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

Integrated Propulsion System for Commercial Aircraft Technology Demonstrator

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EXECUTIVE SUMMARY

Collins Aerospace has developed advanced nacelle acoustic technologies with an intent to implement on the CLEEN II Ground Test (GT) demonstrator unit. The goal of the CLEEN II nacelle has been to enable continued fuel burn performance while improving noise reduction that supports next generation environmental metrics. The CLEEN II Ground Test demonstrator development has been focused on improved drag via introduction of Low Drag Liner and liner configurations including a Fan Duct Novel Liner, and Acoustic Zoned Liner technologies. The initially planned ground test is to enable these technologies to attain TRL 6. Unfortunately, due to unfavorable market and economic scenarios given by the COVID-19 pandemic, the acoustic ground test demonstration has been placed on hold and planned for a mid-term future outside CLEEN. Therefore, the demonstration of benefits in this final report will be solely based on system level acoustic and aerodynamic predictions. These results will serve as the most current measure of the technology performance and benefits, until a ground test validation is performed in the future. The test plan for this future effort has been completed and archived for future use.

Even though it was not possible to execute the ground test, the CLEEN II effort generated multiple outcomes. Selected technologies from the program, e.g. low drag surfaces and zoned liner configurations, have successfully reached production ready status and have been incorporated into current production nacelle applications. In addition, the program helped generate sub-element laboratory test data and advanced prediction tools that allowed quantifying and demonstrating the proposed benefits analytically. The developed acoustic optimization tools have also been incorporated into Aerostructures standard processes for liner optimization. Based on the analytical assessment, it was concluded that the overall EPNL benefit as well as the individual contributions of the liners are in line with the targets and meet the CLEEN II noise improvement goal of 2.0 EPNdB. The predicted total fuel burn benefits of the combined clean fan duct and low drag liner was 0.46%, also in line with expectations.

Finally, the manufacturing maturity of both inlet and fan duct acoustic technologies was significantly advanced by the efforts facilitated by the CLEEN II program and documented in this report.

1. INTRODUCTION

This report documents the efforts conducted by Collins Aerospace to develop advanced nacelle acoustic liners under the Phase II of the Continuous Lower Energy, Emissions and Noise (CLEEN) Program. The CLEEN program is current FAA's principal environmental effort to accelerate the development of new aircraft and engine technologies and advance sustainable alternative jet fuels. The presented efforts support the FAA's Next Generation Air Transportation System airframe level goals:

1. 40% reduction in fuel burn
2. 75% reduction in nitrogen oxide (NOx) emissions
3. 32 EPNdB cumulative noise reduction relative to Stage 4 standards

The Collins Aerospace contribution to CLEEN II is the development of technologies in support of aerodynamically and acoustically optimized nacelle architectures, enabling lower emissions, energy and noise, aimed at maximizing efficiency of the next generation high bypass ratio propulsion systems for reducing climate impact from aviation. The overall effort includes the development of advanced liner configurations for both the inlet and fan duct components. The acoustic liners were designed and optimized by the acoustics R&T group at Aerostructures, in collaboration with the Raytheon Technologies Research Center (RTRC) that developed the optimization software.

1.1. BACKGROUND

In order to contribute to the CLEEN II goals, the development of Ultra high-bypass (UHB) turbo fan engines is vital to achieve maximum efficiency and noise reduction. UHB architecture features a larger, more slowly rotating fan for a given thrust as compared to legacy designs. Larger fan diameters drive larger nacelle and pylon structures. Given the trend in P&W GTF next generation engines to increase fan diameters to favor efficiency, improvements in Thrust Specific Fuel Consumption (TSFC) and community noise reduction become critical (see Figure 1-1), especially as thrust levels and aircraft takeoff weights increase.

However, as fan diameters increase for a given thrust and fan pressure ratios are reduced to realize TSFC improvements, nacelle weight and drag can increase. This underscores the need to develop technologies that reduce drag and weight for power plant installations that feature UHB engines. One approach to improve performance is to use a shorter nacelle that minimizes the weight impact. The Aerostructures vision to achieve the shorter nacelle, with thrust reverser capabilities, is to incorporate an integrated approach to all the major elements of a propulsion system, such as the engine, nacelle, pylon, and systems. Nevertheless, the shorter nacelle ducts can reduce acoustically treated area, driving the need for more effective acoustic treatment.

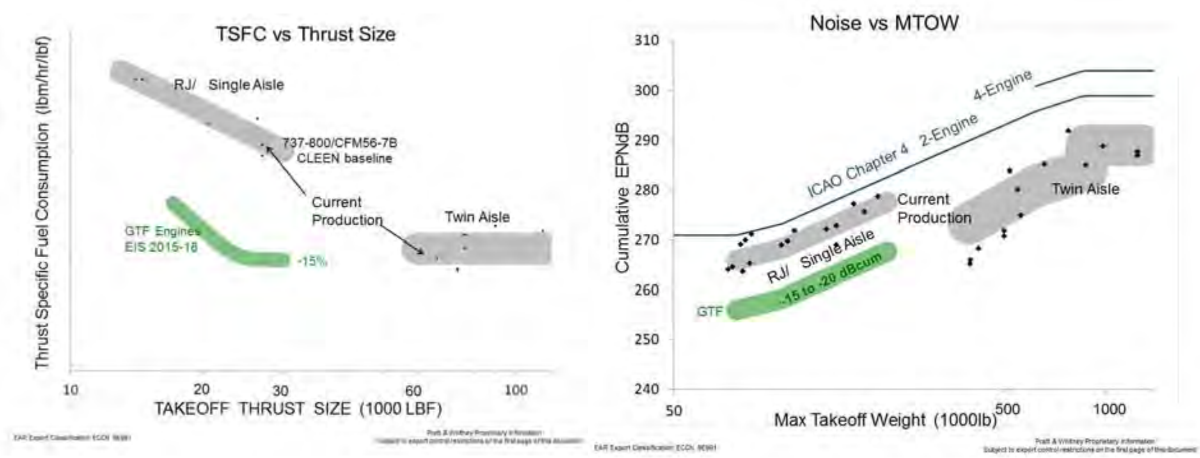


Figure 1-1 Improvements in TSFC and Noise Reduction are Critical on Next Generation Engines

With corresponding improvements in airframe design, this integrated propulsion system (IPS) envisioned by Aerostructures can achieve CLEEN II objectives in the timeframe consistent with an entry into service prior to 2026. The projected benefits of the integrated propulsion system are:

- Fuel Burn Improvement – An additional 1% fuel burn reduction from the reduction in nacelle length and implementation of low drag acoustic surface
- Overall noise benefit of -2.0 EPNdB from implementation of maximum acoustically treated area combined with effective acoustic treatments and segmented liner configurations. This benefit can be utilized to offset the reduction in acoustically treated area that results from a relatively short Inlet and Thrust Reverser ducts.

1.2. ACOUSTIC & LOW DRAG TECHNOLOGIES

The advanced nacelle acoustic technologies developed under CLEEN II are listed in Table 1-1, including the current Technology Readiness Level (TRL) achieved during the program and the description of the intended benefits.

Table 1-1 CLEEN II Collins Aerospace Acoustic Technologies

Technology	Achieved TRL	Benefits
Zoned Acoustic Liner	6	Tailors acoustic treatment to local tones & aerodynamics plus area maximize
Clean Duct	6+	Increased Acoustic Area, including *Exterior Liner*
Fan Duct Novel Liner	5	Improves acoustic attenuation per sq. ft.
Low Drag Liner	6	Reduces drag in acoustic areas
Short Inlet	3	Improved acoustics or reduced drag

1.2.1. Short Inlet

The proposed short inlet configuration consists on a reduction in the overall length of the inlet from L/D 0.6 to 0.4, seeking less external drag (due to the smaller contact surface) and reduced weight, which both have a direct benefit on fuel burn efficiency. Figure 1-2 shows a schematic of the proposed inlet length reduction. However, this reduction in length has a negative impact on community noise as it yields a significant reduction in the acoustic area necessary to control broadband and tonal noise generated at the fan. As an enabling technology, the proposed effort also includes the development of novel liner concepts that provide improved response relative to current double degree of freedom (DDOF) liners in order to offset for the area reduction. These configurations have also been identified to potentially reduce production cost relative to DDOF liners.

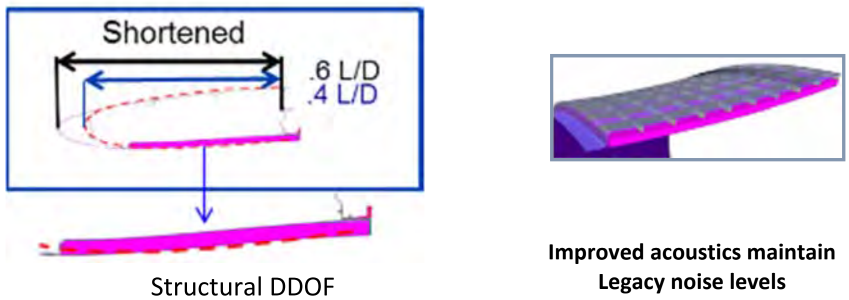


Figure 1-2 Short Inlet Configuration incorporating Advanced Acoustic Liners

1.2.2. Advanced Fan Duct

The Advanced Fan Duct system includes the Clean Duct Acoustic Liner, the Zoned Liner, a novel Fan Duct Liner, and Low Drag Liners. The Clean Duct simulates the acoustic area that would be achieved by a future advanced reverse thrust mechanism that improves fan duct aerodynamic performance (reduces fan duct pressure losses) and increases acoustically treated area for a given fan duct length. To reduce these losses and improve fan duct performance, the envisioned Integrated Thrust Reverser architecture removes blocker door deployment mechanisms (drag links) from the fan stream, where they currently reside on legacy applications, as shown in Figure 1-3. The increased acoustic area configuration also includes treatment on the fan duct inner wall surface located on the aft section outside the fan duct exit plane and thus, external to the fan duct.

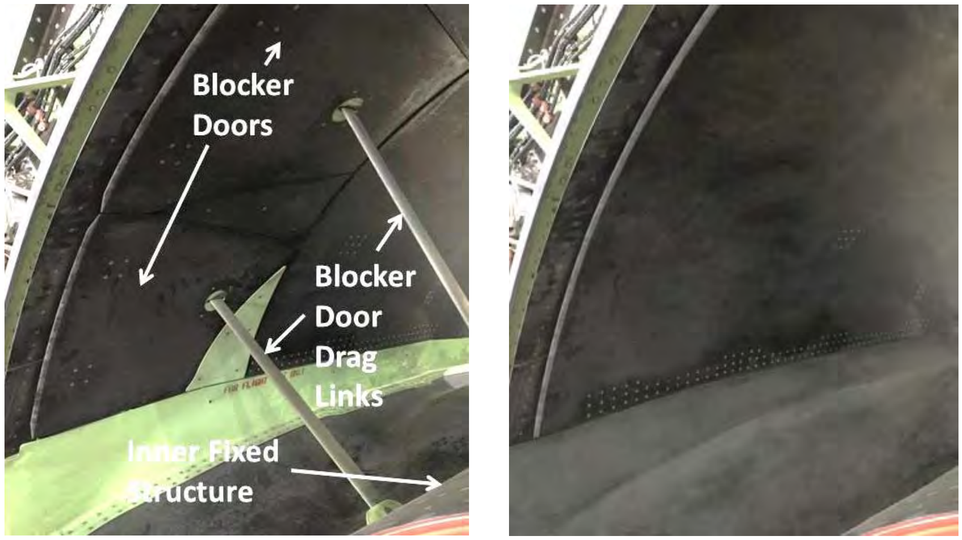
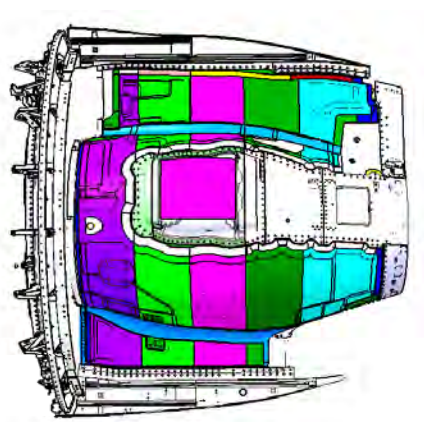


Figure 1-3 Legacy Thrust Reverser Fan Duct (left) Compared to a future Integrated Thrust Reverser

Zoned acoustic treatment offers the potential to tune the attenuation of the treatment down the length of the fan duct. This is achieved by varying the honeycomb core height and skin perforation configuration in the bond panel, allowing, for instance, deeper core to attenuate the prevalent lower noise tones at one location in the fan duct while allowing for reduced height honeycomb core thickness in another part of the fan duct to attenuate the higher noise tones that might be found in that area.

A novel acoustic liner, targeting reduced panel depth, with the potential for equal or better acoustic performance relative to legacy honeycomb is another acoustic technology that is incorporated in the advanced liner configuration. This technology can allow for fewer constraints on designing an optimum fan duct aerodynamic shape as compared to the constraints that legacy honeycomb core heights exhibit. When combined with zoned acoustic treatment, a synergy is created that results in a potential for reduced overall panel thicknesses and more optimal fan duct shapes while increasing broad-band noise attenuation performance. The zoned liner and novel liner are illustrated in Figure 1-4.

(a)



(b)

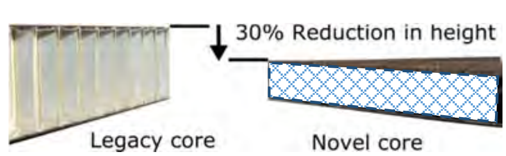


Figure 1-4 (a) Zoned Liner and (b) Novel Acoustics Technologies

The Low Drag Liner technology consists in small hole perforations leading to reduced skin friction and pressure drag in the presence of grazing flow while providing the same acoustic performance as current state-of-the-art liners.

1.3. PROGRAM GOALS

The main objectives of the development program are to mature and demonstrate the performance of the liner technologies listed in Table 1-2. The targeted overall noise benefits of the new nacelle system are 2.5 EPNdB with a legacy (long) inlet and 2.0 EPNdB if the inlet is reduced in length. Therefore, the advanced inlet acoustic liners are primarily intended to offset acoustic area losses due to the shortened length. The overall fuel burn benefits are 0.55% with a legacy inlet, and 1.05% with the short inlet configuration.

For demonstration of these goals, the original plan consisted on reaching acoustic TRL 6 on all fan duct technologies through ground test demonstration using a PW1500G GTF engine at the Pratt & Whitney's C-11 test facility in West Palm Beach, Florida, and acoustic TRL 5 on the short inlet technologies. However, due to evolving market conditions and the recent COVID-19 pandemic, the ground testing has been placed on hold and will be resumed in the future outside of CLEEN II. The test plan for this effort has been completed and archived for future use. In addition, all further tests supporting short inlet technologies have also been placed on hold to be continued as future work. As a consequence, the technology demonstrations will be carried out by analysis.

Table 1-2 Acoustic Technologies Demonstration Goals

Technology	Fuel Burn (%) Improvement Goal	Noise Improvement Goal (EPNdB)
Zoned Acoustic Liner	Neutral	1.0
Clean Duct	0.3	1.0
Fan Duct Novel Liner	Neutral	Included in Zoned Liner
Low Drag Liner	0.25	Neutral
Short Inlet	0.5 if short Inlet (Neutral if legacy Inlet)	Neutral if short Inlet (0.5 if legacy Inlet)
TOTAL	Short Inlet: 1.05 (Legacy Inlet 0.55)	Short Inlet: 2.0 (Legacy Inlet: 2.5)

2. ANALYSIS AND DEMONSTRATION METHODOLOGY

2.1. ACOUSTIC ANALYSIS

The prediction methodology utilized to assess the performance of the CLEEN II fan duct liner is based on a far-field finite element model developed in ACTRAN combined with a propagation scheme to compute EPNL. For this purpose, a set of experimental static engine test data for the PW1500 engine was adjusted based on the finite element predictions. The ground test data was provided to Collins by Pratt & Whitney as the total and source separated far field measurements. The separated source components included jet noise, aft fan broadband, inlet fan broadband, inlet fan tones, aft fan tones, low pressure turbine and haystack, and combustor broadband. The measurements were provided at representative approach, cutback, and sideline corrected low rotor rotational speeds (RPM). In addition, the test measurements included a baseline (fully treated), and a hard wall configuration (no liner).

The methodology for calculating the EPNL improvement relative to the baseline consists in applying the predicted liner attenuation to the P&W-provided source separated database, specifically to the aft fan broadband and aft fan tones components. All other separated noise source components remain constant. The liner attenuation is applied as a correction to the measured spectra, directly at the microphone location as predicted from the ACTRAN far field model. The corrected data is used instead of full predictions in order to keep the sound directivities as close as possible to the measured noise signature while still accounting for the attenuation improvements due to the advanced liner configuration. The new corrected aft fan broadband and tone components are re-combined with all separated noise sources to re-compute the EPNL using the ANOPP code.

2.2. ACOUSTIC LABORATORY TESTS

In addition to the finite element prediction framework, several test equipment and test facilities have been used during the course of the program to support the development and performance validation of the novel liner concepts. The following is a list of the conducted tests to support the liner development:

- Normal Incidence Impedance Tube (flat samples)
- Aerostructures Flow Duct Facility (insertion loss)
- NASA Grazing Flow Impedance Tube (GFIT)
- NASA LTF / Curved Duct Test Rig (sub-element samples, mode propagation)
- Advanced Noise Control Fan (ANCF – NASA/Univ. Notre Dame – sub-component test, circular segments)
- P&W Ground Test Facility (Standard Static Engine Test [Ref. 1] - planned)

2.3. AERODYNAMIC ANALYSIS

The fuel burn efficiency improvements of technologies which are applied to the engine fan duct can be measured by the change in total pressure loss through the duct. This value is meant to describe the amount of energy loss from the fan to the bypass nozzle, with steps and gaps and obstructions in the ducts removing the energy put into the flow by the fan accelerating air through the duct. The CLEEN II project focused on two major areas of increasing the bypass duct efficiency; a clean fan duct (1) free of obstructions including a removal of the thrust reverser drag links, and steps and gaps from the blocker doors as well as a (2) low drag acoustic liner. These modifications were compared to the production baseline model of the same propulsion system to determine the fuel burn benefits.

Two techniques were used to verify the fuel burn efficiency gains from the CLEEN II technologies. The first was the use of trade factors for the engine, a simple set of relationships that directly correlate the reduction in pressure loss to increased fuel efficiency of the propulsion system. The second technique involved the use of a more complex NPSS propulsion system model built by Georgia Tech's Aerospace Systems Design Laboratory. That model was built off publicly-available data on the CLEEN II PW1500G engine and then verified for accuracy by Pratt & Whitney. GA Tech's model used the total pressure loss reduction in a standard mission profile of the CLEEN II propulsion system to determine the overall fuel burn savings. The conclusions of these two techniques did not differ significantly, validating the use of the trade factors throughout the project.

For liner surface drag, the CLEEN II project sought to reduce the effects of the pressure drag of the perforation by creating low drag liners which made use of smaller diameter acoustic liner holes enabled by Collins' novel perforation developments. A physical model calculating an equivalent sand grain roughness Reynolds number was developed. This model allows utilizing existing models which correlate flow resistance with sand grain roughness by estimating the equivalent roughness associated with perforations. The methodology was validated with test data from NASA and RTRC test facilities.

2.4. DEMONSTRATION PROCESS

The adopted demonstration approach for the inlet and fan duct technologies is illustrated in Figure 2-1. The short inlet demonstration of the aerodynamic and fuel burn benefits was performed based purely on analysis that accounts for the less surface area and lower weight. In addition, the novel acoustic liners were to be demonstrated and validated to TRL 5 via laboratory and sub-component tests on the NASA CDTR facility and the ANCF test rig. For the advanced fan duct demonstration, the approach to reach TRL 6 is to integrate all CLEEN II technologies into a full scale demo and perform a static engine ground test at the P&W C-11 Test Stand. The individual fan duct technologies were incrementally validated through the TRL 3-5 testing (see Section 2.2) in parallel with the CLEEN II program. Unfortunately, due to unfavorable market and economic scenarios given by the COVID-19 pandemic, the acoustic ground test demonstration and the short inlet TRL4/5 testing have been placed on hold and planned for a mid-term future outside CLEEN. Therefore, the demonstration of benefits was solely based on system level acoustic and aerodynamic predictions. Looking out into a future ground test, the original strategy will still apply, and consists on the modification of a production thrust reverser (TR) to incorporate the advanced acoustic liners.

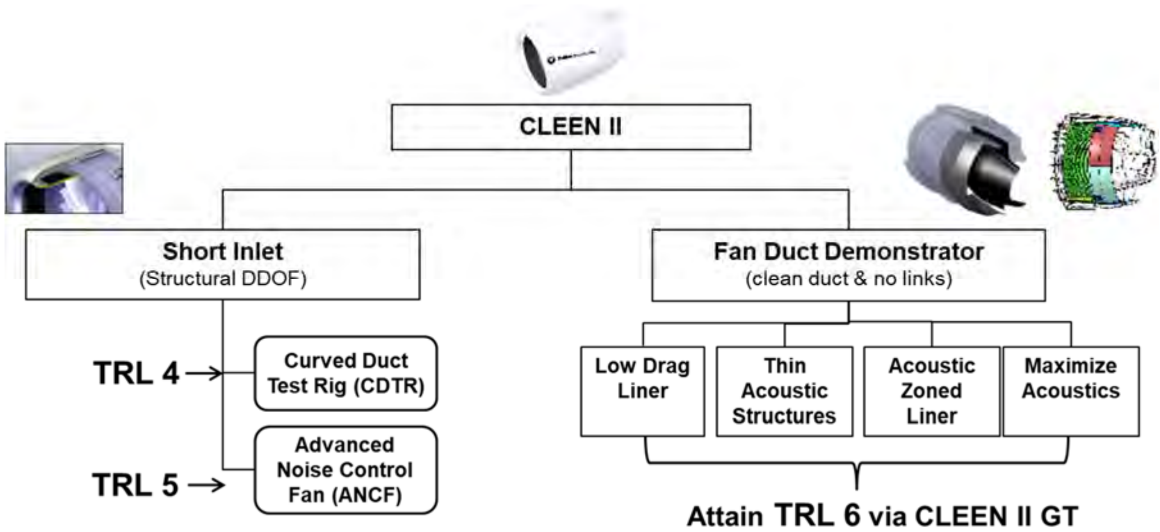


Figure 2-1 Demonstration Scheme.

3. CLEAN FAN DUCT DESIGN

The acoustic design layout of the fan duct acoustic zoned liner is presented. The section includes a brief description of the acoustic optimization, system design, stress analysis and engineering tree.

3.1. ACOUSTICS

An optimization loop was developed in Simulia iSight by RTRC and provided to Aerostructures to perform the liner design. An integral part of this optimization loop is the acoustic liner prediction module, which combines the Aerostructures liner impedance prediction code and a finite element ACTRAN model to compute the zoned liner attenuation. Figure 3-1 shows the basic flow chart utilized by the optimizer. The optimization process provided the liner specifications (core depth, face sheet parameters, etc.) for each of the liner segments to be incorporated in the design.

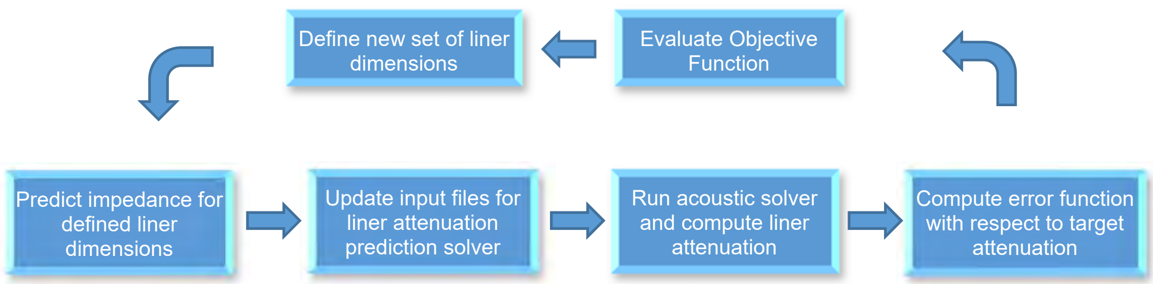


Figure 3-1 Optimization loop flow chart

3.2. DESIGN

A section cut of the overall fan duct acoustic layout is illustrated in Figure 3-2. The design includes three (3) acoustic segments on the outer sleeve, incorporating two zones with the novel core; and five segments on the inner surface including one segment outside of the fan duct (most aft segment). The liner specifications were designed according to the acoustic optimization results. As the duct simulates a clean TR with hidden blocker doors and no drag links, one of the major advantages from the design standpoint is the maximization of acoustic areas. In order to reduce aerodynamic drag in the fan duct, all surface were provided with small hole perforations.

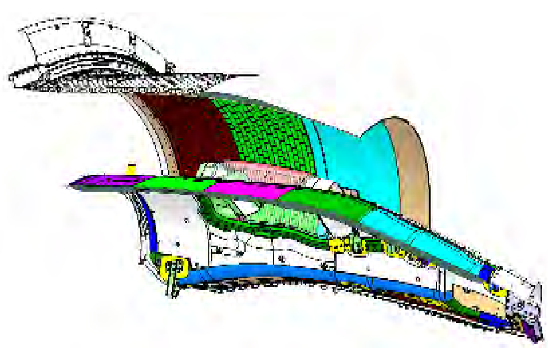


Figure 3-2 Acoustic Zoned Layout of CLEEN Fan Duct

3.3. STRESS ANALYSIS METHODS

This section summarizes the structural modeling and analysis developed in support of the FAA CLEENII Collins Aerospace contribution.

3.3.1. FEM and Loads

A FEM was used to calculate internal forces within the CLEEN II fan-duct given the loading from the production Thrust Reverser model. The stiffness and load paths of the CLEEN II duct are mostly similar to the production TR.

3.3.2. Duct Outer Sleeve

Two new analysis methods were necessary to substantiate the design of the novel core:

- Faceskin buckling
- Lap Shear analysis of the transition from one core-height to another

In addition, the splicing of the novel core segments was verified by test, with corresponding adhesive materials.

3.3.3. Duct Inner Surface

Analysis to accommodate core height transition due to the Zoned Liner was performed. Based on this analysis, suitable core transition ramps are added where varying core depths are required in adjacent acoustic zones.

The flatwise analysis at core height transitions is per Collins Standard Method. Core flatwise compression and core-to-face sheet flatwise tension at the transition location were accounted for in the margin of safety calculation.

3.4. ENGINEERING DRAWING TREE

Ninety (90) new Collins Engineering drawings for inner wall liner parts (referred to as IFS) and 159 new Collins Engineering drawings for outer wall liner parts (XLS) for the ground test TR have been generated and released as of March 2020. The new ground test TR will be manufactured in combination with existing production part drawings and it is defined in Collins Engineering drawing, 501-9300-501, and its top-level drawing tree is shown in Figure 3-3.

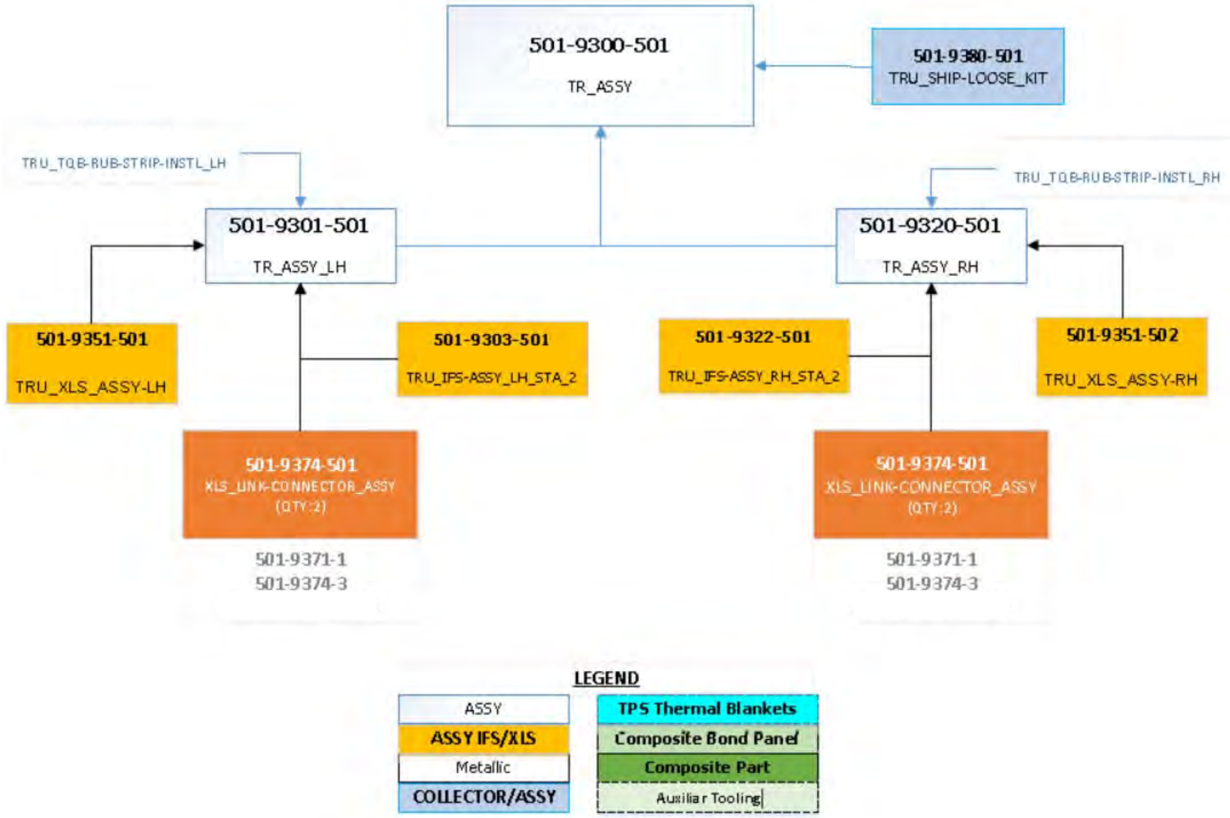


Figure 3-3 Top Level Engineering Tree for CLEEN II Modified TR

4. CLEAN FAN DUCT DEMONSTRATION RESULTS

This section presents the prediction-based assessment of the CLEEN II acoustic fan duct performance. The assessment metric is the calculated EPNL improvement based on the predicted attenuation by each CLEEN II liner technology. As the ground test demonstration of the CLEEN II fan duct has been placed on hold, this analytical assessment serves as the most current measure of the technology performance and benefits, until a ground test validation is performed at a later development program. The following sub-sections summarize the assessment methodology as well as the prediction results.

4.1. PREDICTION-BASED BENEFIT DEMONSTRATION

This section presents the methodology to demonstrate the proposed benefit goals in Table 1-2 and the contribution breakdown of each individual technology.

4.1.1. EPNL Benefits

The EPNL calculations are performed following the process described in Section 2.1, using both ANOPP and P&W legacy code SyLNT for each configuration in Table 4-1.

Table 4-1 Final CLEEN II Prediction Matrix

Cfg #	ID	Description
1	HW	Hard Wall
2	Full Treated	All liners active, zoned configuration, including outside fan duct exit plane.
3	Ducted Treatment	Only in-duct liners active, zoned configuration.
4	Production Liner	Production acoustic area and production liner specifications (Uniform liner)
5	Zoned with Production Area	Zoned Liner configuration on production acoustic area layout.
6	Uniform with Increased Area	Uniform liner on CLEEN II acoustic area layout, in-duct only (no exterior liner)

Based on the configurations in Table 4-1, the EPNL benefits and contribution breakdown of each technology are estimated as:

- Cfg#4-Cfg#2: Overall CLEEN II Fan Duct Benefit
- Cfg#4-Cfg#3: Contribution of In-Duct Treatment
- Cfg#3-Cfg#2: Contribution of Area Outside Duct
- Cfg#4-Cfg#5: Contribution of Zoned Liner (production acoustic area)
- Cfg#6-Cfg#3: Contribution of Zoned Liner (CLEEN acoustic area – in-duct only)
- Cfg#5-Cfg#3: Contribution of added In-Duct Treatment (in zoned configuration)

- Cfg#4-Cfg#6: Contribution of added In-Duct Treatment (in uniform configuration)

Note the HW configuration is only used to compute absolute attenuation.

4.2. EPNL PREDICTIONS

The overall EPNL reduction improvements are calculated relative to a production liner configuration with traditional blocker door thrust reverser and conventional SDOF uniform liner. These EPNL results are reported as the overall benefit of the CLEEN II demonstration package as well as the contribution breakdown of each individual technology. The predicted benefits are also compared to the program goals.

4.2.1. Goals

In order to quantify the benefits, the technology package summarized in Table 1-1 can be grouped into two main contributions for the overall improvement target of 2.0 EPNdB. The two contributions are the new zoned liner layout, which incorporates two segments of the novel acoustic liner, and the additional benefit due to the added acoustic area that would be enabled by a clean surface, next generation thrust reverser. The noise goal breakdown for each contribution is presented in Table 4-2.

Table 4-2 CLEEN II Noise Improvement Targets

Technology Contribution	CLEEN II Goal (EPNdB)
Zoned Liner (including Novel Liner)	1.0
Clean Duct TR with Aft Core Cowl Treatment	1.0
Overall Goal	**2.0**

4.2.2. Breakdown of Technology Contributions

The predicted EPNL benefits and individual technology contributions are presented in this section according to the rationale in Section 4.1.1. The calculations are performed based on the liner attenuations predicted by Collins, and using both the NASA prediction code ANOPP and the P&W in-house code SyLNT. Both results are presented in Table 4-3 and Table 4-4, respectively. The breakdown contributions are consistent for the two methods, but the P&W results yields a smaller overall benefit at 2.2 EPNdB relative to the production configuration, while the ANOPP estimation predicts a 2.7 EPNdB benefit. The two results are shown for comparison, but the P&W estimation should be considered most accurate since it includes the real flight trajectories, proprietary airframe noise, and a validated prediction methodology.

Note that the contribution of the zoned liner and the in-duct added area was evaluated in different scenarios in order to understand the incremental benefit relative to alternative baselines that could be applicable to different nacelle installations. However, for reporting purposes, the estimated benefit is computed as the average of these alternative scenarios.

Table 4-3 EPNL Benefit Breakdown by Technology (ANOPP)

Technology Contribution		Assumption	Relative Comparison	Predicted EPNL Increment (EPNdB)	Estimated Benefit (Average- EPNdB)
Liner type	Zoned Liner	Production Acoustic Area	Cfg4 - Cfg5	1.4	1.1
	Zoned Liner	CLEEN Acoustic Area	Cfg6 - Cfg3	0.8	
Added area	Added Area (In-Duct)	Zoned	Cfg5 - Cfg3	0.5	0.7
	Added Area (In-Duct)	Uniform	Cfg4 - Cfg6	1.0	
	Total CLEEN In-Duct Treatment	Zoned + Added Area (In-duct)	Cfg4 - Cfg3	1.8	**1.8**
	Exterior Liner (Aft Core Cowl)	Out-of-duct area only	Cfg3 - Cfg2	0.9	**0.9**
Total CLEEN II Benefit		Zoned + Added Area Total	Cfg4 - Cfg2	2.7	**2.7**

Table 4-4 EPNL Benefit Breakdown by Technology (P&W SyLNT)

Technology Contribution		Assumption	Relative Comparison	Predicted EPNL Increment (EPNdB)	Estimated Benefit (Average- EPNdB)
Liner type	Zoned Liner	Production Acoustic Area	Cfg4 - Cfg5	1.1	0.9
	Zoned Liner	CLEEN Acoustic Area	Cfg6 - Cfg3	0.8	
Added area	Added Area (In-Duct)	Zoned	Cfg5 - Cfg3	0.5	0.6
	Added Area (In-Duct)	Uniform	Cfg4 - Cfg6	0.8	
	Total CLEEN In-Duct Treatment	Zoned + Added Area (In-duct)	Cfg4 - Cfg3	1.5	**1.5**
	Exterior Liner (Aft Core Cowl)	Out-of-duct area only	Cfg3 - Cfg2	0.7	**0.7**
Total CLEEN II Benefit		Zoned + Added Area Total	Cfg4 - Cfg2	2.2	**2.2**

4.2.3. Overall Benefits and Conclusions

In summary, the contribution of the zoned liner is in line with the target and the added acoustic area seems to provide more attenuation than expected, partly due to the great predicted benefit of the exterior liner (Aft Core Cowl). The overall assessment relative to the CLEEN II goals is presented in Table 4-5. All estimations meet or exceed the CLEEN II goal. The P&W estimation of the zoned liner contribution barely misses the target by 0.1 EPNdB, but it is compensated by the additional area, making the overall total benefit be slightly over the requirement.

In conclusion, the overall CLEEN II acoustically optimized fan duct configuration meets the program targets, while these result remain to be validated at a later date by ground testing.

Table 4-5 EPNL Benefit Breakdown by Technology (P&W SyLNT)

Technology Contribution	CLEEN II Goal (EPNdB)	Collins Assessment (ANOPP)		P&W Assessement (SyLNT)	
Zoned Liner (inlcuding Thin Acoustics)	1.0	1.1	Meets Req	0.9	Marginal OK
Clean Duct TR with Aft Core Cowl Treatment	1.0	1.6	Exceeds Req	1.3	Exceeds Req
Overall Goal	**2.0**	**2.7**	**Exceeds Req**	**2.2**	**Meets Req**

4.3. FUEL BURN RESULTS

4.3.1. Clean Duct Benefits

The steps and gaps removed by the clean fan duct design resulted in a DP/P decrease of 0.016% from the removal of the blocker doors and decrease of 0.08% for the drag links, bases and fittings. This translated to a reduction of 0.19% SFC which in turn resulted in a fuel burn reduction of 0.21%. DP/P values were converted from the to the fuel burn benefit by the trade factors given by Pratt & Whitney for the PW1500G.

4.3.2. Low Drag Liner Benefits

The drag reduction from the low drag perforation effected the bypass by decreasing the pressure delta through the duct. Using the effect of perforation drag from the baseline design of the PW1500 propulsion system, the CLEEN II team determined that a reduction in drag was directly proportional to a reduction in pressure loss through the duct. Therefore, because the experiments performed in the test facilities showed that micro-perforations replacing the current baseline perforation would correspond to a 50% reduction in drag, it was found that the CLEEN II design could achieve a 50% reduction in pressure losses through the bypass duct. This corresponded to a fuel burn benefit of 0.25%.

4.3.3. Overall Benefits

In total the benefits of a clean fan duct and low drag liner combined to generate a fuel savings of 0.46%. This was assuming that both improvements acted independently from one another which was consistent with our own experience with both these technologies. Additionally this result correlates well with validating work done by the Georgia Institute of Technology for the same improvements on the same platform which showed a fuel burn benefit of 0.43%.

5. INLET DEMONSTRATION RESULTS

This section summarizes the efforts in support of the short inlet development. Both the aerodynamic assessment and the acoustic initial efforts will be discussed.

5.1. AERODYNAMIC BENEFITS

Fuel savings benefits derived by the short inlet architecture fall into two categories; weight reduction from the removal of structure and reduced skin friction drag due to extended laminar flow on the surface. The CLEEN II study assumed inlets with laminar flow extended to aft end of outer inlet cowl. This was achieved via deep draw lip skins, specialized joints that did not trip the flow to the turbulent regime and specialized surface treatments that would mitigate the effect of small excrescences. The reduction in drag accounted for a fuel burn reduction of 0.35%.

In addition, the inlet was shortened from the baseline L/D (Length of Inlet/ Diameter of Fan Face) of 0.6 to an L/D of 0.4. This change resulted in a fuel burn savings of 0.15% determined via the delta of weight between the two designs and the trade factor which converts weight of propulsion system to the equivalent fuel burn for the PW1500G. Overall, the short inlet fuel burn reduction is 0.5%.

5.2. ACOUSTICS EFFORTS

The focus of the short inlet acoustic efforts has been the development of advanced liner concepts targeting equal or better performance than current state-of-the-art DDOF, at significantly lower cost, to enable shortening the inlet without acoustic impact.

Since the inlet architecture does not require reduced thickness acoustic panels, the investigated concepts allow for having multiple layers that act as DDOF or MDOF systems. The evaluation of initial concepts was conducted in the Chula Vista Flow Duct facility in order to understand the frequency range capabilities of these new concepts. The measurements were qualitatively compared to a production representative DDOF liner panel, which led to the down-selection of a novel configuration consisting of large acoustic cavities combined with traditional honeycomb core. The total thickness of the panel was comparable to the production DDOF liner. The selected concept was investigated by focusing on manufacturing variations that enable feasibility and low cost production. To this end, Aerostructures is closely working with a supplier that can address these challenges while still providing a manufacturing competitive product. The technology is currently at TRL/MRL 3 with completed coupon trials, but unfortunately, these efforts have been put on hold for the remainder of the CLEEN II program and will be resumed in 2021.

Once the development resumes in 2021, the manufacturing trades will continue towards defining the most viable liner configuration and subsequently validating its performance through Collins standard process for TRL development. This process includes test campaigns in the NASA LaRC CDTR (Curved Duct Test Rig) followed by tests at the NASA ANCF Rig, operated by the University of Notre Dame Turbomachinery Lab.

6. MANUFACTURING EFFORTS

From late 2018 to early 2019, process mapping and manufacturing flow events were held with manufacturing teams in Riverside, CA and Foley, AL. Following the engineering drawing tree and process maps, fabrication planning was developed, and planning books were issued to respective R&T laboratories and production stations. The fabrication of the ground test TR was split among three Collins Aerospace locations as shown in Figure 6-1.

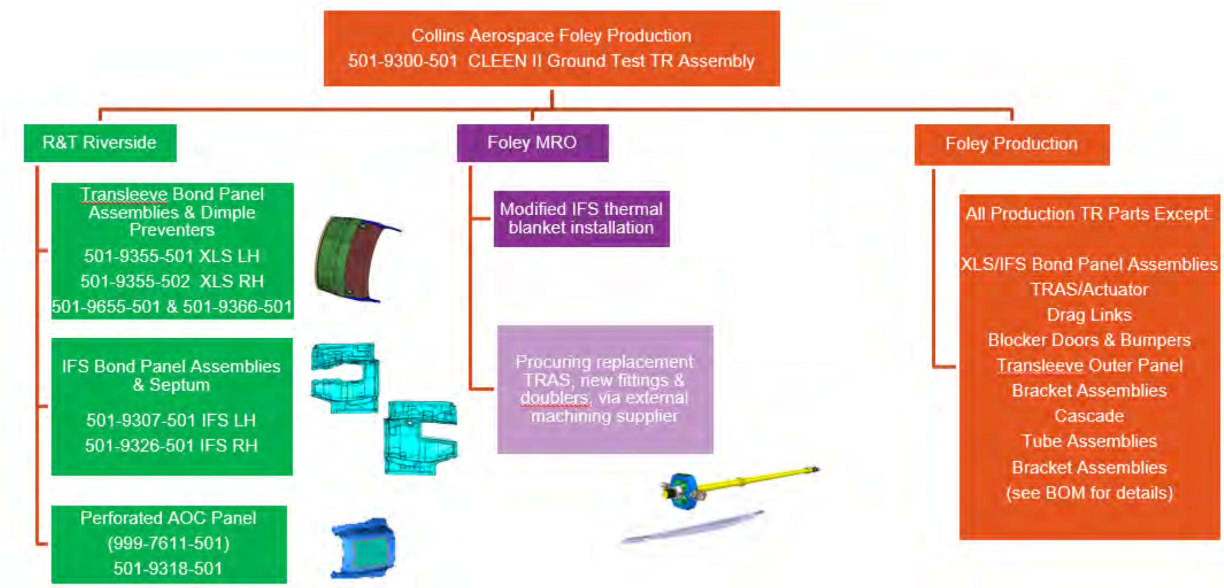


Figure 6-1 Manufacturing plants to support CLEEN II Demo Build.

The manufacturing of all new acoustic bond panels was performed in Riverside, CA, while the integration into the production TR was planned for Foley, AL. In Riverside, a right hand inner wall liner and an AOC fairing bond panel were completed. Perforated skins for the right and left outer wall liners and the left hand inner wall liner were also produced. In addition, Nover Core parts for the outer wall liner were also manufactured. The next sub-sections provide highlights about the final products. Since the ground test efforts are on hold, the assembly and modification procedures planned for Foley have been halted.

All manufacturing has been performed per existing, released Rohr Materials Specifications (RMS) and Rohr Process Specifications (RPS).

6.1. PERFORATION TECHNOLOGIES

Perforation of the inner and outer wall bond panel skins was performed by an automated perforation technology (APT). All APT perforations exhibit excellent hole quality and are very close to nominal POA specifications.

6.2. FAN DUCT NOVEL LINER

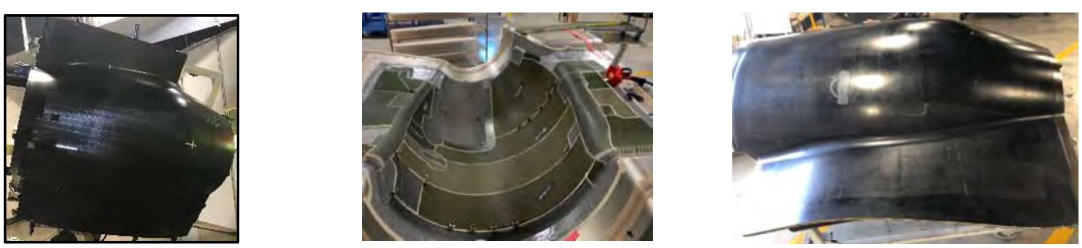
Core fabrication supporting the ground test TR was completed in October of 2019. Post fabrication manual operations were performed for the one-off CLEEN II unit, and 75% complete by May 2020. This will resume when the ground test is potentially restarted in 2022. Currently, Collins is working to develop a fully automated process without post-fabrication manual adjustments. Additional components to complete the liner assembly were completed prior to March 2020. All manufacturing and assembly tooling for the novel liner were procured by January 2020.

6.3. ZONED LINER

This section presents manufacturing efforts supporting the zoned liner design described in Section 3.2. A right-hand fan duct inner wall liner was completed. All other components, except for 25% of acoustic core have been fabricated but not assembled as an acoustic liner. These acoustic liners will be fabricated at a future date. In addition, an AOC panel has been completed. All fabricated zoned liner panels and components will be stored in a locked crate along with the fabrication planning books as of December 2020. The following sub-sections describe the progress.

6.3.1. Fan Duct Inner Wall Liner

The manufacturing of the inner wall zoned liner was performed in three steps: skin perforation, bond panel lay-up, and cure. A trial perforation began in September 2019 followed by perforation of actual ground test skins in February 2020. All skins for inner and outer surfaces were completed in May 2020 following the zoned liner requirements from Section 3.2. The right hand inner liner panel was then combined with the core layout (also supporting the intended segmented configuration) and final assembly was complete in August 2020. The manufacturing process is illustrated in Figure 6-2. All other fabricated components supporting the left hand inner surface and both outer surfaces will be stored for future use.



(a) *(b)* *(c)*

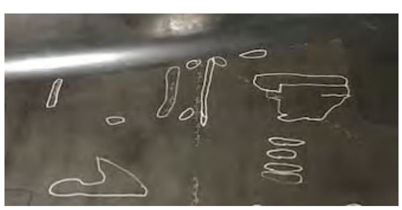
Figure 6-2 Fan Duct Inner Surface Liner Manufacturing: (a) Skin Perforation, (b) Bond Panel Assembly, (c) Final Acoustic Panel.

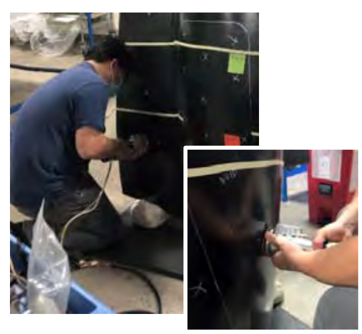
In addition, the AOC acoustic panel, used as a small portion of the left hand inner wall liner, was also produced and it is depicted in Figure 6-3.

Figure 6-3 Acoustic ACOC fairing panel.

6.3.2. Inspections and Repairs

Inspections were conducted to verify the structural integrity of the panel as well as the acoustic specifications. Acoustic quality was verified through visual inspection of adhesive blockage, geometric (pin gauge) inspection of percent open area (POA), and acoustic impedance, following an inspection plan specifically developed for this unit. Overall, the quality of the panel was satisfactory and presented small defects commonly found in production programs. In terms of hole blockage, there was a few scattered areas that required manual drilling to clean excessive adhesive that migrated to the holes during curing operation. Even though plans are in place for improvement, the extent of the affected areas was quite small and very encouraging given the small size of the low drag perforations. The POA was compliant on all segments except for one small area on the upper bifurcation surface. This area was also manually re-worked to recover nominal properties. Impedance testing revealed favorable results for all segments. Finally, the structural integrity was verified by C-Scan, which revealed a small area that also required repair. All repairs were conducted using standard procedures coordinated with traceable documentation. After repair, the unit was compliant to all specifications. Figure 6-4 illustrates the visual hole blockage and impedance inspections.





(a) *(b)*

Figure 6-4 (a) Visual Hole Blockage, and (b) Impedance Test Inspections

7. TECHNOLOGY READINESS SUMMARY

7.1. LOW DRAG LINER

Low Drag Liner technology, developed to provide lower surface drag than legacy perforated acoustic panels, reached a technology readiness level of 5 and a manufacturing readiness level of 4 in March 2017. CLEEN II had plans to progress low drag liner development for TRL/MRL 6 via the inner wall zoned liners (5 segments) and sleeve zoned liners (3 segments) in ground test unit. Meanwhile, a production program adopted CLEEN II LDL technology using automated mechanical drilling of small holes for the Aft section of the thrust reverser. TRL 6 was achieved via successful implementation on first production unit, which tested compliant to all acoustic specifications approved by the customer. TRL 7 is expected as full production begins in Q2 2021.

7.2. FAN DUCT NOVEL LINER

The fan duct novel liner secured a technology readiness level of 5 and a manufacturing readiness level of 4 in March 2017. This readiness level was achieved through the following focus areas: Design, Stress and Acoustic Analysis, Prototype Liner fabrication and repair, and Test at NASA GFIT which validated acoustic properties and prediction models. The progression to TRL/MRL 6 is still planned via the liner demonstration for the ground test unit, but it has been placed on hold for future work.

7.3. ACOUSTIC ZONED LINER

Acoustic Zoned Liner technology, a purposely segmented impedance configuration targeting an acoustic optimized duct, reached a technology readiness level of 5 and a manufacturing readiness level of 4 based upon completion of acoustic tests at the NASA ANCF (Advanced Noise Control Fan) Rig operated by the University of Notre Dame Turbomachinery Laboratory, in September 2017, and subsequent validation of prediction models. A picture from the ANCF test program is provided in Figure 7-1. The test configuration consisted of a 2-segment zoned liner. All manufacturing efforts presented in Section 6, have contributed to achieving TRL6/MRL6.

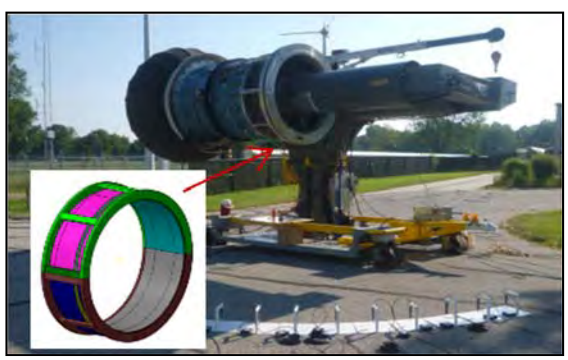


Figure 7-1 Simulated Acoustic Zoned Liner at the NASA ANCF Rig

In parallel to CLEEN, Collins Aerospace successfully achieved TRL6/MRL6+ for a low drag zoned liner via implementation in a production program. The design targeted uniform impedance across the fan duct inner surface while segmenting the liner for the sole purpose of reducing drag. The first, most forward zone, is built to the original standard hole specifications, and the second, aft zone, was modified with a smaller hole size. This configuration is planned to achieve TRL 7 with first commercial flight and full production in Q2 of 2021.

7.4. CLEAN DUCT AND EXTERIOR LINER

The acoustic area layout developed during CLEEN II simulated a clean duct surface that is envisioned for future compact nacelle architectures. While the thrust reverser mechanisms for these future platforms remains with low maturity, the integration of acoustic liners into continuous nacelle internal surfaces is quite mature and can be achieved by using legacy production methods.

The exterior liner concept is an essential element to support the future development of a clean duct TR for compact nacelle applications. As described throughout this report, the type of acoustic liner envisioned for an exterior surface is an aft extension of treated surface on the inner wall of the fan duct. As mentioned above, all manufacturing processes for this liner are state-of-the-art and production-ready with minimal risk for implementation. The technology maturity, including industrialization and certification, is quite elevated at TRL/MRL9. Nonetheless, efforts to formally quantify the value of placing acoustic liners on exterior surfaces are needed to justify the increased complexity, cost, and trades with other competing requirements. In other words, a ground test validation is not necessarily tied to TRL demonstration but instead, it allows the industry gain justification for implementation. Collins will continue to consider opportunities for this demonstration, including possibly resuming plans for ground testing on the PW1500 engine.

7.5. SHORT INLET ACOUSTICS

Short Inlet Acoustic technology, which combines structural DDOF, Low Drag Liners, and Inner Barrel perforation reached a technology readiness level of 3 and a manufacturing readiness level of 3, with its DDOF prototypes fabricated and tested, in September 2018.

While down selecting primary concept in Q4 2019, producible core selection led to study core configuration closely as manufacturability once again proved to be the main challenge. In September 2019, an assessment was completed for fabrication feasibility. During this time 3 demos were produced using material readily available. Resulting data allowed this method to progress in TRL/MRL 3 in November 2019. After this efforts, it was determined that further modification were required in order to achieve a lower cost, more competitive solution. As of February 2020, a clear path to development was identified. Although progression showed high potential for a new Aerostructures product, COVID-19’s resource reduction/budget constraints delayed further progression. Once the effort resumes, the next steps will be towards incremental validation using the CDTR (Curved Duct Test Rig) followed by ANCF (Advanced Noise Control Fan) testing into 2021 and 2022, respectively.

8. PROGRAM CONCLUSIONS

Advanced technologies have been developed by Collins Aerospace – Aerostructures in support of aerodynamically and acoustically optimized nacelle systems, enabling lower emissions, energy and noise, aimed at the next generation of high bypass ratio propulsion systems for reducing climate impact from aviation. The overall technology suit included novel acoustic configurations for both the inlet and fan duct. Even though it was not possible to execute the planned acoustic ground test demonstrations, the program generated sub-element laboratory test data and advanced prediction tools that allowed quantifying and demonstrating the proposed benefits analytically. In addition, the manufacturing maturity of both inlet and fan duct acoustic technologies was significantly advanced by the efforts facilitated by the CLEEN II program and documented in this report. Selected technologies from the program, e.g. low drag surfaces and zoned liner configurations, have successfully reached production ready status and have been incorporated into current production nacelle applications. Also, the acoustic optimization tools developed in support of CLEEN II have been incorporated into Aerostructures standard processes for liner optimization.

The prediction-based assessment of the advanced TR acoustic benefits included the EPNL calculations based on the predicted attenuation levels for the advanced liner configurations. The investigation included the overall assessment of the full treated system and the contribution of each individual technology being demonstrated, e.g. clean duct added treatment and zoned liner. The liner was designed and optimized by the acoustics R&T group at Aerostructures, in collaboration with the Raytheon Technologies Research Center (RTRC) that developed the optimization software. In summary, it was concluded that the overall EPNL benefit as well as the individual contributions of the liners are in line with the targets and meet the CLEEN II noise improvement goal of 2.0 EPNdB. The liner performance suggests that the overall system has similar behavior as a DDOF system. As the ground test demonstration of the CLEEN II fan duct has been placed on hold, the completed analytical assessment serves as the most current measure of the technology performance and benefits, until a ground test validation is performed at a later development program.

For the inlet liners, only qualitative screening tests were conducted, showing great potential to improve attenuation of legacy DDOF liners. However, further demonstration tests for inlet liners was left for future work.

Total fuel burn benefits of the clean fan duct and low drag liner combined to generate a fuel savings of 0.46%. This was assuming that both improvements acted independently from one another which was consistent with our own experience with both these technologies. Additionally this result correlates well with validating work done by the Georgia Institute of Technology for the same improvements on the same platform which showed a fuel burn benefit of 0.43%. The inlet length reduction resulted in a fuel burn savings of 0.5% determined via the delta of weight between the two designs and the trade factors.

In addition, significant progress was achieved on the manufacturing maturity of the advanced liner configurations. Small hole laser perforation methodology has been scaled up to full scale nacelle parts and provided excellent quality holes relative to the nominal POA specifications, including the ability to create a zoned layout. The perforation technique was successfully used to perforate all CLEEN II skins. Novel core fabrication that supported the ground test TR was completed using advanced proprietary fabrication. For zoned liner manufacturing demonstration, a right hand inner wall liner was completed as of November 2020. An AOC panel to be combined with the left hand inner wall surface was also completed. However, as aforementioned COVID-19 impact on CLEEN program at Collins

Aerospace, the fabrication of the rest of acoustic liners will resume followed by the TR assembly after the acoustic ground test schedule is reassessed in late 2022. Meanwhile, previously fabricated parts including but not limited to perforated skins, procured/machined cores, composite accessories, etc. along with fabrication planning books, will be securely stored for the future fabrication at Collins Aerospace in Riverside, CA.

For inlet liner, the major manufacturing breakthrough from the program was the establishment of a collaboration agreement with a core supplier, which gives Collins a clear path to achieve competitive manufacturing process when efforts resume in 2021.

9. ACKNOWLEDGEMENTS

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The collaboration with GTRC has been conducted under a Non-Disclosure Agreement signed between Rohr, Inc. and Georgia Tech Research Corporation (GTRC) on January 13, 2016 and its 3-year extension signed in June 2019.

Lastly, accomplishments of this project are greatly contributed by dedicated Collins Aerospace colleagues at R&T Lab, APT Lab, QA, and the production in Riverside, CA, design and analysis support in Chula Vista, CA, and the assembly planning support in Foley, CA as well as project and manufacturing engineers, management, and SCM at all three facilities for coordinating and cooperating.

10. REFERENCES

1. ARP 1846A, ‘Measurement of Far Field Noise From Gas Turbine Engines During Static Operation,’ March, 2008.