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Fan Noise Control Using Herschel-Quincke Resonators

Ricardo A. Burdisso and Wing F. Ng
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January 2003

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Space Administration

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This report contains preliminary findings, subject to revision as analysis proceeds.

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1. PROGRAM GOALS

The research effort proposed for this NASA NRA [1] is mainly experimental. In addition, Virginia Tech is working in partnership with Goodrich Aerospace, Aerostructures Group for the analytical development needed to support the experimental endeavor, i.e. model development, design, and system studies.

In this project, HQ-liner technology experiments will be performed at the NASA Glenn Active Noise Control Fan (ANCF) facility. Figure 1 shows a schematic of both inlet and aft HQ-liner systems installed in the ANCF rig as well as a picture of the Glenn facility. As shown, the main goal is to simultaneously test in both the inlet and bypass duct sections. The by-pass duct will have HQ-systems in both the inner and outer duct walls. The main advantages of performing tests at the ANCF facility are that the effect of the inlet HQ-system on the by-pass HQ-system and vice versa, can be accurately determined from the in-duct modal data. Another significant advantage is that it offers the opportunity to assess (on a common basis) the proposed noise reduction concept on the ANCF rig which in the past has been used for assessing other active and passive noise reduction strategies.

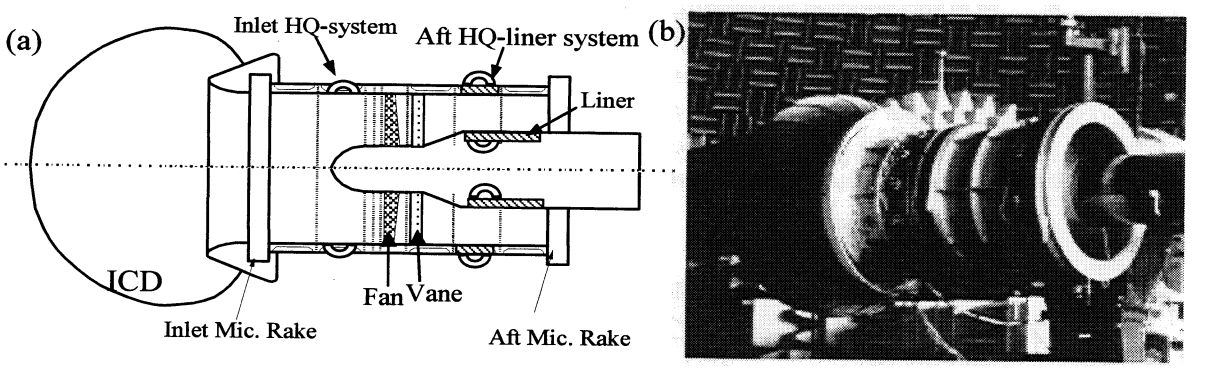

Figure 1: (a) Schematic of complete proposed experiments on the (b) NASA Glenn ANCF rig.

The main goals of the project are as follows:

- ***To extend the application of the HQ-waveguide approach to the control of aft fan noise***: In the last few years, the HQ-waveguide resonator technology has been successfully applied to ***inlet fan noise*** reduction from turbofan engines [2,-5]. These efforts involved testing in small turbofan engines as well as state-of-the-art engine inlet simulation facility simulating large bypass turbofan engines. Thus, this project will extend this technology to the control of aft radiated fan noise.

- ***To develop the model for the aft HQ system in conjunction with liners:*** Models of the HQ technology applied to the inlet duct have been previously developed by

Virginia Tech under NASA and Goodrich support. Thus, a model for the HQ applied to the aft duct will be developed. The difference between the inlet duct and the aft duct is that in the aft section, the HQ can also be applied to the inner wall, i.e. the center body.

- ***To investigate the simultaneous implementation of the HQ-system to the inlet and aft ducts:*** The experiments on this project will allow to determine the performance of simultaneously implementing HQ-liner systems in both the inlet and aft ducts to control fan noise.

- ***To validate the HQ-liner models***: The analytical model developed for predicting the attenuation of the HQ-system is based on the assumption of knowledge of the fan complex modal amplitudes, i.e. magnitude and phase. Though numerical tools are available to predict these disturbance amplitudes for the tonal components, the accurate measurement of the inlet modal amplitudes in the ANCF rig makes these experiments ideal for the validation of the modeling approach.

To accomplish these goals, three set of experiments will be performed at the ANCF rig. The first experiment consists of testing a HQ-liner system tested in the inlet of the ANCF rig as shown in Figure 2. These experiments will assess the effect of the inlet HQ-tube system on the resulting sound field in the by-pass duct. This will be accomplished by comparing modal measurements with and without an inlet HQ-system. Note that in these experiments there is no aft HQ-system implemented. This first set of experiments is planned to take place during November-December 2002 (FY02).

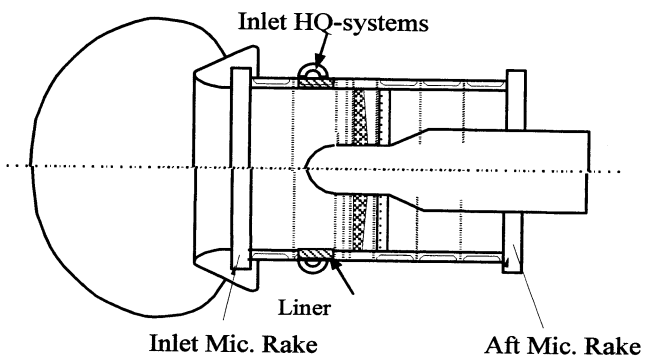

Figure 2: Experimental setup using an inlet HQ-liner system to be tested Nov.-Dec. 02 (FY02).

2. TASK PERFORMED DURING FY02

In this section, the tasks performed during FY02 on this project are described in detail.

2.1. Define ANCF rig configurations

The first step in this project was to define the configuration to be tested at the ANCF rig. This task was performed in cooperation with NASA Glenn personnel to identify the most relevant fan modal structure to be tested. The ANCF fan configuration selected is described in Table I. This fan configuration has been previously used for active noise control experiments.

Table I: Test configuration for ANCF test.

Parameter	*Value*
Number of Blades	16
Number of Vanes	28
Design speed	1800 RPM
Range of testing speeds	1400 – 1900 RPM

Since the 2 blade-passage-frequency (2BPF) tone is the main noise fan component sought to be minimized, the sound power of the modes generated at the 2BPF at presented in Table II for both the inlet and aft ducts.

Table II: Modal sound power at 2BPF tone due to Rotor-Vane Interaction – 1800 rpm.

Inlet Duct		*Bypass Duct*	
Modes	Power dB	Modes	Power dB
(4,0)	106.1	(4,0)	110.2
(4,1)	107.0	(4,1)	101.2
Total	109.6	Total	110.7

Note that the rotor-vane interaction is cut-off at BPF tone. It is also important to remark that at ~ 1500 RPM the (4,1) mode is cut-on in both inlet and exhaust ducts. This will allow investigating the performance of the HQ-system for modes that are just after cut-on that radiates towards the side lines. Previous work on the JT15D engine has shown very good attenuation of these modes.

2.2. Design Inlet HQ-Liner-system:

Two inlet HQ-systems were designed for the ANCF rig configurations selected in the previous task. The first design assumed the HQ-resonators were mounted on a hard walled inlet while the second considered the HQ system to be integrated with a liner. The design of the HQ-system was performed by Virginia Tech personnel using a Goodrich "proprietary" analytical model (developed under a current Goodrich sponsored project

[6]). For this design task, the fan tonal modal amplitudes previously measured on the ANCF rig were used.

The criterion to design the HQ-liner systems was based on the concept that the HQ-system should complement the liner's attenuation. Since liners are mostly used as broadband attenuators, it was decided that the liner should be designed to reduce both broadband and the 3BPF, 4BPF and 5BPF tonal noise components. The HQ system was then designed to attenuate the 2BPF tone and potentially provide additional broadband reduction, in particular around and below the 2BPF tone. Figure 3 illustrates this HQ-liner design approach.

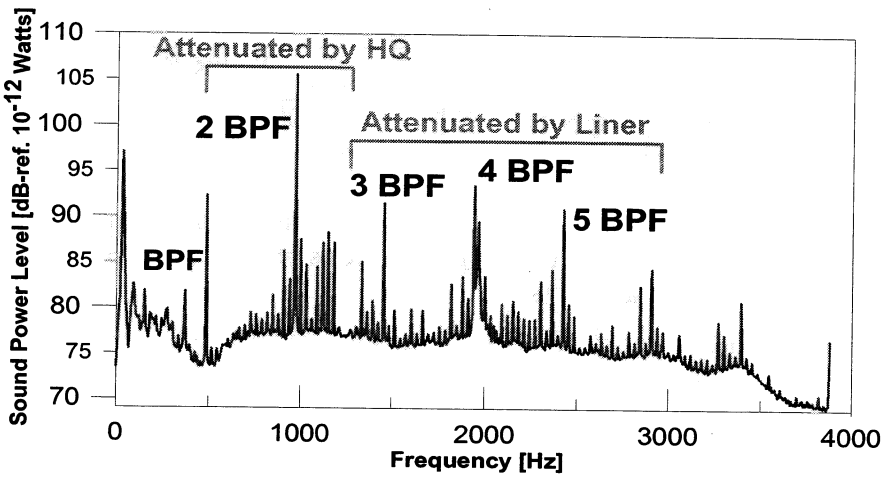

Figure 3: Approach for the design of the HQ-liner systems. The liner was designed for attenuation of the broadband component and 3BPF, 4BPF, and 5BPF tone. HQ resonators designed to reduce 2BPF tone and broadband.

a. Liner Design and Performance

The liner was designed by Goodrich personnel. The liner selected was a "linear" liner of 0.85" core depth. The normalized acoustic admittance of the liner implemented on the inlet of the ANCF rig is shown in Figure 4. Note the relatively high resistance of this liner (~ 1.7 ρc).

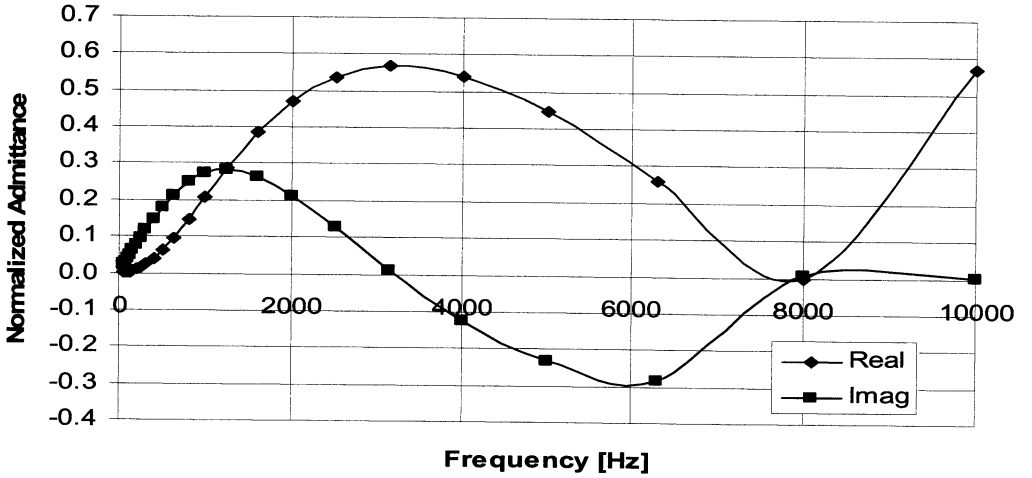

Figure 4: Normalized liner admittance assumed implemented on inlet.
ANCF rig at 1800 rpm – Inlet flow speed M=0.11.

Because the same liner will be used in the by-pass duct, the liner property was also computed (again by Goodrich personnel) assuming it is installed in the aft section. Figure 5 shows the normalized admittance. Note that the resistance of the liner installed in the bypass duct is lower (~1.4 ρc) that in the inlet.

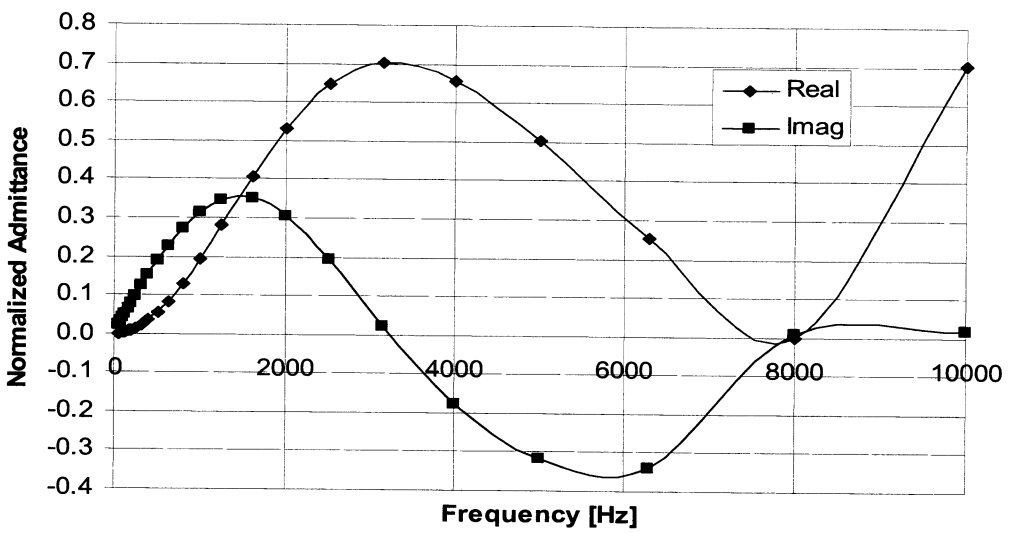

Figure 5: Normalized liner admittance assumed implemented on bypass.
ANCF rig at 1800 rpm – Aft duct flow speed M=0.15.

The liner is currently been fabricated by Goodrich with an expected completion at the end of October 2002.

Using the liner properties shown in Figures 4 and 5, the inlet and bypass duct eigenproblems were solved. The acoustic mode properties for the first 25 circumferential ($m=0,1,\ldots 24$) and 25 radial ($\mu=0,1,\ldots 24$) mode orders for both positive and negative propagating modes were computed at small frequency steps. This information is required for the design of the HQ-waveguide system.

The expected sound power attenuation of the liner installed in the inlet was determined assuming a liner length of 16". The predictions were performed separately for the broadband and tonal components. For the broadband component, the equal energy approach was implemented. For the BPF, 2BPF, and 3BPF tones, the actual hard wall modal amplitudes (measured using the rotating rake system by personnel at NASA Glenn) were used in the predictions. The results are presented in Figure 6 which shows the sound power spectrum for the hard wall (HW) and lined duct cases. Sound power spectrum for hard wall was estimated from far-field microphone spectra (measured by personnel at NASA Glenn). The results show that the liner is very effective for frequencies > 1200 Hz, i.e. frequencies above the 2BPF tone. The inlet liner broadband attenuation is about 3-5 dB at frequencies > 1200 Hz. The liner attenuated the 2BPF tone by ~ 6 dB.

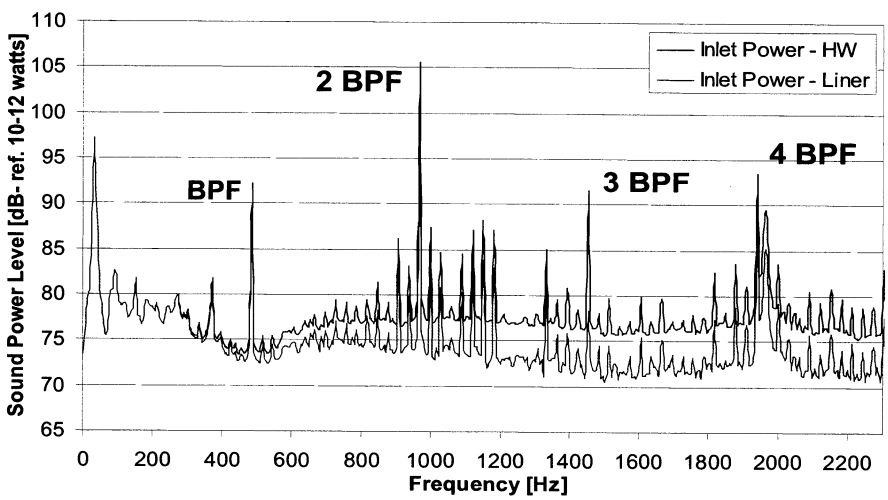

Figure 6: Sound power level spectrum for the inlet duct – Hard wall and liner.

b. HQ-system Design and Performance

The HQ-system for the inlet was next investigated. The design of the HQ system was first carried out assuming a hard-wall inlet duct. The HQ-system was designed for maximum attenuation of the 2BPF tone at 1800 rpm, i.e. 2BPF frequency = 960 Hz. The measured hard wall duct modal amplitudes (using the rotating rake) were used in the design, i.e. (4,0) and (4,1) modes. The main parameters of the HQ-systems are described in Table III.

Table III: Main HQ-system parameters for Hard wall and lined inlet.

Parameter	Hard Wall Inlet	Lined Inlet
Number of arrays	2	2
Number of HQ-tubes in each array	24	24
Configuration	Staggered	Staggered
HQ-tube length, L	12"	12"
HQ-tube interface distance, ℓ	7.62" (0.193 m)	5.9" (0.15 m)
HQ-tube area (each)	7.56 in^2	7.56 in^2
Surface liner area ratio	--	0.3
Cross sectional area ratio	0.1	0.1

In this table, two area ratio parameters are defined:

(a) Cross sectional area ratio = $\dfrac{\textit{(HQ-tube cross section area)*number of tubes in array}}{\textit{Inlet cross sectional area}}$

(b) Surface liner area ratio = $\dfrac{\textit{(HQ-tube cross section area)*2*total number of tubes}}{\textit{Liner surface area}}$

From experience, the first parameter is normally selected to be as high as possible within practical limitation. Previous experiments at Virginia Tech and other facilities, this area ratio has been ~ 0.1. The second parameter indicates how much of the available liner surface treatment is "taken" by the HQ-system. The two arrays of HQ tubes are "taken" about 30% of the liner surface. Figure 7 shows the HQ-design for hard wall condition. Note that the HQ-waveguide will be mounted on the back of the liner. Thus, the core of the liner forms part of the HQ-waveguide. The hard wall condition will be simulated by taping the "wet" side of the liner.

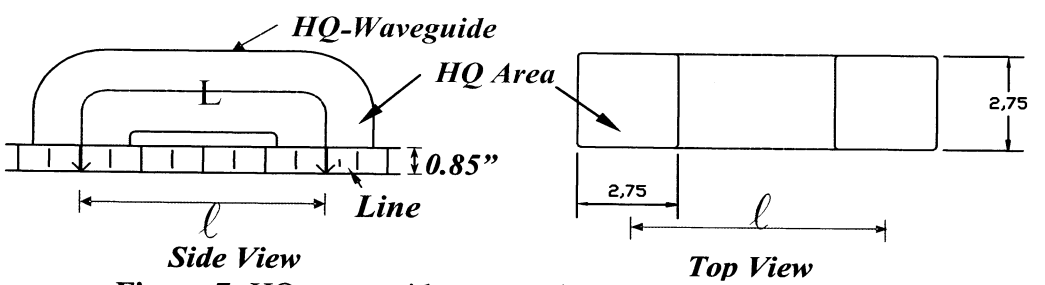

Figure 7: HQ-waveguide mounted on the back of the liner.

The predicted attenuation for the HQ-system is presented next. Figures 8a and 8b shows the sound power attenuation ***due to the HQ-system*** for the 2BPF tone at 960 Hz (fan at 1800 rpm) as a function of the tube length L and interface distance ℓ for hard and soft wall conditions, respectively. In both figures, the optimum HQ parameters are indicated. It can be observed that the HQ system when used in conjunction with the liner performs

much better than when used on a hard wall inlet, i.e. 6.14 dB for the HQ-liner as compared to 3.37 for the HQ-hard wall case. This will be further investigated to determine the physical mechanism for the improvement in performance. The figures also show that, within reasonable range, the HQ performance does not seem to be very sensitive to the tube parameters for either case.

To investigate the overall performance of the inlet HQ-liner system, figure 9 shows the sound power spectra for the hard wall (HW) case and for the HQ-liner system. Comparing the result in Figure 9 (HQ-liner) to Figure 6 (Liner), the HQ system resulted in an additional 2BPF tone reduction of 6 dB as well as an increase of the broadband attenuation (~ 1.0 to 1.5 dB) at frequencies > 700 Hz. If confirmed experimentally, the results will validate the potential of the HQ-liner system to be used in conjunction with liner to reduce fan noise.

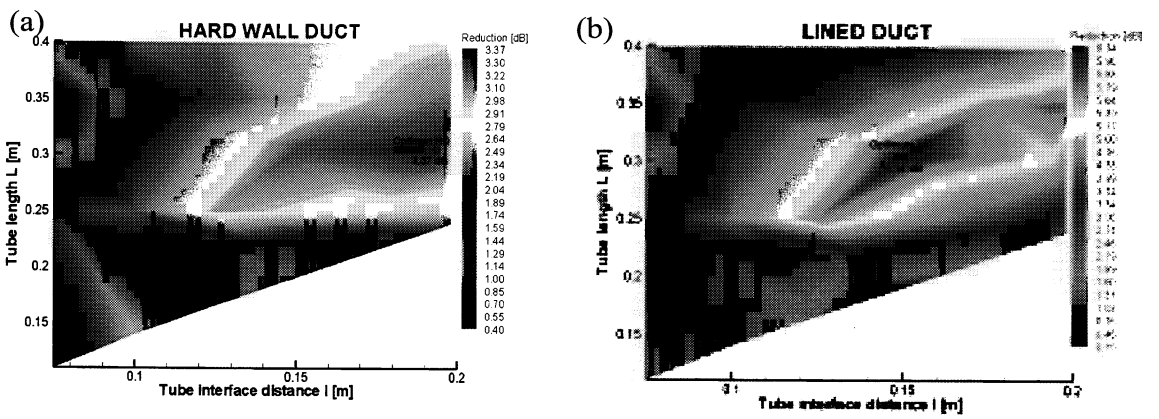

Figure 8: Sound power attenuation of the 2BPF tone as a function of the tube length L and interface distanceℓ: (a) hard wall and (b) soft wall.
Fan at 1800 rpm for a 2BPF tone at 960 Hz
NOTE: the color bar codes are for different ranges.

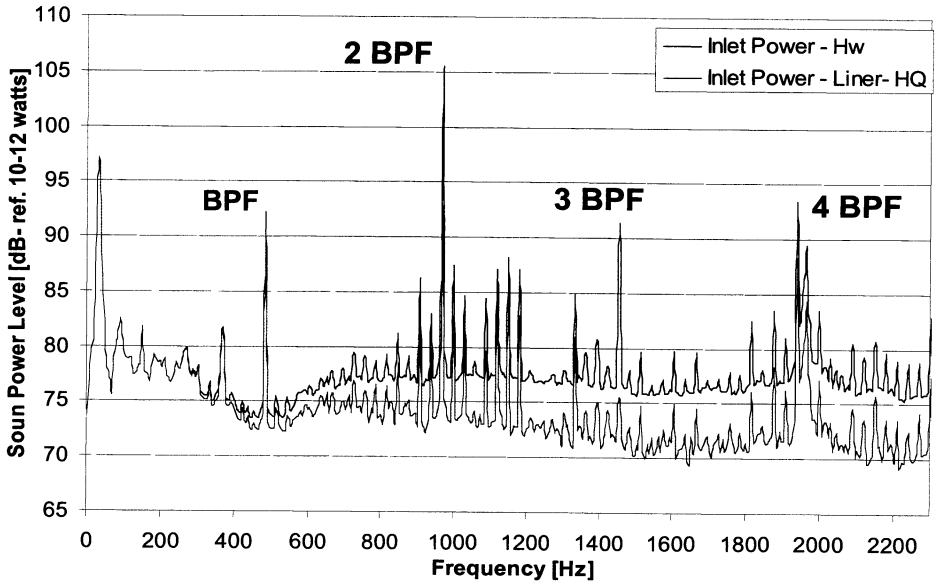

Figure 9: Inlet sound power spectra for hard wall and HQ-liner system. Fan at 1800 rpm.

2.3. Fabrication of spool-piece for inlet HQ-liner system:

A spool section for the inlet of the ANCF rig was fabricated to implement the HQ-liner system. The spool piece structure was made in two halves to also allow its implementation on the bypass duct of the ANCF rig. The integration of the liner and the supporting structure is illustrated in Figure 10. The liner (also made in two halves) will be bonded to the two aluminum supporting rings and the beams connecting the rings. Figure 11 shows a picture of the liner supporting structure (without liner installed). This structure was fabricated by Virginia Tech and delivered to Goodrich for installation of the liner. The liner will be then bonded to the supporting structure. The inner diameter of the spool-piece as well as for the liner is 48".

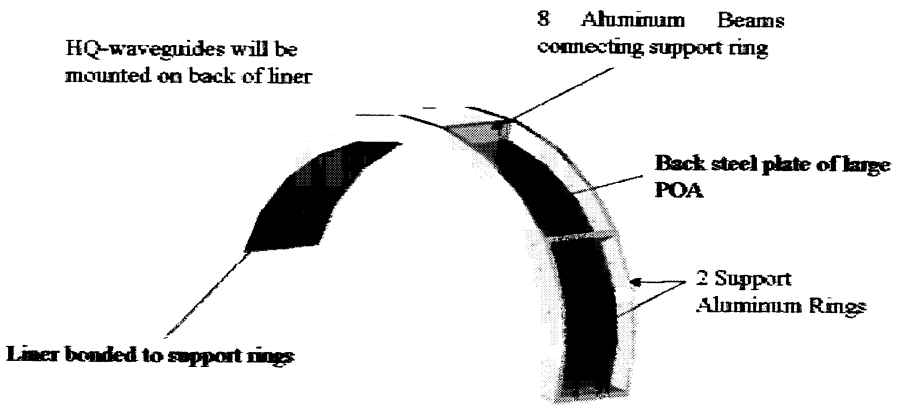

Figure 10: Schematic of spool piece to implement HQ-liner system.

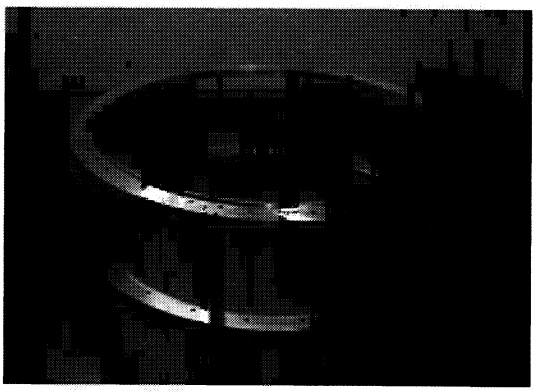

Figure 11: Picture of aluminum supporting spool piece where liner will be mounted.

The HQ-resonators will be mounted on the back of the liner. To allow for flexibility in the HQ configurations, the back plate of the liner will be a perforated plate with a high POA (50%) to minimize the acoustic effects, i.e. low resistance and reactance. An schematic of the HQ-resonator mounted on the back of the liner is shown in Figure 12. This figure is to scale and thus it provides a good indication of the relative size of the liner and HQ-waveguides. It is important to note that "relative large" size of the HQ devices is because of the low frequency for the 2BPF tone. In a practical implementation, the BPF tone of a large turbofan engine will be at higher frequency and the HQ resonator will be smaller (relative to the liner core depth).

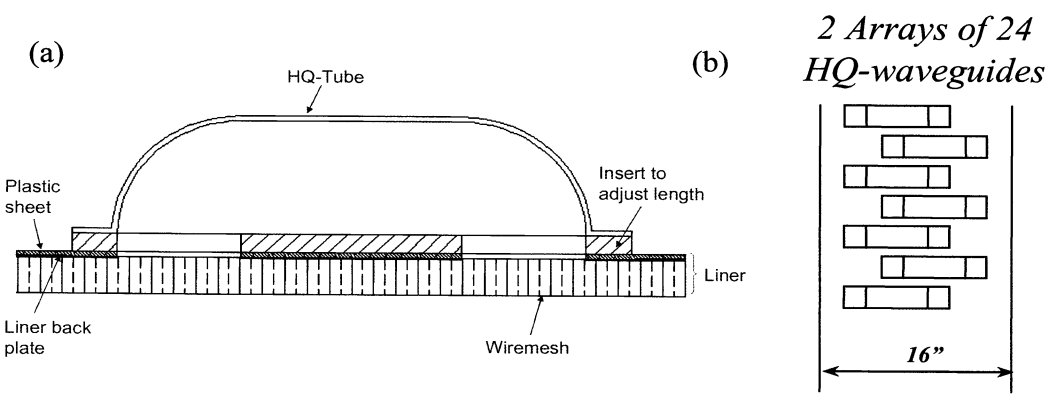

Figure 12: (a) Diagram of HQ-resonator mounted on back of liner and (b) system layout.

The liner will be fabricated and bonded to the supporting structure. Delivery to Virginia Tech is expected by the end of October 2002.

2.4. Test inlet HQ-Liner-system

The HQ-liner system designed and been built in the previous tasks will be installed and tested on NASA Glenn ANCF facility. Two HQ-systems will be tested corresponding to the optimum design for hard and soft wall conditions, respectively. The fan will be operated in two conditions: (a) steady state and (b) decel. In steady-state condition, the fan will be operated at a fixed speed in the range [1700-1900] rpm. In a decel condition, the fan will be set to maximum speed (~ 1900 rpm) and it will be slowly decelerated. The rate of deceleration will be ~3000 rpm/30 sec.

The instrumentation to be used in these experiments is described in Table IV. It consists of the following systems: (a) NASA's inlet and aft duct rotating rakes to measure modal amplitudes, (b) NASA's 30-microphone inlet wall mounted array ("spool array"), (c) NASA's far-field microphone array, and (d) Boeing's 80-microphone ICD array system. In addition, narrow band noise spectra of selected HQ-waveguides will be recorded by Virginia Tech, i.e. microphones flush mounted to the tube. It is important to note that the ICD array technology, recently developed by Boeing to measure inlet modes, is an addition to the originally planned instrumentation.

The proposed experiments are going to be performed in two phases. In the first phase (referred as "A"), the HQ-liner system will be implemented in the inlet of the ANCF rig. The rig configuration for this phase is illustrated in Figure 13 including the instrumentation described in Table IV. Since the spool pieces of the ANCF rig can be used both in the inlet and aft ducts, the HQ-liner section will be installed in the aft duct to perform preliminary experiments. Though not originally planned, this second experimental phase (referred as "B") will be carried out if time is available in this entry.

Table IV: Instrumentation for HQ-liner tests.

Instrumentation	***Observation***	***Responsibility***
Inlet Mic. Rake	➢ Only for steady state condition ➢ Measure Inlet Modes at BPF, 2BPF, and 3BPF ➢ Upstream direction only	NASA Glenn
Aft Mic. Rake	➢ Only for steady state condition ➢ Measure Aft Modes at BPF, 2BPF, and 3BPF ➢ Downstream direction only	NASA Glenn
Inlet Wall Mounted Array "Spool Array"	➢ For steady state and decel conditions ➢ Measure Inlet Modes – Tones and broadband ➢ Both directions	NASA Glenn Virginia Tech
Far-Field Array	➢ For steady state and decel conditions ➢ Far-field radiation	NASA Glenn Virginia Tech
ICD Array	➢ For steady state and decel conditions ➢ Measure Inlet Modes – Tones and broadband ➢ Upstream direction only	Boeing

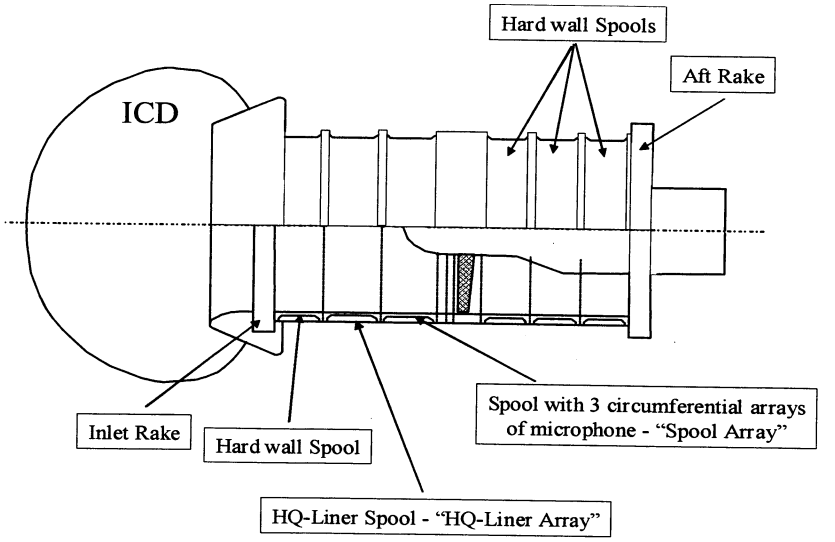

Figure 13: ANCF configuration for Phase "A" tests – Inlet HQ-liner configurations.

The basic test cases to investigate are:

a. Inlet HQ-system without liner (hard wall inlet).
b. Inlet HQ-system with liner (soft wall inlet).
c. Hard wall (baseline) and soft wall without the HQ-system.

The hard wall condition will be obtained by using tape to cover the liner section.

2.5. Data reduction and analysis:

NASA will be responsible for acquiring the data while the post processing will rest on the different team members. The rotating rake data post processing will carried out by NASA while Virginia Tech will be responsible for the analysis of the far-field and in-duct arrays. Finally, Boeing will process the ICD data. Upon completion of the analysis, the reduced data and reports will be distributed among NASA, Goodrich, and Boeing personnel.

2.6. Develop model for aft HQ-Liner-system:

An analytical model to predict the performance of the aft HQ-Liner system applied to the aft duct was developed. The modeling approach was based on the same technique as used in the inlet duct HQ-liner system developed under a Goodrich sponsored program. Here a general description of the effort involved in this model development and sample results are presented. The complete and detailed theoretical description of the model will be prepared later.

The model is based on considering the aft duct as part of an infinitely long annular duct with both inner and outer walls lined in a uniform flow as illustrated in Figure 14. The

first step on this development was to solve the eigenvalue problem at small frequency steps. The technique used to find the duct's eigenproperties is by tracking the roots of the characteristic equations as a function of frequency starting from a hard wall condition at low frequency. Unlike the previous cylindrical inlet models, HQ-resonators are modeled in both the inner and outer surfaces of the annular duct.

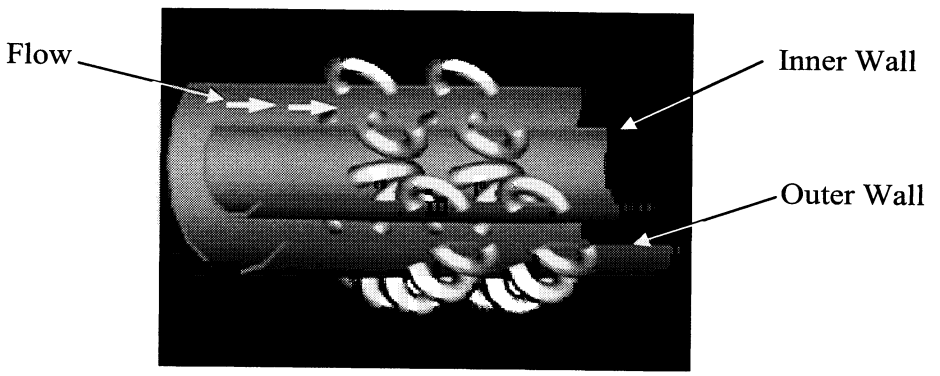

Figure 14: Annular duct with HQ-resonators mounted on both surfaces to model HQ-liner applied to aft duct of turbofan engines – Note liners not shown in figure.

The aft duct model is currently been used to perform preliminary prediction of the performance of the HQ-liner system (same system designed for the inlet) assumed to be installed in the aft of the ANCF rig, i.e. hard wall for inner duct surface. Figure 15 shows the sound power spectrum for the hard wall (HW) and lined duct cases, i.e. no HQ-system. The results show the liner is effective at frequencies > 800 Hz.

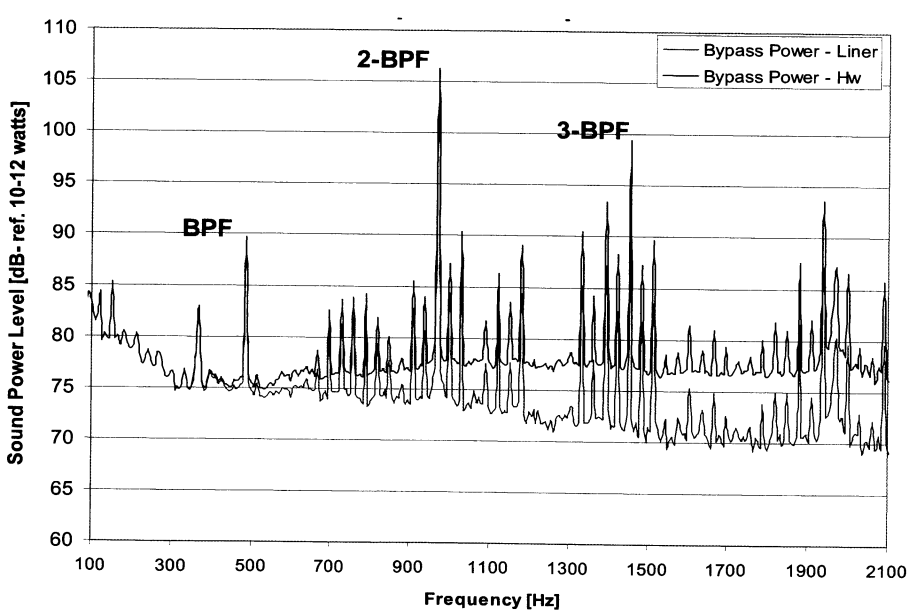

Figure 15: Sound power level spectrum for the aft duct – Hard wall and lined outer wall.

The sound power spectra for the hard wall and HQ-liner (again designed for the inlet) cases are shown in Figure 16. Comparison of the results in Figures 15 and 16 shows that the HQ-system is very effective at reducing the BPF tone and provide additional broadband attenuation at low frequencies. However, it also shows that the HQ-system is not effective at controlling the 2BPF tone. This last result is not unexpected since the HQ system was designed for the inlet.

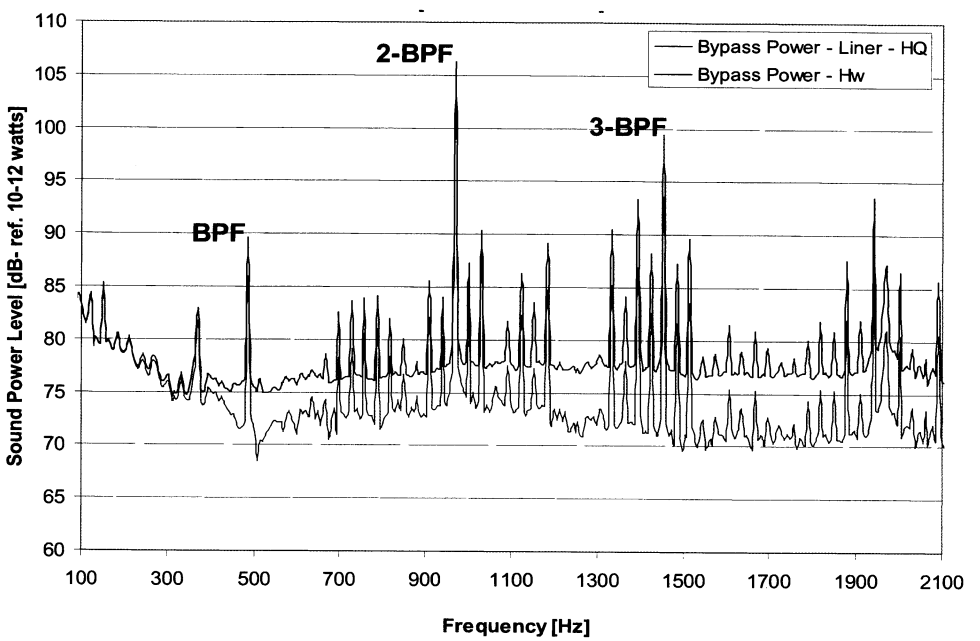

Figure 16: Sound power level spectrum for the aft duct – Hard wall and HQ-liner system on outer wall. Note: HQ-liner system designed for inlet.

2.7. Design Aft HQ-Liner-system:

An aft HQ-liner-system will be designed for the ANCF rig configurations selected in task 2.1. While the liner will be the same used in the inlet experiments, a new set of HQ-waveguides will be designed. For this design task, fan modal amplitudes measured on the ANCF rig will again be required from NASA Glenn.

3. ACCOMPLISHEMENTS DURING FY02

The key accomplishments during FY02 are:

a) ***Designed a HQ-Liner system for the inlet of the ANCF rig:*** Using a model developed under a Goodrich sponsored project, an HQ-liner system was designed for testing on the NASA Glenn ANCF rig. A state-of-the-art linear liner used in the nacelles of turbofan engines was designed by Goodrich. An optimum HQ system was then designed by Virginia Tech for the optimum attenuation of the 2BPF tone.

b) ***Fabricated of HQ-liner Spool Section for ANCF rig:*** To implement the HQ-liner system, a new spool piece for the ANCF rig was designed. The liner will be bonded to the supporting spool piece. The spool piece was fabricated and delivered to Goodrich for mounting of the liner. Goodrich is now in the process of fabricating the liner. Virginia Tech is fabricating the HQ-resonators. The HQ-liner spool piece will be completed by beginning of November.

c) ***Developed a model for HQ-liner system applied to the Aft duct:*** A model for the HQ-liner system applied to the aft duct section has been developed. This model will then be used to design an HQ-liner system for testing on the next ANCF test entry (to be determine).

Though the project started on January 2003, the tasks outlined in the proposal for the first year has mostly been completed. The most important remaining task is to perform the experiments on the ANCF rig. These experiments are planned to take place during Nov.-Dec. 2002 timeframe as originally scheduled. Thus, the program schedule is been met.

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13. ABSTRACT ***(Maximum 200 words)***
Over the last few years, the novel concept of Herschel-Quincke (HQ) waveguide resonators has been successfully applied to inlet fan noise reduction from turbofan engines. In this project, the Vibration and Acoustics Laboratories (VAL) of Virginia Polytechnic Institute and State University is extending this HQ-technology to the simultaneous control of radiated inlet and aft fan noise. To this end, a series of experiments will be performed at the NASA Glenn Active Noise Control Fan (ANCF) facility, where extensive model measurement of both the inlet and aft ducts is possible. The experiments proposed include testing of inlet and aft HQ-systems separately. Based on the results from these experiments, a test will be designed to evaluate the benefit of the simultaneous implementation of inlet and aft HQ-systems. For the above experiments the HQ-systems will be integrated with state-of-the-art acoustic liners which will provide a realistic evaluation of the potential of the HQ-technology in "production" turbofan engines. Goodrich Aerospace, Aerostructures Group (Rohr), through both financial and hardware contributions is supporting this program. The financial support is for the development of an analytical model to predict the noise reduction performance of the aft HQ-system, the design of experiments, and data analysis. Goodrich is also providing the liners to be used in the ANCF experiments. This report describes the work performed for the first year effort corresponding to the period from January through September 2002 of FY02. For the sake of brevity, the most important results and accomplishments are described here. A full detailed report including predicted and experimentally measured results will be prepared upon completion of the first set of experiments during November through December 2002.

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