Propulsion Noise Reduction Research in the NASA Advanced Air Transport Technology Project

Dale Van Zante
Dale.E.VanZante@nasa.gov
NASA Glenn Research Center
Aircraft Noise Reduction Sub-project
Cleveland, OH
United States

Douglas Nark and Hamilton Fernandez
NASA Langley Research Center
Aircraft Noise Reduction Sub-project
Hampton, VA
United States

ABSTRACT

The Aircraft Noise Reduction (ANR) sub-project is focused on the generation, development, and testing of component noise reduction technologies progressing toward the NASA far term noise goals while providing associated near and mid-term benefits. The ANR sub-project has efforts in airframe noise reduction, propulsion (including fan and core) noise reduction, acoustic liner technology, and propulsion airframe aeroacoustics for candidate conventional and unconventional aircraft configurations. The current suite of propulsion specific noise research areas is reviewed along with emerging facility and measurement capabilities. In the longer term, the changes in engine and aircraft configuration will influence the suite of technologies necessary to reduce noise in next generation systems.

Keywords: Propulsion; Noise; Acoustic liners

1.0 INTRODUCTION

Aircraft noise is an amalgam of sources from both the airframe and propulsion system. The community noise from aircraft is typically quoted as a ‘cumulative’ value which is the summation of three certification points: lateral, flyover and approach. Noise regulations limit the cumulative noise from the three certification points with the total cumulative noise allowed being based on the aircraft weight and the number of engines. Propulsion system noise typically dominates at the lateral and flyover conditions. At the approach condition the airframe can be equivalent to or exceed the propulsion system noise, especially for the newer engines. Thus, reductions in propulsion system noise are still critical for lowering the overall noise signature of aircraft. Additionally, unconventional installations can increase the noise of the propulsion system (e.g. increased engine inlet flow distortion) or increase the airframe noise from secondary effects (e.g. jet surface interaction). This paper will focus on noise sources directly related to the propulsion system. Airframe specific sources, such as flaps and landing gear, will not be discussed here.

Engine noise sources have changed in character as the primary large transport propulsion cycle has evolved from turbojets to high-bypass turbofan engines. As shown in Figure 1 from Epstein, the 1960s engines were dominated by jet noise and high frequency core turbomachinery noise. The introduction of high bypass ratio engines in the 1990s resulted in noise signatures that are a mixture of fan and jet noise. Fan noise is very tonal and has a well-defined directivity around the engine. Jet noise is a distributed source from the plume that extends far downstream of the engine. This distinction in noise character has implications for the use of static engine acoustic measurements for estimates of inflight noise. The 2015 era engines are dominated by fan noise with jet noise being a minor contributor. Additional sources such as the turbine and combustor may now become contributors due to the increase in the overall pressure ratio. The ANR research portfolio will be influenced by this change in character of the engine noise sources.

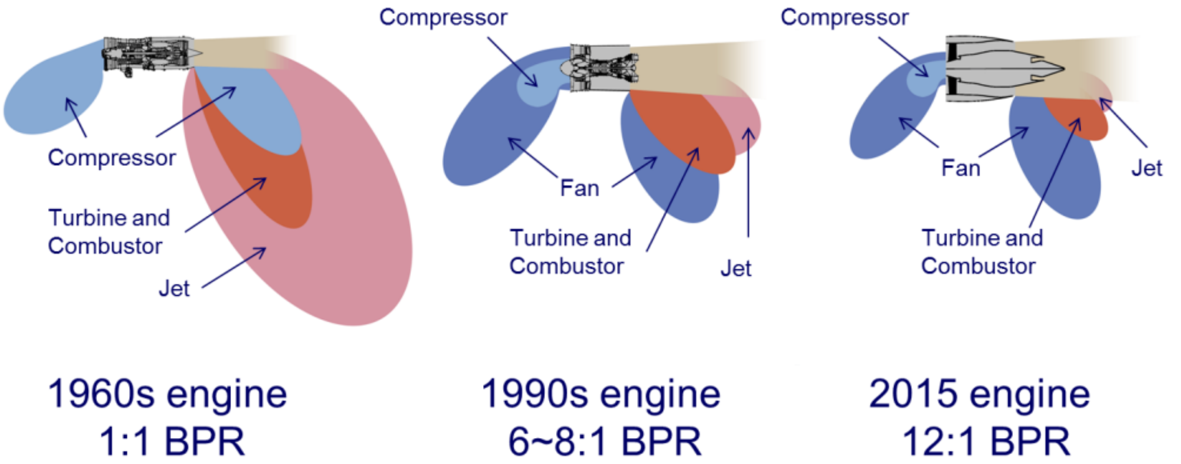

Figure 1: Evolution of noise from Epstein (2015) showing the change in acoustic sources as the engine bypass ratio (BPR) increases.

In addition to the evolution of the noise character, there are also changes in the propulsor configuration that will influence the noise reduction technology needs. The pursuit of ever higher propulsive efficiency results in low pressure ratio (and thus, ultra high bypass ratio) propulsor designs. As illustrated in Figure 2, these propulsor designs have large fan diameters, short overall nacelle length and close rotor-to-guide vane spacing. Those design changes are beneficial, and necessary, for reducing fuel burn however they are potentially detrimental to acoustics. For example, the reduced nacelle length results in less area for acoustic treatment in addition to the length/diameter ratio of the duct making the liners less effective. Non-traditional liner placement and reduction of noise at the source are important acoustic technology maturation areas. The newer engine designs also have higher overall pressure ratio and are using (or soon will be) lean burn combustion systems for lower emissions. Both of these design characteristics are potential contributors to increased combustion noise.

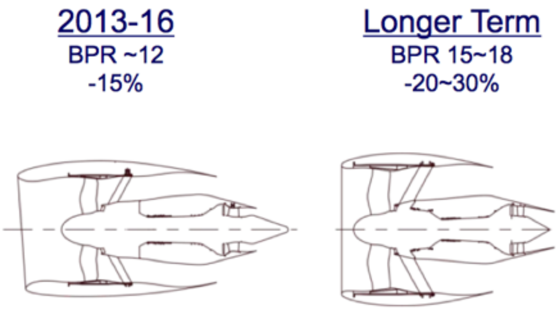

Figure 2: Current and future propulsor configurations for low fan pressure ratio engines (Epstein, 2015). Estimated reductions in fuel burn are shown relative to current generation engines.

Future aircraft configurations and installation of the propulsion system will also influence the noise production and radiation from the vehicle. The Aurora D8, shown in Figure 3, is an example future aircraft configuration that uses a lifting body type of airframe with, potentially, boundary layer ingesting engines. The D8 uses the airframe body to shield ground observers from engine inlet radiated noise but the presence of distorted flow into the fan at all times will be a source of noise that is yet to be quantified. The engine exhaust also could pass over part of the airframe which adds additional noise source mechanisms/reflections which are not present in conventional installations. Other proposed future configurations, such as the truss braced wing or blended wing body, have possible acoustics challenges that are different than the contemporary tube and wing. Even conventional installations with short inlets may have higher levels of distorted flow into the fan face and thus the possibility of increased source noise. The accuracy of noise estimates for new aircraft and engine configurations will depend on better models for the noise mechanisms which are unique to the configurations.

Figure 3: The Aurora D8 configuration as an example of possible future aircraft (https://www.nasa.gov/content/the-double-bubble-d8-0).

The current NASA ANR portfolio of propulsion noise reduction technologies is reviewed first. The primary propulsion noise focus has been maturing technologies for fan noise reduction, characterization of combustion noise, and development of more representative test beds for technologies. For the future, the ANR portfolio will change to address the emerging noise challenges of the new engine and airframe configurations, such as jet surface interaction noise. The technical justification and primary foci of the new ANR portfolio topic areas are discussed.

2.0 PROPULSION NOISE REDUCTION RESEARCH IN THE CURRENT ANR PORTFOLIO

Current ANR propulsion research efforts involve unconventional liner concepts, core/combustion noise characterization, and improvements to propulsion airframe aeroacoustics (PAA) for some aspects of unconventional configurations.

2.1 Unconventional Liners

Acoustic liners have traditionally been installed in the engine inlet and fan bypass duct. Liners can also be installed in the intra-blade region, between the fan rotor and outlet guide vane (OGV). Engine configuration changes such as reduced length, large diameter nacelles, result in less available area for liners and a duct length/height ratio that makes the liners less effective. Thus the push for 'unconventional' liners, which means placing liners in non-traditional locations as well as developing liners that are more effective.

2.1.1 Acoustic Casing Treatment (ACT)

An Over-The-Rotor (OTR) liner, also called acoustic casing treatment, is an example of a non-traditional liner location. Previous implementations of OTR treatments resulted in 2.75% to 8.75% loss in fan aerodynamic efficiency which was clearly not acceptable (Hughes and Gazzaniga, 2009). Subsequent efforts overcame the efficiency penalty issue (see, for example, Bozak, et al., 2013) but fabrication of the treatments was problematic and increased noise due to fabrication flaws remained a concern.

The aerodynamic environment at a location above the rotor tip consists of large amplitude pressure fluctuations and potentially large temperature increase if fluid is worked on multiple times by the rotor. The addition of circumferential grooves reduces the pressure fluctuation amplitude at the face of the acoustic treatment as inferred from an FJ44 engine test (Sutliff, et al. 2013). Figure 4 shows the fan rotor and OTR treatment for a recent test in the NASA W8 facility. The lower left corner of the image shows the casing grooves over the fan tip. The bottom of the grooves has porosity that allows the unsteady pressure field to 'communicate' with the rectangular chambers where absorbing concepts could be inserted. The image shows empty chambers at the top of the annulus and expansion chambers (they look like fir trees) on the right side. In total, 4 different acoustic absorbing concepts were tested as well as a groove only configuration and a smooth wall (no grooves) configuration. Preliminary analysis of the test data indicated that the acoustic absorber concepts performed as intended in the design frequency range with no impact on fan efficiency. Final results will be published by Bozak in the future.

Figure 4: Fan acoustic casing treatment hardware showing the casing grooves, empty chambers and expansion chamber concepts (GRC-2017-C-00942).

2.1.2 Soft Vane

An additional unconventional liner application is the soft vane, wherein a portion of the engine fan exit guide vane surface is made porous to allow communication between pressure fluctuations at the vane surface and multiple, internal, resonant chambers (Jones, et al., 2009, Hughes et al., 2009). Soft vanes are intended to reduce rotor-stator interaction noise radiated through the inlet and aft-fan duct. The internal chambers and porous surface are designed to an optimum impedance that minimizes the self-noise generated at the surface of the vane while maximizing absorption of radiated fan noise.

As discussed by Jones and Howerton (2016), initial tests of the soft vane concept were conducted in the NASA Langley Normal Incidence Tube (NIT) and NASA Glenn Advanced Noise Control Fan (ANCF). The general design approach was to use variable-depth chambers to achieve the desired surface impedance. Given the volume constraints, only a limited number of chambers could be incorporated into the design, and those chambers had to be skewed and splayed. Lacking clear guidance on treatment location (i.e., which portion of the vane surface should be made porous and connected to internal chambers), the porous surface was positioned on the suction side of the vane and covered from approximately 20% to 60% of the chord length. This allowed the remainder (forward 20% and aft 40%) of the vane to be used as available volume into which to extend the internal chambers.

Multiple configurations were fabricated using additive manufacturing, such that NIT test results could be used to down-select to a final design for use in the ANCF test. Ultimately, a design incorporating a 200 MKS Rayl facesheet (to increase the resistance) was chosen based on NIT results. This configuration was subsequently tested in the ANCF, with encouraging results (nominally 1 dB attenuation across 2.5 octaves).

Follow-on tests were conducted with two 22” fan rigs in the ANCF and NASA Glenn 9- by 15-Foot Low Speed Wind Tunnel (LSWT). The first was conducted with the Advanced Ducted Propulsor (ADP) fan. This fan rig produces dominant tones at six frequencies from 1645 to 5306 Hz, corresponding to BPF (blade-passage-frequency) and 2BPF (two times BPF) at the three certification points (takeoff, cutback, and approach). The goal was to simultaneously achieve a ρc-impedance (normalized impedance of unity) at each of these frequencies, and to maximize absorption at off-target frequencies. A configuration incorporating four resonant chambers of different length terminating on the suction surface of the vane was selected. Each internal chamber communicated with the exterior of the vane via a perforated sheet covered with a wire mesh to achieve the desired surface resistance. This soft vane configuration provided 1 to 2 dB noise reduction over at least two octaves.

The second LSWT test used the Source Diagnostic Test Fan (SDT). A number of lessons learned from the earlier tests were applied in preparation for this test. First, linearized unsteady aerodynamic calculations were used to gain significantly more insight regarding placement of the liner and choice of surface impedance. This analysis confirmed that a ρc-impedance was appropriate. It also indicated that, at least for this fan rig, the porous surface should be placed on the pressure side of the vane and should not extend beyond approximately 50% of the chord. The goal was to attenuate sound from 3000 to 9000 Hz.

Figure 5 provides a photograph of the full set of vanes as installed in the fan rig. Test results from the SDT test indicate these soft vanes provided from 1 to as much as 3 dB attenuation over the full frequency range, with an estimated 1.5 EPNdB (effective perceived noise level in decibels) noise reduction. Based on these positive results, hardware modifications to the NASA Langley Curved Duct Test Rig (CDTR) have recently been completed to allow future planned component testing to enhance the noise mechanism knowledge base and improve soft vane design practices.

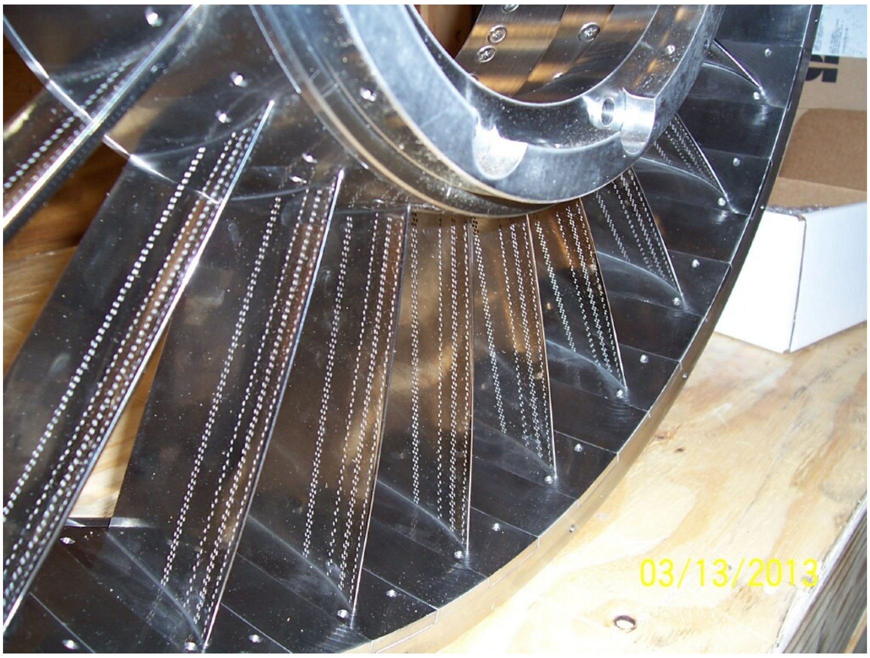

Figure 5. Photographs of installed SDT soft vanes.

2.1.3 Multi-Degree of Freedom Liners

In addition to the unconventional placement of acoustic liners within the engine nacelle, advanced broadband liner designs departing from conventional uniform impedance configurations (e.g., zone liners, variable impedance liners) have received increased interest. One design in particular that had been tested over a range of increasing technology readiness levels is a multi-degree of freedom (MDOF) design incorporating buried septa (or "mesh-caps") embedded into a honeycomb core. This concept allows the acoustic liner to be customized such that the surface impedance of each individual cell is independently controlled. This is achieved by the combination of parameters used to set the impedance in each cell. As seen in the variable depth example of Figure 6, the various cells are then customized into a grid pattern of different mesh-cap depths or resistances within the acoustic panel to achieve a desired distributed impedance (Nark et al., 2016).

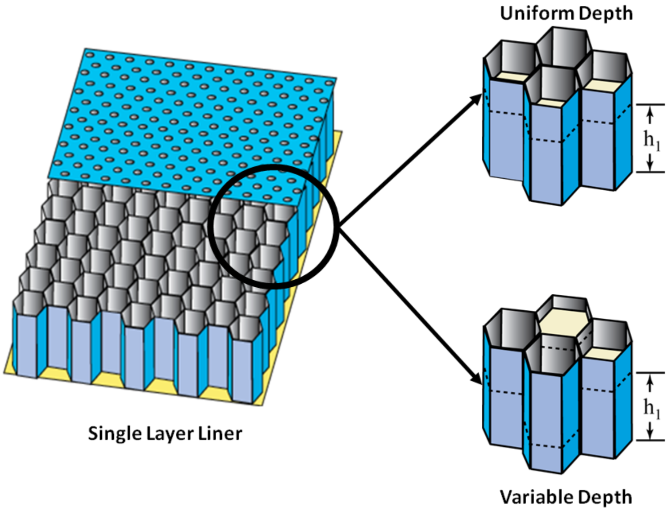

Figure 6: Parent single layer liner and resultant two-layer liner configurations (uniform and variable depth) via meshcap insertion.

As mentioned above, a series of MDOF liner design studies at increasing technology readiness levels has been conducted as the overall design methodology has been enhanced. Initial liner designs targeting the NASA Langley Liner Technology Facility (LTF) demonstrated a broadband benefit for the MDOF designs. Subsequent design and testing in the ANCF (Sutliff et. al., 2014, Nark et al., 2015) provided further confidence in the design process. Additionally, measured in-duct and far-field power levels from this test again showed broadband benefit from the MDOF design over a frequency range encompassing from one to three times the blade passage frequency.

Based on positive previous results, fabrication and testing of an MDOF liner design for a high speed fan was also pursued (Sutliff et. al., 2016, Nark et al., 2016). A comparison of the Honeywell SDOF liner to the NASA MDOF design is presented in Figure 7. Specifically, the overall benefit of the MDOF design is illustrated over the full range of polar angles in the figure on the left. Representative broadband benefits for a downstream observer angle of 135° are shown in the figure on the right. It can be seen that the MDOF liner offers an attenuation benefit of at least 1 dB over the SDOF liner over the frequency range considered. Additional results from this test will be published in the future. The team continues to research the MDOF design process to improve performance and reduce manufacturing complexity and further testing in the new DGEN Aeropropulsion Research Turbofan (DART) facility, described later in this paper, is scheduled for the summer of 2017.

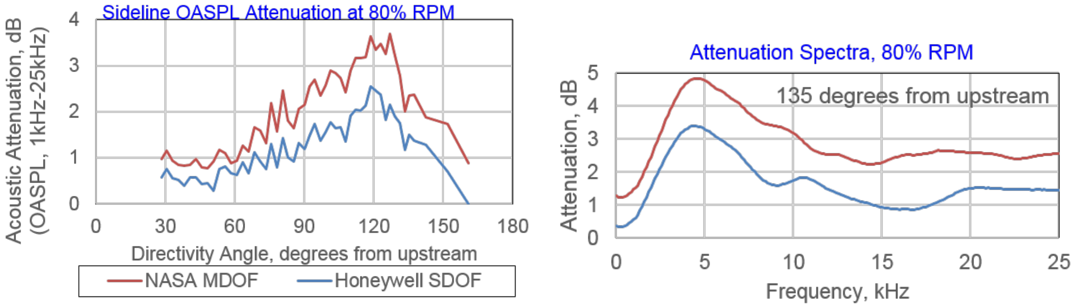

Figure 7. Comparison of measured attenuation demonstrating MDOF broadband benefit (Fernandez, 2016).

2.1.4 Bio-Inspired Acoustic Absorbers

Liner configurations inspired by natural materials have also shown promise for increasing the effectiveness and/or absorption frequency range of liners. Koch noted that researchers in the United Kingdom had found that 2 inch deep bundles of natural reeds were effective at absorbing sound in the 400-1000 Hz range (Koch and Jones, 2016). The frequency range of absorption is surprising given the shallow depth of the liner material.

Various configurations of synthetic reeds have been evaluated for their sound absorbing qualities since natural reeds are not a material that is suitable for use in aircraft engine applications (Koch et al., 2017). Figure 8 shows an example of a synthetic reed test sample with the loose tubes packed into the sample holder. The underlying geometry was determined from X-ray computed tomography images of packed natural reeds and then produced by fused deposition modelling, a form of 3D printing.

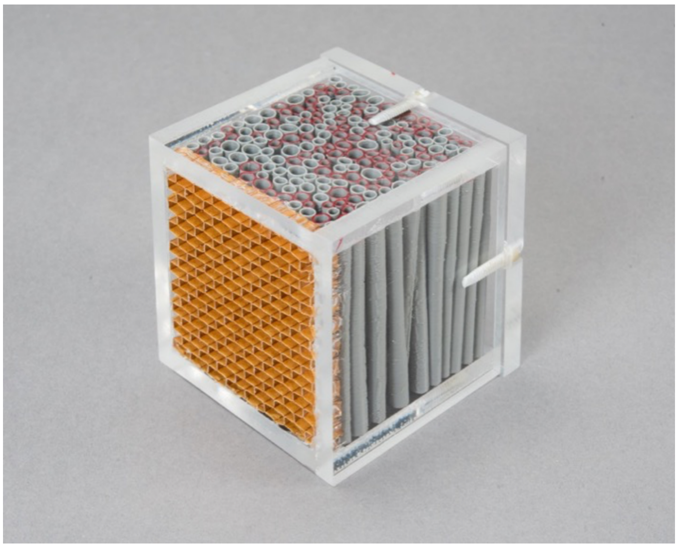

Figure 8: Loose synthetic reeds in a sample holder (from Koch, 2017).

Configurations with a baseplate to hold the reeds in place (the "fixed" synthetic reeds) have also been produced with 3D printing. The performance of 'loose' and 'fixed' shows a broad absorption character with a pronounced low frequency increase that outperforms even double degree of freedom (DDOF) conventional liners, see Figure 9. The absorption of a standard melamine foam is shown also. The results indicate that structures can be manufactured of synthetic materials that mimic the geometry and low frequency absorption of natural reeds. The team continues to research the characteristics of the structure that enable the absorption and has a patent pending on the concept.

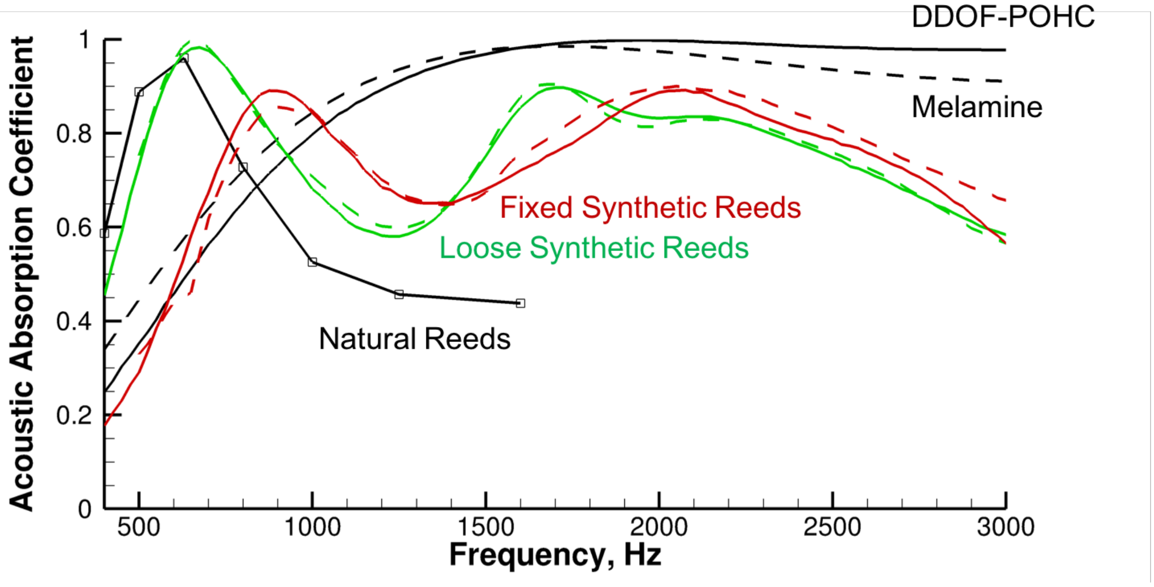

Figure 9: Comparison of natural reed and synthetic reed acoustic absorption (from Koch, 2017).

3.0 CORE/COMBUSTION SOURCE NOISE REDUCTION

As the fan and jet noise sources are reduced for ultra-high bypass ratio cycles, noise from the core that is related to the combustor may become more prominent for two main reasons (Hultgren, 2017). First, the Overall Pressure Ratio (OPR) is rising for next generation engines. Current combustor noise scaling laws such as ANOPP GECOR are:

$$Acoustic\ Power\ Level \sim (\Delta T)^2 \times W_c \times (OPR)^{8/3.5}$$

where acoustic power is a strong function of OPR. However, note that future cores also have reduced mass flow which is offsetting the OPR increase. The net change in acoustic power due to these potentially offsetting effects is still to be determined.

Secondly, the move from rich quench lean (RQL) combustor systems to lean-lean systems has the potential to change the combustor noise source structure and increase pressure fluctuations in the combustor. Lean systems are beneficial for their low NOx and soot emissions, but they are inherently less stable than RQL systems. A less stable combustor could generate pressure fluctuations that produce the low frequency 'rumble' that is characteristic of combustor noise. General Electric continues development of its TAPS series of radially staged, lean burn combustors. Figure 10a shows a flame for a TAPS series combustor with the inner pilot region and outer main. Pratt and Whitney is developing the Axially Controlled Stoichiometry (ACS) lean burn combustor which uses a pilot injector at the front of the combustor with a main injector an axial distance downstream as shown in Figure 10b. Notably, Rolls-Royce continues to pursue advanced RQL combustion systems that are 'suitable for emerging high pressure ratio, small core engines' (Cummings, 2017). Rolls-Royce continues to use the RQL configuration but has added advanced mixing strategies to meet the emissions goals.

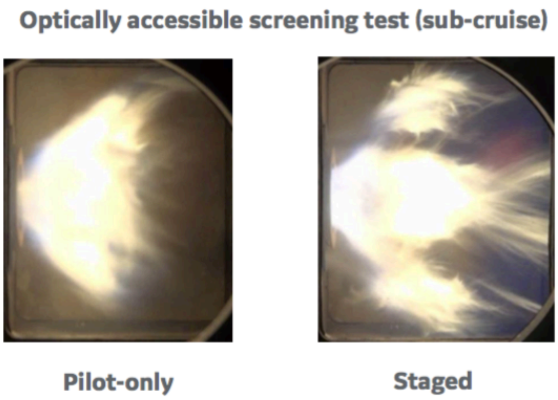

Figure 10a: GE TAPS radially staged, lean burn combustor flame image showing the inner pilot flame (left image) and outer main flame with the pilot flame in the fully staged case (right image) (GE Aviation, 2017).

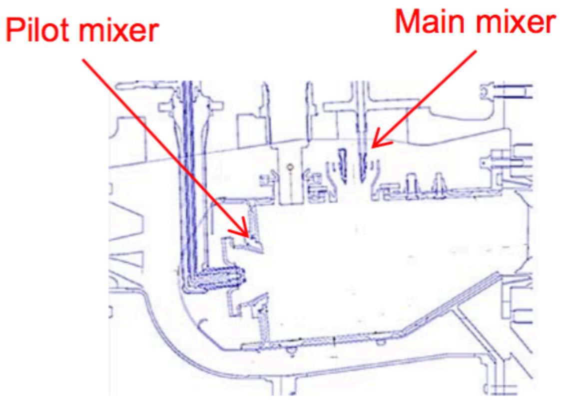

Figure 10b: Pratt and Whitney ACS lean burn concept cross section showing the pilot injector at the front of the combustor and the main injector axially downstream (United Technologies Research Center, 2016).

NASA is pursuing risk reduction strategies to enable the next generation of lean burn systems through external partnerships and in-house research. United Technologies Research Center (UTRC) was selected to perform detailed measurements of unsteady, multi-point heat release and pressure for current RQL and next generation lean burn systems. This will establish scaling principles to extend reduced order models to the lean burn systems. The research will also mature prediction tools and optical measurement techniques for the far term or 'N+3' engine conditions. Internally, NASA is maturing source separation methods, instrumentation techniques for high temperature and pressure environments as well as looking at system level combustor installations such as the DART engine to be discussed next.

4.0 HIGHER TRL SYSTEM NOISE RESEARCH

The type of configuration changes that engines and aircraft are undergoing require a more system level approach to noise reduction research. For example, as discussed in the previous section, lean burn combustor systems are more susceptible to acoustic instabilities. The combustor must have the proper upstream and downstream boundary conditions to properly study a combustor configuration or screen the configuration for instabilities. One method to accomplish this is to test the combustor in an engine environment, thus the desire to move toward system level configurations to study propulsion noise with the same logic holding true for propulsion airframe integration work. The higher TRL research activities are described next.

4.1 DART: A research turbofan engine

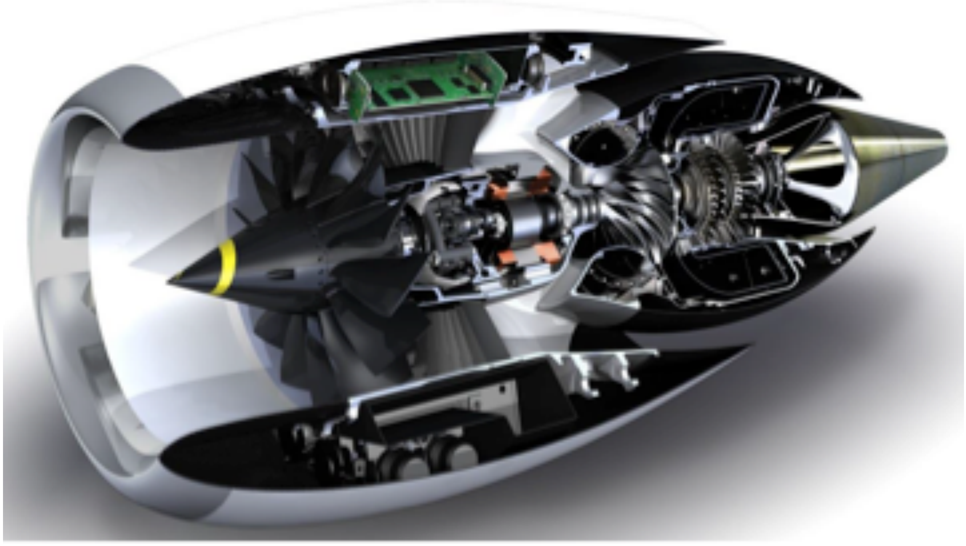

Figure 11: Schematic view of the DGEN380 turbofan engine from Price Induction (http://www.price-induction.com/dgen-engine/).

NASA Glenn has commissioned the DGEN Aeropropulsion Research Turbofan (DART) facility to perform technology maturation on noise, fuel burn and emissions reduction concepts in a more realistic engine environment. The DART facility consists of a DGEN engine, shown in Figure 11 above, and a control/data acquisition truck. DGEN is a 7.6 bypass ratio, geared fan engine that produces 500 lbf of thrust. The fan has a pressure ratio and tip speed that is representative of the coming generations of low pressure ratio fans which makes it a good surrogate for the much larger, more complex and highly expensive turbofan engines that dominate the commercial transport market. NASA performed some initial acoustic characterization of the engine prior to purchase to ensure that its noise characteristics are representative (Berton, 2015).

The DART facility is installed within the AeroAcoustic Propulsion Laboratory (AAPL) at NASA Glenn. Figure 12 shows an acoustic configuration of DART with microphone arcs in the forward and aft quadrants. The engine has undergone an initial series of baseline acoustics measurements and will be used in the summer of 2017 for tests of multi-degree of freedom liner concepts. DART is considered a mid-TRL facility, TRL 3-4, due to its scale, but it does offer a more realistic system environment for technology maturation. Future uses of DART include maturation of technologies for fan noise reduction, combustor noise characterization, engine controls research and noise source separation research.

Figure 12: The DGEN engine in an acoustic configuration within AAPL (GRC-2017-C-02250).

The DART facility was designed to be portable; the DGEN is mounted to a movable support base and the control truck can travel with the engine as necessary. The portability enables future use in wind tunnel environments or an outdoor test arena.

4.2 Improved Fan Noise Prediction Modules and Measurements

Low pressure ratio (LPR) fans with reduced drag nacelle systems are expected to be a prevalent feature of future engine configurations. A recent test of an LPR fan propulsor with a short inlet is shown in Figure 13. LPR Fans exhibit different aerodynamic behaviour than contemporary fans with supersonic tip speeds. This aerodynamic behaviour, combined with a short inlet and other engine configuration changes, results in a noise signature that is not well modelled by existing fan noise prediction modules in codes like ANOPP. Propulsor models such as the one shown, also have engine realistic features such as the pylon/bifurcation and non-axisymmetric bypass duct flow lines that influence the acoustic character. Shortcomings of the current ANOPP fan noise models were highlighted during the effort to calculate noise estimates for "N+2" systems during the Environmentally Responsible Aviation Project (Thomas and Nickols, 2016). Data from the wind tunnel tests were used in place of existing noise models. It became clear that a new fan acoustic module is needed for ANOPP that better characterizes the evolving LPR Fan/short inlet design space. The new module will have improved tone and broadband noise estimate capability for this design space.

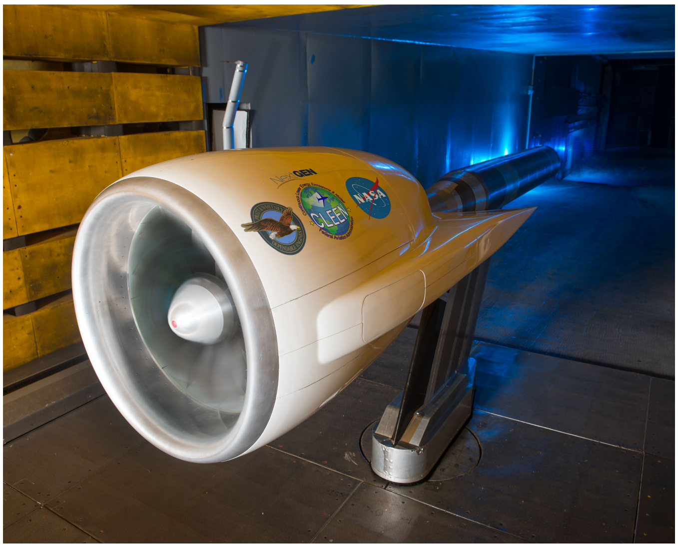

Figure 13: P&W "Rig 2" installed in the GRC 9x15 LSWT (GRC-2015-C-04209).

Wind tunnel acoustics measurement methods improvements are also needed to assure adequate signal to noise ratio for testing of quiet fan systems at Mach numbers that are more similar to aircraft landing and takeoff conditions. Contemporary fan systems with conventional length inlets are not as sensitive to wind tunnel Mach number. Most previous 9x15 LSWT acoustics testing was done at Mach 0.1 to reduce background noise in the wind tunnel. With the transition to short inlets, the inlet/fan system performance and behaviour becomes sensitive to wind tunnel conditions so much of the recent testing has been done at Mach 0.2. The 9x15 LSWT background noise goes up substantially with increasing Mach number thus the desire for improved acoustic measurement capabilities. Note that the 9x15 LSWT is undergoing a major acoustic upgrade that is designed to lower the tunnel background and enable testing of the next generations of propulsors at Mach 0.2.

In addition to lowering the background noise level via physical changes to the wind tunnel, NASA is developing advanced measurement systems which resolve acoustic signals that are masked by background noise. Work is ongoing to determine the performance of microphone phased arrays combined with advanced signal processing methods for resolving low-level acoustic signals out of background noise. A test of a microphone array called the Level Sensing Array was recently completed at the GRC Aeroacoustic Propulsion Laboratory. The acoustic signals were provided by two high-frequency sources, a tweeter and an airball. The background noise was provided by the free-jet flow at the Nozzle Acoustic Test Rig. The test setup is shown in Figure 14. Signal-to-noise ratios were varied by controlling the output of the acoustic sources and speed of the free-jet flow. The data are now being analyzed to determine how well the array method is able to resolve the acoustic signals within the background noise.

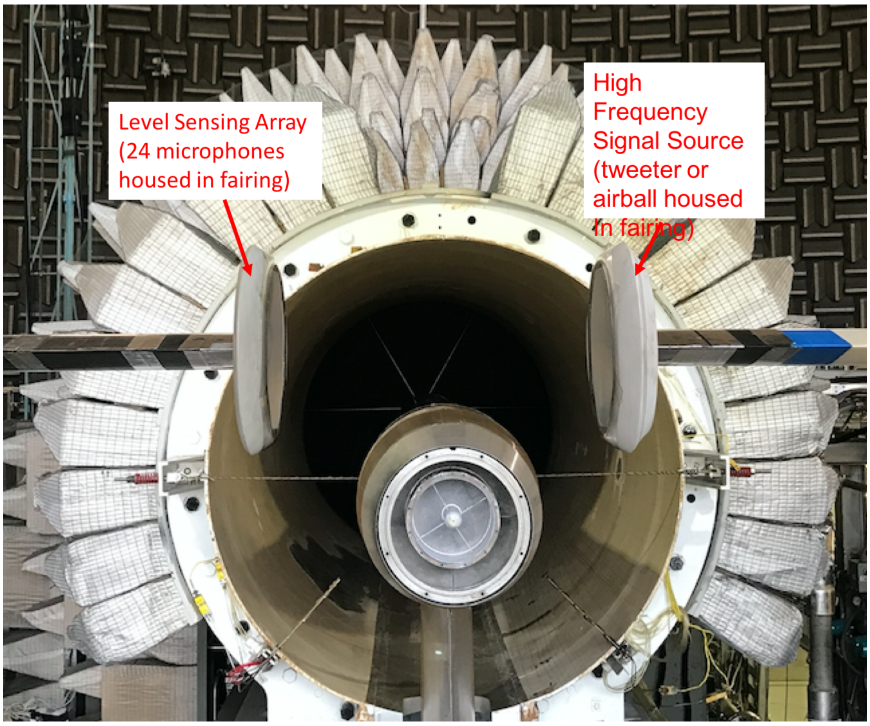

Figure 14: Level Sensing Array and sound source mounted in NATR (Podboy, 2017).

4.3 Jet Surface Interaction (JSI)

Far term aircraft concepts, such as the NASA N3-X shown in Figure 15, feature distributed propulsion systems where the high velocity jet exhausts over or close to a surface. The propulsion inlet is a high aspect ratio ‘slot’ with multiple channels separated by septa. Each channel would contain an electrically driven, low pressure ratio fan to produce a very high effective bypass ratio propulsor.

Figure 15: NASA N3-X concept aircraft (www.nasa.gov/sites/default/files/nasa_hwb_full.jpg).

The noise character of high aspect ratio nozzles was studied by Brown (Brown, 2017). A 16:1 aspect ratio nozzle meant to be representative of the N3-X is shown mounted in AAPL in Figure 16 (right image). The acoustics of the isolated nozzle were found to be similar to a single stream, simple nozzle of a diameter equal to the channel height of the high aspect ratio nozzle. The inclusion of an aft surface, Figure 16 (left image), added a new jet mixing noise source. The noise shielding benefit was masked, for some conditions, by this new noise source. In general, jet noise is assumed to be of minor importance for low FPR propulsion systems. However, interactions with the airframe may lead to significant and unexpected contributions of exhaust noise.

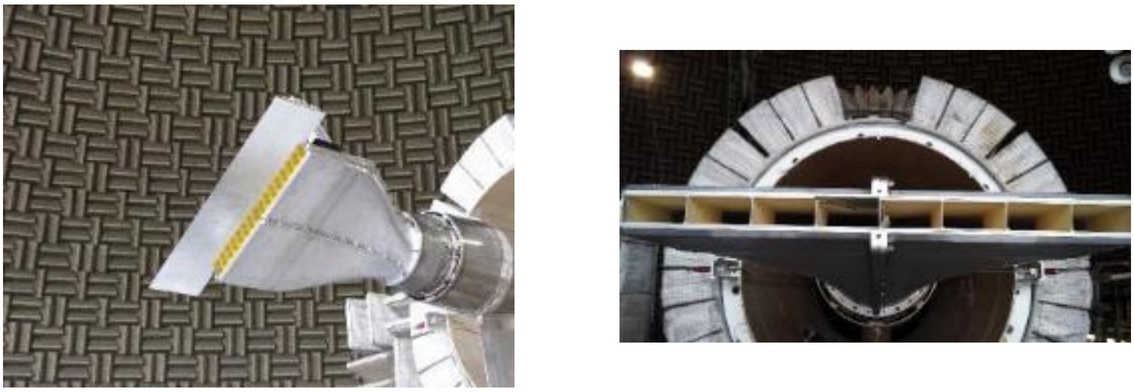

Figure 16: High aspect ratio nozzle jet surface interaction experiment setup with the 16:1 aspect ratio nozzle with septa (right image) and the nozzle with an aft surface (left image) (Brown, 2017).

5.0 FUTURE ACTIVITIES

Future propulsion systems are likely to feature large-diameter, low pressure ratio propulsors that are tightly integrated with the airframe, either ‘podded’ outside of the boundary layer or boundary layer ingesting. The final, ‘end state’ configuration of podded systems is still evolving as Garnier shows in Figure 17 (Garnier, 2011) and as discussed by Button (2016). In this view the fuel burn reduction that is possible with ducted systems is expected to asymptote while the noise margin continues to increase as the fan pressure ratio reduces. Garnier proposes that the technology path to lower fuel burn is to move to unducted systems with the final state being the “Ultimate Green Engine” which has lower fuel burn and equivalent noise to the best ducted system. Existing contra-rotating open rotor systems are estimated to meet the fuel burn and noise performance of the ‘Cert 2025’ engine shown (Van Zante et al., 2014). The technology challenges to achieving even lower noise for unducted systems are substantial.

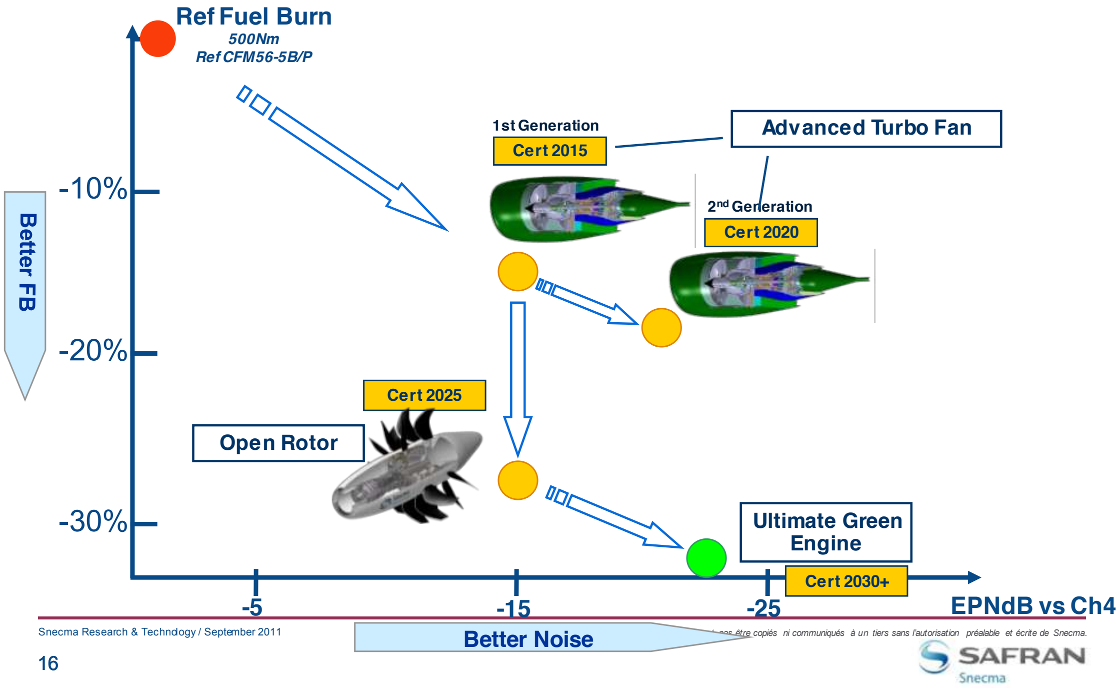

Figure 17: Engine architecture road map. (Garnier, 2011)

NASA is proposing a research effort to better characterize the aerodynamics/acoustics of LPR Fan systems including variable pitch ducted fans. The effort is also intended to reduce technology maturation risk for unducted systems and provide better estimates of the installed performance achievable from these types of systems.

Recent noise certification results for the Airbus A321neo illustrate the need to better characterize LPR Fan systems. It was thought that the A321neo with the PW1100G engine, a geared low-pressure fan configuration, would be quieter than the A321neo with the GE LEAP-1A engine, a direct drive architecture. Certification results showed the LEAP-1A configuration had a lower cumulative noise signature. Both A321neo configurations have substantial margin to current noise regulations and fuel burn comparisons are not yet published. The A321neo certification results illustrate how the engine configuration changes that are required to implement LPR fans can impact the acoustic performance of the engine. NASA is pursuing a LPR fan benchmark test case that will be a vehicle for noise reduction technology maturation with a next generation propulsor cycle and architecture. Concepts such as acoustic casing treatment, soft vanes, multi-degree of freedom liners, among others, are being considered.

NASA has previously investigated both ducted and unducted variable pitch fans. The historical and contemporary efforts for open rotors at NASA have been recently published so will not be discussed here (Van Zante, 2015). Examples of NASA supported efforts for variable pitch fans date back to the early 1970s with the GE QCSEE (Quiet, Clean, Short-Haul, Experimental Engine) and, more recently, the PW Advanced Ducted Propulsor (ADP) in the mid 1990s (Huff, 2013). The ADP was the predecessor of the newly in-service PW Geared Turbofan engine. A future propulsion system, the proposed Rolls-Royce UltraFan concept, uses a geared, variable pitch fan. As was noted with the ADP testing, there are still aerodynamic and mechanical challenges to be overcome for variable pitch fans of the thrust level and rotational speed needed for commercial transport service.

Configurations with extremely short nacelles, see Figure 18, were proposed, but never tested, as part of studies to improve engine efficiency. The limited acoustic treatment area and reduced acoustic liner effectiveness will make noise reduction a challenge for these types of systems. Non-traditional liner locations and novel blade shapes are technologies that could be matured to meet this noise challenge.

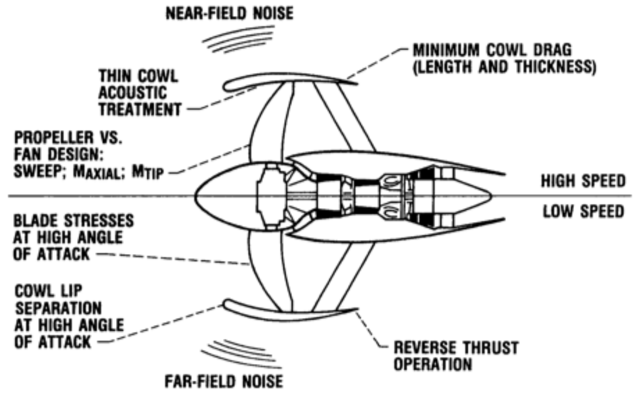

Figure 18: The ‘ducted propeller’ concept and technical challenges (Groeneweg et al., 1988)

In addition to maturation of engine specific technologies, the installation of large diameter or highly integrated propulsors onto an airframe will be challenging. Furthermore, the *installed* aerodynamic and acoustic performance of the new concepts must be validated. Future research efforts must include propulsion airframe integration research as well as propulsion airframe aeroacoustics measurements for the future aircraft configurations.

6.0 SUMMARY

The NASA Aircraft Noise Reduction sub-project of AATT has a diverse portfolio of technologies for propulsion noise reduction for future engine and aircraft configurations. NASA will continue to pursue technologies such as source noise reduction and more effective liners that will enable continued noise reduction in next generation low pressure ratio fans. Better source characterization of next generation engines integrated with advanced airframes will enable system level estimates of noise for these future aircraft.

ACKNOWLEDGMENTS

The ANR subproject involves contributions from many individuals at the three primary NASA Aeronautics research centers, Glenn, Langley and Ames.

REFERENCES

Epstein, Alan, "The Lessons of P&W's Geared Turbofan^{TM} Engine and the Implications for the Future," Keynote Address, International Symposium on Air Breathing Engines (ISABE), Phoenix, AZ, October 2015.

Nickol, Craig L. and Haller, William J., "Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project", 54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2016-1030).

Thomas, Russell H., Burley, Casey L. and Nickol, Craig L., "Assessment of the Noise Reduction Potential of Advanced Subsonic Transport Concepts for NASA's Environmentally Responsible Aviation Project", 54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2016-0863)

Hughes, Christopher and Gazzaniga, John, "Effect of Two Advanced Noise Reduction Technologies on the Aerodynamic Performance of an Ultra High Bypass Ratio Fan", 15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference), AIAA 2009-3139, Miami, FL, May 11-13, 2009.

Bozak, Richard F.; Hughes, Christopher E.; Buckley, James, "The Aerodynamic Performance of an Over-the-Rotor Liner With Circumferential Grooves on a High Bypass Ratio Turbofan Rotor", ASME GT2013-95114, ASME Turbo Expo 2013, San Antonio, TX, June 3-7, 2013.

Sutliff, Daniel L., Jones, Michael G. and Hartley, Thomas C., "High-Speed Turbofan Noise Reduction Using Foam-Metal Liner Over-the-Rotor", Journal of Aircraft, Vol. 50, No. 5 (2013), pp. 1491-1503.

Jones, Michael G., Parrott, Tony L., Daniel L. Sutliff, and Christopher E. Hughes, "Assessment of Soft Vane and Metal Foam Engine Noise Reduction Concepts," AIAA Paper 2009-3142, May 2009

Jones, Michael G. and Howerton, Brian M., "Evaluation of Novel Liner Concepts for Fan and Airframe Noise Reduction", AIAA Paper 2016-2787, June 2016.

Sutliff, Daniel L., Jones, Michael G. and Nark, Douglas M., "In-Duct and Far-field Experimental Measurements from the ANCF for the Purpose of Improved Broadband Liner Optimization", AIAA Paper 2014-3231, June 2014.

Nark, Douglas M., Jones, Michael G. and Sutliff, Daniel L., "Modeling of Broadband Liners Applied to the Advanced Noise Control Fan", AIAA Paper 2015-2693, June 2015.

Sutliff, Daniel L., Jones, Michael G. and Nark, Douglas M., "Efficacy of a Multiple Degree of Freedom Acoustic Liner Installed in the Bypass of a Scale Model High Speed Fan", AIAA Paper 2016-3005, June 2016.

Nark, Douglas M., Jones, Michael G., and Sutliff, Daniel L., "Further Development and Assessment of a Broadband Liner Optimization Process", AIAA Paper 2016-2784, June 2016.

Fernandez, Hamilton, "Aircraft Noise Reduction Subproject Overview", Acoustics Technical Working Group Meeting, NASA Langley Research Center, Hampton, VA, April 19-20, 2016.

Koch, L. Danielle and Jones, Michael, "Measurement of the acoustic absorption of natural reeds and comparison to aircraft engine acoustic liner prototypes," NASA TM-2016-218851, 2016.

Koch, Bonacuse, Kuczmarski, Johnston, Miller, Jones, "The development of acoustic absorbers that mimic assemblies of natural reeds: Progress Report 1," NASA TM-2017-219438, 2017.

Koch, L. Danielle, "Investigation of a Bio-Inspired Liner Concept," Acoustics Technical Working Group Meeting, NASA Langley Research Center, Hampton, VA, April 11-12, 2017.

Hultgren, Lennart S., "Core/Combustor Noise – Research Overview," Acoustics Technical Working Group Meeting, NASA Langley Research Center, Hampton, VA, April 11-12, 2017.

GE Aviation, "FAA CLEEN II Consortium Program Update – Public Plenary," 2017 FAA CLEEN II Consortium, hosted by GE Aviation, Evendale, OH, May 2-4, 2017.

United Technologies Research Center, “Acoustics of Future Low-Emissions Combustor Technology,” NASA Contract NNC16CA39C, presented at Acoustics Technical Working Group, NASA Glenn Research Center, Cleveland, OH, October 25-26, 2016.

Cummings, Bill, “FAA CLEEN II Technologies, Rolls-Royce CLEEN II Low NOx Combustor Program,” 2017 FAA CLEEN II Consortium, hosted by GE Aviation, Evendale, OH, May 2-4, 2017.

Berton, Jeffrey J., “System Noise Prediction of the DGEN 380 Turbofan Engine,” 21st AIAA/CEAS Aeroacoustics Conference, Dallas, Texas, 22-26 June, 2015.

Abbas Khavaran, Richard Bozak, and Clifford A. Brown. "Jet Surface Interaction Noise in a Planar Exhaust", 22nd AIAA/CEAS Aeroacoustics Conference, Aeroacoustics Conferences, (AIAA 2016-2863), Lyon, France, 30 May – 1 June, 2016.

Button, Keith, “The Green Engine Debate,” Aerospace America, pp 35-40, January, 2016.

Podboy, Gary, private communication, May 2017.

Brown, Clifford, “Jet Surface Interaction Noise from High Aspect Ratio Nozzles,” AIAA 2017-3522, AIAA Aviation Forum and Exposition, Denver, Colorado, June 5-9, 2017.

Garnier, V., “Aero engines of the 21st Century Evolution or Revolution,” 20th ISABE Conference Keynote presentation, Goteborg, Sweden, September 15, 2011.

Van Zante, D.E., Collier, F., Orton, A., Khalid, S. Arif, Wojno, J.P. and Wood, T.H., “Progress in open rotor propulsors: The FAA/GE/NASA open rotor test campaign,” The Aeronautical Journal, Vol. 118, No. 1208, October 2014.

Huff, Dennis L., “NASA Glenn’s Contributions to Aircraft Engine Noise Research,” ASCE Journal of Aerospace Engineering, Vol. 26, pp. 218-250, 2013.

Groeneweg, John F., Bober, Lawrence J., “NASA advanced propeller research,” NASA-TM-101361, Advanced Propellers and Their Installation on Aircraft, Cranfield, England, 26-27 Sep. 1988.