integrated product teams (CIPTs) to confirm adequate capability for the proposed test program and confirm flightworthiness for the hardware. Several minor items were noted, along with some specific teardown inspection requirements. Upon completion of the teardown, the hardware was transferred from the donor engine Bill of Material (BOM) to the CLEEN engine BOM. The CLEEN engine was designated XGTF101-01, and reassembly was initiated in August 2016 at the P&W Middletown facility. TRRs were conducted with the FAA in November 2016 and at P&W in December 2016, and approval was received to go to test. Similar to the integrated UHB fan rig, a comprehensive set of aero performance, aeroacoustic, and aeromechanical pretest predictions was completed using advanced CFD methodologies. *Figure 5-3* shows XGTF101-01 ready for shipment to P&W's West Palm Beach test facility. The engine was received and then installed in the test stand on 23 December 2016. Note that there were over 1,200 pieces of instrumentation (*Figure 5-4*) and an addi-



*Figure 5-3. CLEEN UHB Engine (XGTF101-01) Being Installed on Shipping Stand for Delivery to West Palm Beach*



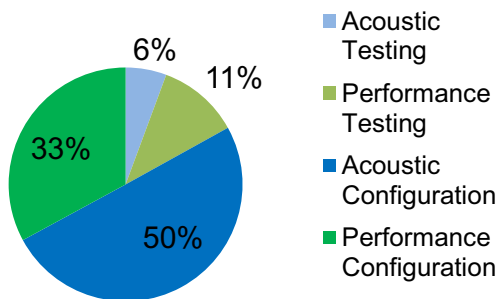
*Figure 5-4. Distribution of Instrumentation Installed in XGTF101-01*

tional 1,000+ calculated parameters. In addition to a complete set of major station probes, the majority of the instrumentation was concentrated in the propulsor area and included aerodynamic, acoustic, operability, and structural measurements. Noted that the engine acoustic instrumentation replicated the instrumentation suite installed in the integrated UHB fan rig test.

## 6. TEST PROGRAM

### 6.1 TEST PROGRAM — INTEGRATED UHB RIG

Initial break-in of the rig was conducted on 2 April 2015, with calibration of the performance bellmouth completed on 7 April. Testing continued through 22 June, with over 135 hours of testing conducted. Note that overall instrumentation survivability during the test campaign was greater than 95 percent, providing significant data for evaluation and correlation with advanced CFD predictions. **Figure 6-1** shows that a significant portion of the wind tunnel occupancy time (over 80 percent) was allocated to changes between acoustic and performance configurations. Minor issues were resolved throughout the test program and upon completion all hardware was acceptable for continued use. **Figure 6-2** is a photograph of the rig in the acoustic configuration installed in the wind tunnel as well as a side view showing the 3-D aero nacelle and pylon capturing installation effects. This represented the first rig run in the NASA facility incorporating these realistic features. This assisted in providing representative data for rig to engine scalability.



**Figure 6-1.** Distribution of Wind Tunnel Occupancy Time



**Figure 6-2.** Integrated UHB Fan Rig Acoustic Configuration Showing Installation Relevant Features

### 6.2 TEST PROGRAM — FAA CLEEN ENGINE

As previously mentioned, the engine was mounted into the test stand on 23 December 2016 with test preparation work resuming on 3 January 2017. The engine was started on 16 January, with idle leak check leading to fan break-in and vibration surveys to clear the engine for subsequent testing. There were a number of testing issues (ranging from an oil leak to instrumentation interference) resolved during the original test startup. **Figure 6-3**



**Figure 6-3.** CLEEN UHB Engine (XGTF101-01) in Performance and Fan Mapping Configurations Installed in CII Test Stand (Fan Structural Response and Inlet Performance Testing Also Conducted in Configuration on Right)

shows the engine in the performance bellmouth and fan mapping/structural configurations installed in the P&W West Palm Beach C11 Test Stand. As can be seen from the photos, testing was conducted in an outdoor test stand. The first block of testing included performance, structural, and fan mapping objectives. Upon completion the configuration was swapped over to acoustics and acoustic testing initiated on 5 April. The final performance calibration runs were completed on May 5th and engine preservation and stand dismount completed. Over 175 hours of engine test time was conducted. The engine is currently stored pending use in additional test programs.

Acoustic testing of the UHB configuration was a major test objective and several configurations were tested as part of the overall program. A summary of the acoustic test blocks is presented in **Table 6-1** along with the learning objective. In addition, **Figure 6-4** illustrates representative acoustic configurations. Both near- and far-field microphone data was collected along with engine instrumentation to provide a comprehensive dataset for acoustic noise assessment, source separation and validation of advanced CFD capability.

**Table 6-1.** Summary of Acoustic Engine Test Configurations and Learning Objectives

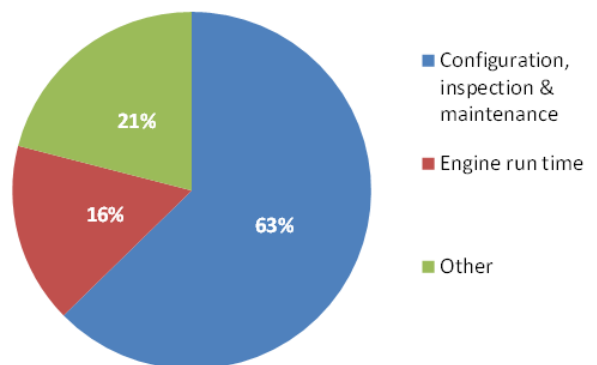
<i>Taped Locations<sup>1</sup></i>	<i>Barrier Wall</i>	<i>Learning Objective</i>
Inlet, interstage, duct, exhaust insert	No	Rig to engine scalability
Duct and exhaust insert	No	Inlet treatment impact
None	No	Product database
Inlet	Yes	Isolated inlet impact
None	Yes	Inlet/aft split, isolated total inlet impact

<sup>1</sup> Hardware covered with tape to eliminate acoustic treatment impact



**Figure 6-4.** Illustration of Engine Configured With Inlet Control Device (Left) Used for Acoustic Testing and With Barrier Wall Installed for Forward/Aft Separation

As **Figures 6-3** and **6-4** suggest there were significant infrastructure and configuration changes required as part of the XGTF101-01 test program. **Figure 6-5** shows the rough distribution of test time with respect to configuration changes, engine run time and other items. Similar to the integrated UHB rig test a significant amount of test occupancy time was associated with configuration changes. This is not a surprise given the large number of instrumentation swaps, major test stand modifications and configuration changes. Over 40 engine configuration changes were executed during the test campaign.



**Figure 6-5.** Distribution of XGTF101-01 Test Stand Occupancy Time

## 7. TEST RESULTS

### 7.1 RESULTS

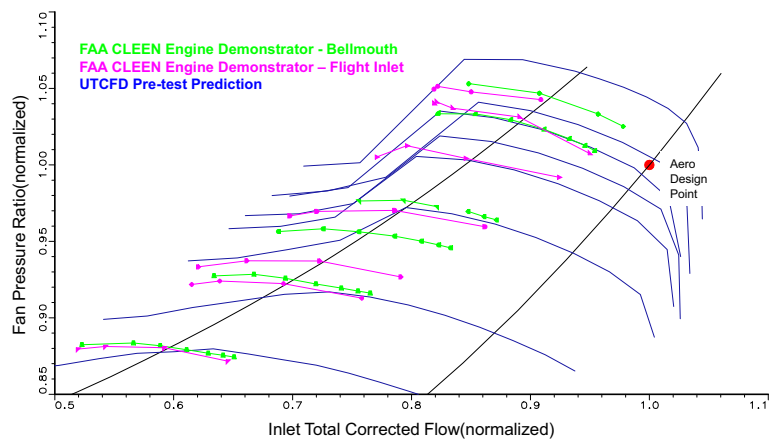
Both the integrated UHB fan rig and UHB ground engine tests verified the capability of the UHB technology hardware to meet existing performance objectives. A summary of the overall learning from each of the tests is presented in **Table 7-1**, illustrating the highly complementary interaction between the two test programs.

**Table 7-1. Summary of Key Learning From Integrated UHB Fan Rig and UHB Ground Engine Demonstrator Tests**

Objective	Integrated UHB Fan Rig Test	XGTF101-01 UHB Ground Engine Demonstrator
Inlet Performance	Meets angle of attack objective	Meets ground flow objective
Fan Performance	Meets cruise performance, flow angularity objectives	Meets ground performance and flow distortion objectives
Fan Aeromechanics	Meets flutter margin objectives	Meets flutter margin, distorted flow objectives
Operability	Meets fan operability objectives	Meets fan and core operability objectives
Acoustics	Consistent with pretest predictions. Product capable	Consistent with pretest predictions. Support vision engine product goal.
Rig-to-Engine Scalability	N/A	Confirmed rig to engine fan and acoustic scalability.

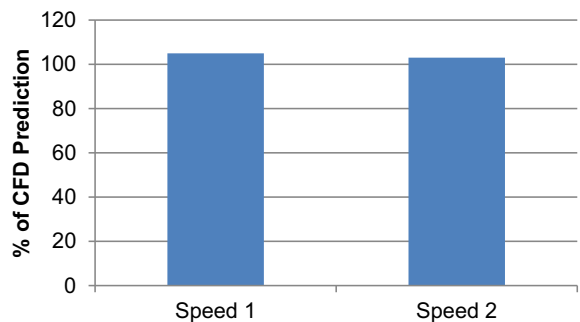
### 7.2 GROUND ENGINE TEST RESULTS

A fan map comparison between pretest predictions and measured performance for the ground test engine in both the performance bellmouth and UHB inlet configurations is shown in **Figure 7-1**. Also shown are several data points taken under distorted flow conditions. The results show that the measured performance is consistent with pretest CFD predictions and expectations for the lower pressure ratio fan and not significantly impacted by distorted flow conditions. A variable fan area nozzle was used to map the fan performance over a range of operating lines and flow conditions to operability and/or structural limitations. For reference a sea-level static operating line is also shown in **Figure 7-1**. Relative to the operating line, the UHB fan system demonstrated adequate operating margin.



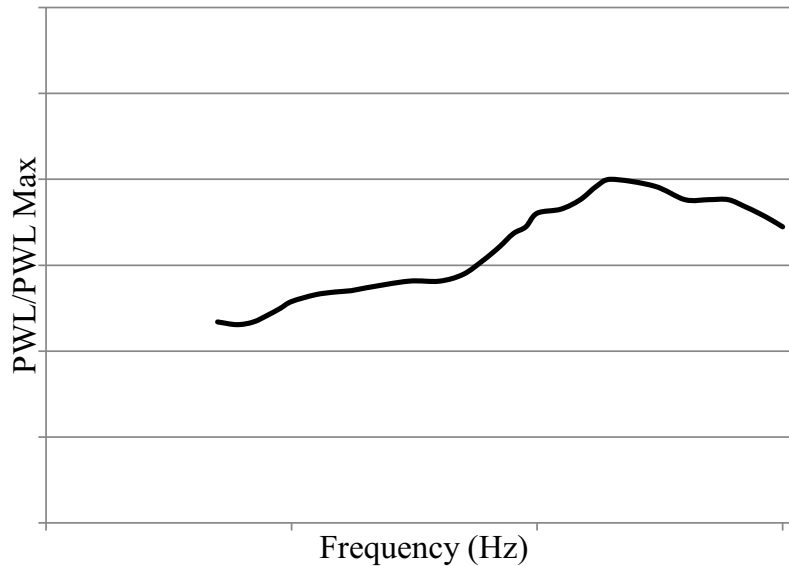
**Figure 7-1. Fan Map Showing Test Results Consistent With Pretest CFD Predictions**

**Figure 7-2** shows a comparison between the measured and predicted inlet performance (attachment flow limit) under cross-wind conditions. The results show good agreement with pretest CFD predictions and indicate that the inlet meets current requirements (CFD based design was executed to meet requirements).



**Figure 7-2. Measured Versus Predicted Inlet Performance Comparison**

One of the key objectives was to generate a comprehensive acoustic database for Vision engine product configurations and that testing was successfully completed. **Figure 7-3** shows a typical far-field spectra measured for the demonstrator engine at each of the assessment conditions (approach, cutback, and sideline). This dataset was subsequently processed for incorporation into vision engine projections.

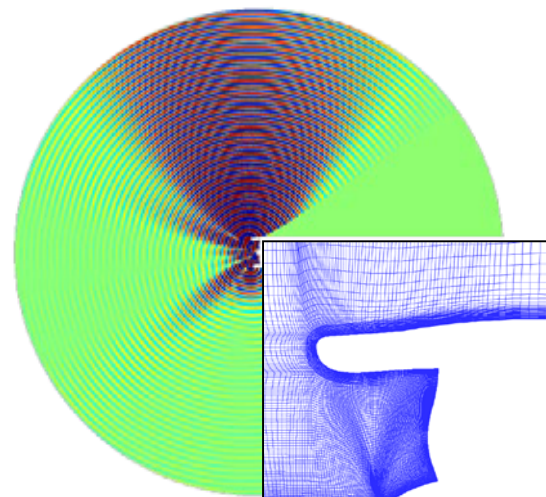


**Figure 7-3.** Typical Far-Field Acoustic Spectra Measured During CLEEN Demonstrator Engine Acoustic Testing for Each Acoustic Characterization Condition

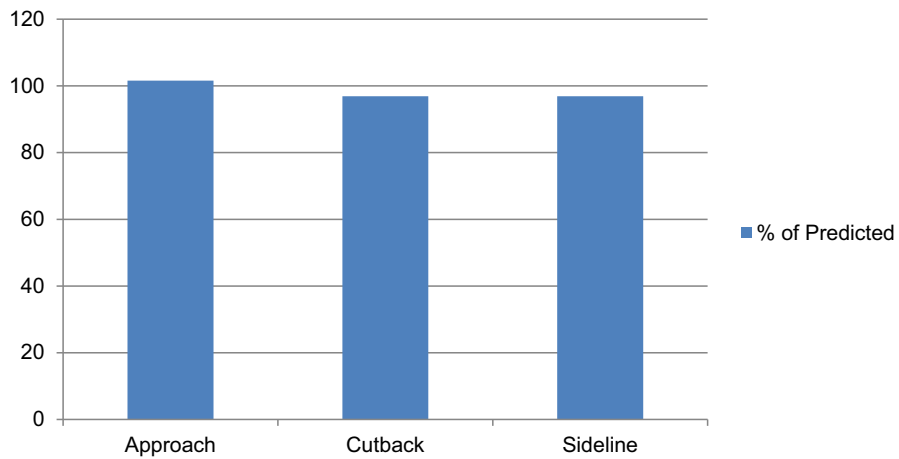
Data was also generated in the fully taped *hardwall* condition to evaluate rig-to-engine scalability, as well as to assess untreated predictions for noise. Pretest predictions were generated through a fully coupled CFD analysis that produced a comprehensive set of steady and unsteady aero loads as input into an aero/acoustic prediction tool. This tool uses unsteady aero characteristics to calculate and propagate acoustic pressures from near field to far field. **Figure 7-4** shows a typical mesh used (300+ million elements) and resultant far field pressure propagations generated during the pretest prediction process. This physics based methodology has been under development for several years and has been subjected to extensive validation and verification.

**Figures 7-5** through **7-8** show a comparison between the predicted and measured broadband and tones for both forward and aft datasets at all three acoustic measurement conditions. In general, there was good agreement between predicted and measured values. Fan broadband measurements (**Figures 7-5** and **7-6**) were within 3 percent of predicted, and fan tones (**Figures 7-7** and **7-8**) were typically within 7 percent of predicted. The one exception was aft tones at the approach condition, where the measured response was 15-percent lower than predicted. This trend was also observed for the other aft blade passing frequency (BPF) tones.

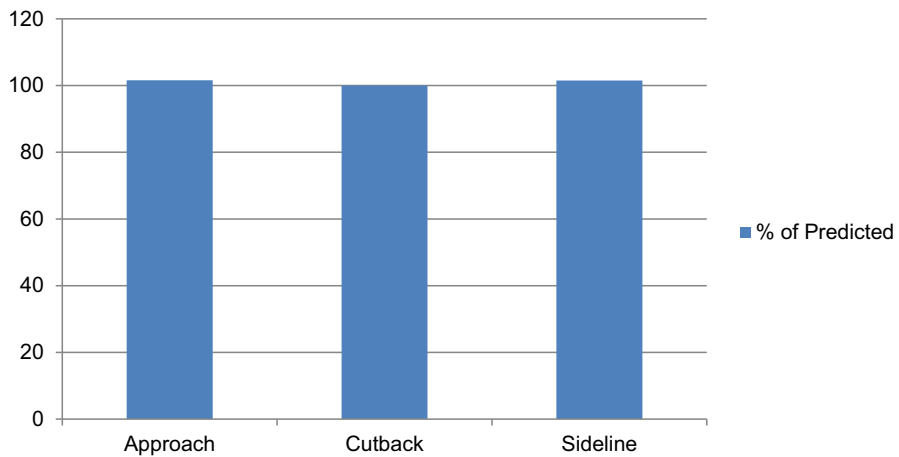
The measured fan, inlet, and acoustic performance validated pretest predictions for component performance and these component predictions were incorporated along with other technology under development into a vision product engine. Fuel burn, noise and emissions predictions were made for the Vision engine (**Table 1-1**) and indicate significant contribution to meeting FAA CLEEN goals. P&W continues to look for product opportunities to incorporate elements of the CLEEN Vision engine.



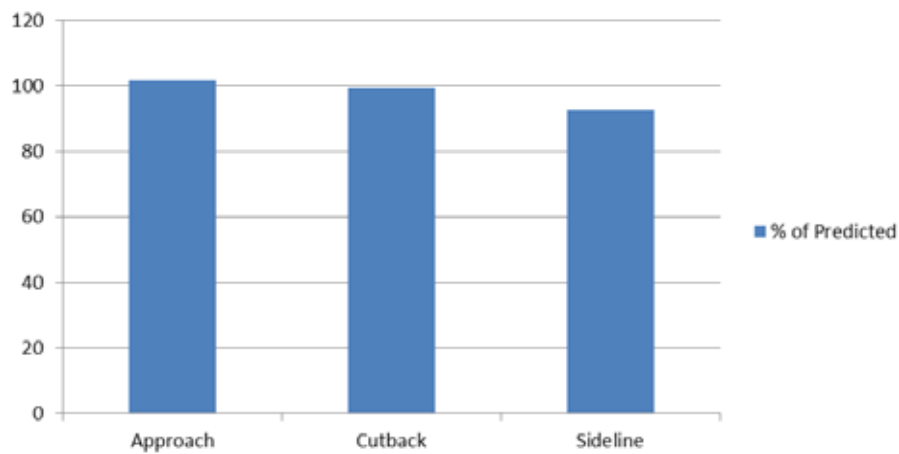
**Figure 7-4.** Typical CFD Mesh and Associated Far-Field Propagation From Acoustic Pretest Predictions; Mesh Includes Duct Bifurcations and Coolers



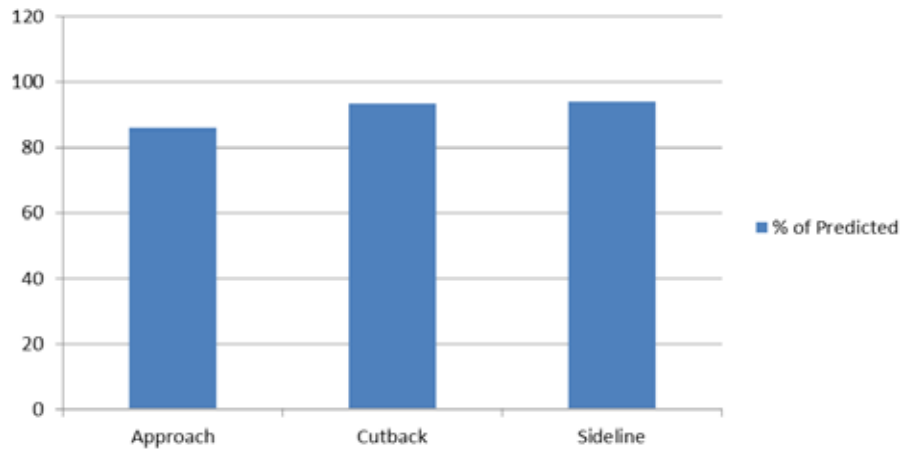
**Figure 7-5.** Comparison Between Measured and Predicted Fan Forward Broadband Response at Each Acoustic Characterization Condition



**Figure 7-6.** Comparison Between Measured and Predicted Fan Aft Broadband Response at Each Acoustic Characterization Condition



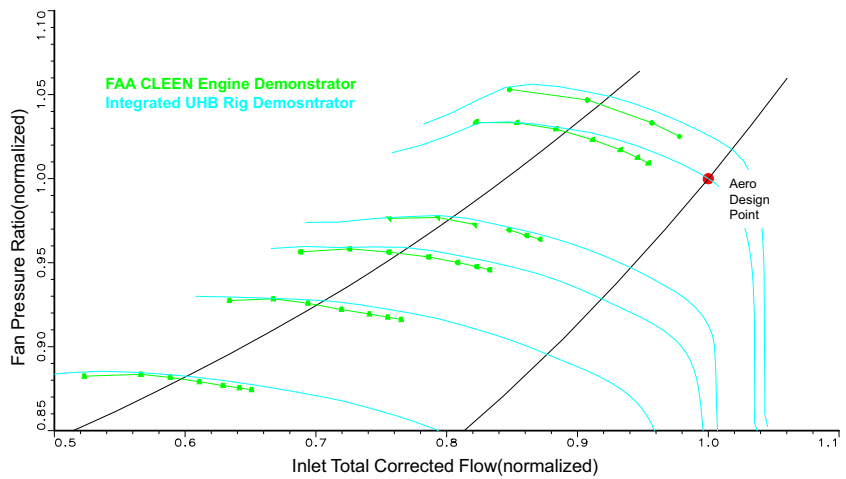
**Figure 7-7.** Comparison Between Measured and Predicted Fan Forward BPF Tone Response at Each Acoustic Characterization Condition



*Figure 7-8. Comparison Between Measured and Predicted Fan Aft BPF Tone Response at Each Acoustic Characterization Condition*

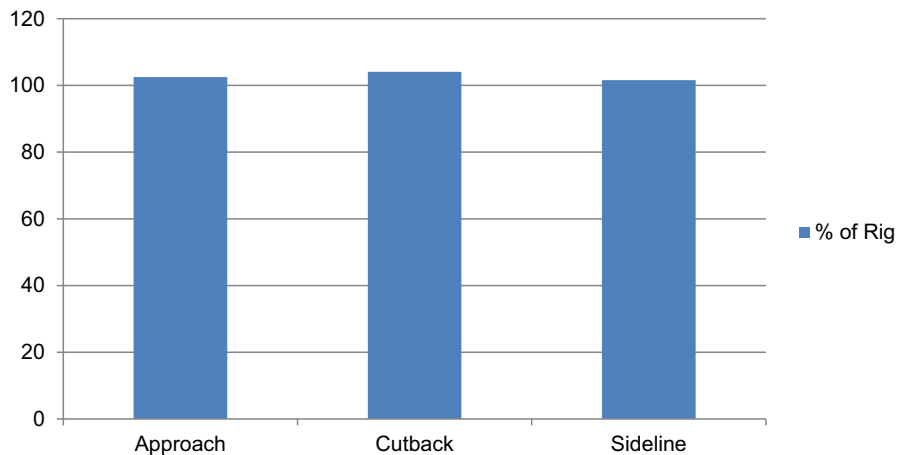
### 8. RIG-TO-ENGINE SCALABILITY

In addition to technology maturation and demonstration, a key objective of the program was to validate fan rig to ground engine scalability for noise and performance. Fan performance between the integrated UHB fan rig demonstrator and the CLEEN test engine is compared on the fan map in **Figure 8-1**. The results indicate that the scaled rig and engine are behaving equivalently across a broad range of operating conditions. In addition, both the rig and engine are exhibiting similar fan pressure rollover characteristics. As expected, the results support rig-to-engine scalability for fan performance testing.

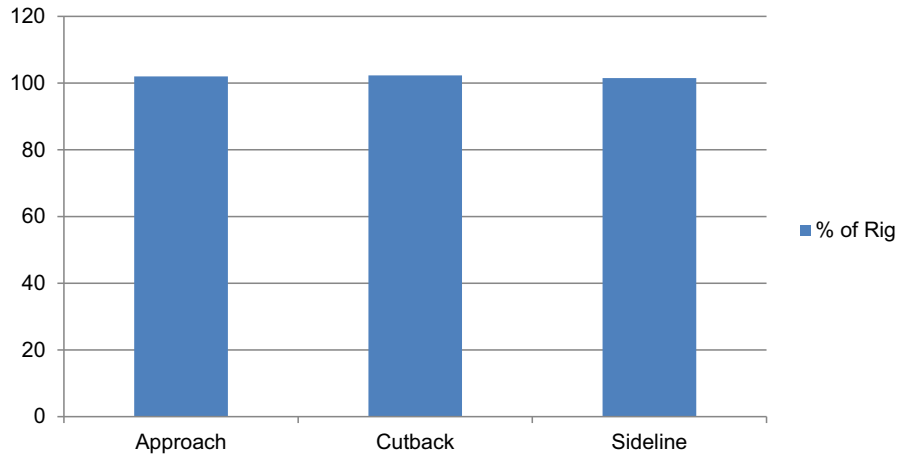


**Figure 8-1.** Fan Map Showing Consistent Fan Performance Results Between Fan Rig and Ground Engine Tests

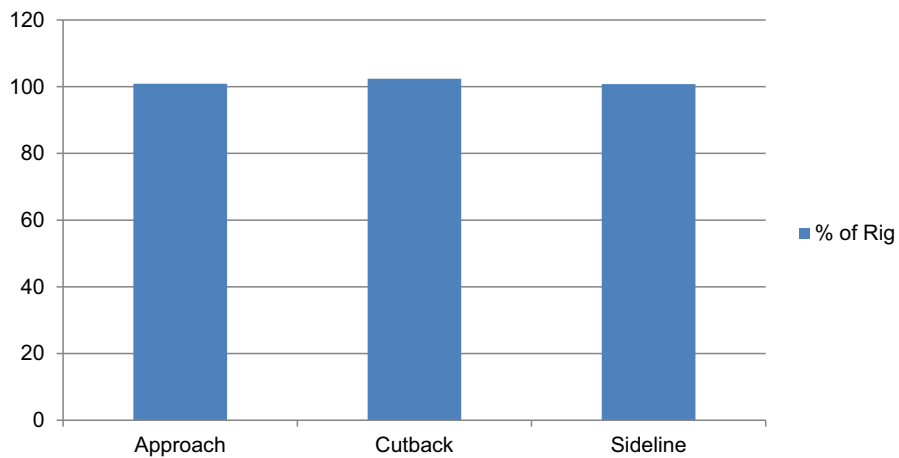
The second key scalability objective was acoustic response. Since the fan rig was tested without any acoustic treatment installed, it was necessary to generate a dataset for the untreated (hardwall) condition in the engine. **Figures 8-2** through **8-5** show comparisons between engine and rig broadband and tones for both the fan forward and fan aft conditions at each of the acoustic measurement conditions (approach, cutback, and sideline) indicating good agreement between the results at all test conditions. Engine results were consistently higher than rig results suggesting slightly higher noise (not all features in the engine were simulated in the rig). This difference was quite small, with measured broadband typically within 1.5 percent to 2.5 percent of rig measurements and tones typically within 1.5 percent. Similar to fan performance, the results confirm rig-to-engine scalability for acoustics.



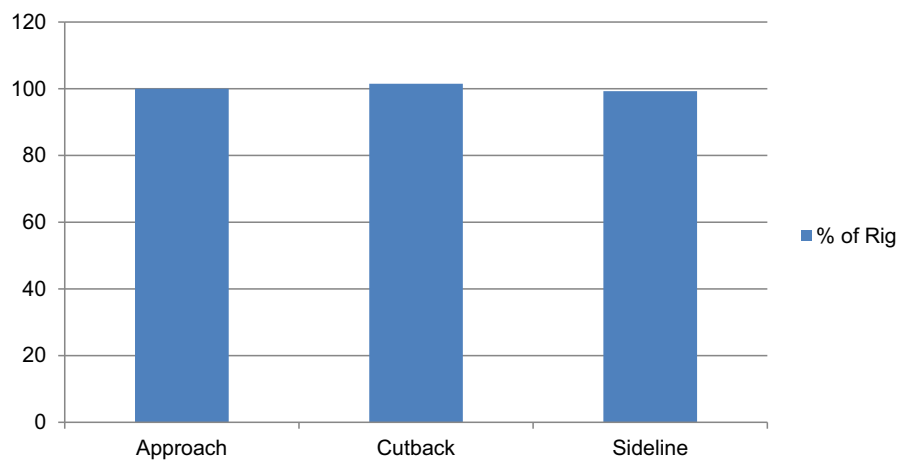
**Figure 8-2.** Comparison Between Fan Rig and Engine Fan Forward Broadband Results at Each Acoustic Characterization Condition



**Figure 8-3.** Comparison Between Fan Rig and Engine Fan Aft Broadband Results at Each Acoustic Characterization Condition



**Figure 8-4.** Comparison Between Fan Rig and Engine Fan Forward Overall Power Level Tone Results at Each Acoustic Characterization Condition



**Figure 8-5.** Comparison Between Fan Rig and Engine Fan Aft Overall Power Level Tone Results at Each Acoustic Characterization Condition

## 9. CONTINUED DEVELOPMENT

The FAA CLEEN program was highly successful demonstrating capability of the UHB technology in a ground engine test. Test results confirmed the performance capability of the UHB technology, and complementary rig testing confirmed rig-to-engine scalability. The next step in technology maturation is to conduct flight tests of the UHB configuration to validate flight characteristics. P&W is evaluating opportunities for flight test and implementation of the technologies demonstrated in this program.