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THE NOISE REDUCTION STUDY OF COMPOSITE ACOUSTIC LINER ON HIGH BYPASS RATIO TURBOFAN AEROENGINE

Peng HOU [1], Xu-Jing SHANG [2] and Yang DONG [1]

[1] Shenyang Aero Engine Research Institute, 2 Department, Shenyang, China

[2] Shenyang Aero Engine Research Institute, 8 Department, Shenyang, China

Abstract

Fan noise of high bypass ratio turbofan aeroengine has a larger energy, wider frequency bandwidth, and stronger destructive power, which is becoming the main noise source of aircraft. At present, “passive acoustic liner” is the mainly effective measure for reduction of fan noise, together with contrast analysis of single layer and multilayer liners were carried out. Compared with metal liner, composite acoustic liner has the advantages of lighter weight, better fatigue resistance, and stronger ability of noise absorption. The design process of composite acoustic liner mainly includes aerodynamic / acoustic integration design, structure / process integration design, special process research, design of fiber / resin composite material, experimental acoustic research, and so on. According to the demand of noise reduction level and frequency at different fan speed, different parameters of single and multilayer liners introduced to match the optimum acoustic impedance. In order to verify the noise reduction effect with different parameters of composite liner, the acoustical test of the composite flat sample and liner were carried out. The insertion loss curves of liners were obtained, and the noise reduction study of composite flat sample and liner was carried on, which provided technical and data support for liner and flat sample, as well as for lower noise design on aeroengine.

Keywords: fan noise; composite acoustic liner; insertion loss; multilayer liner; structure / process integration design; composite flat sample

1. Introduction

As the international test flight standards are increasingly strict on the noise of large aircraft, advanced noise reduction technology is required to meet the test flight requirements. Fan noise becomes the main source of high bypass ratio aeroengine, and the SPL (sound pressure level) could reach to 150～160dB. Fan noise has the characteristic of high noise radiation intensity, wide frequency bandwidth and strong destructive power. How to reduce fan noise is the key technology for low noise design of aeroengine. The main method to reduce the inlet noise level is the use of sound-absorbing acoustic panels, or acoustic liners. The acoustic panel is a structure normally built with metal or composite materials by means of a complex production process [1]. Acoustic liner generally comprises a perforated face sheet, which permits the passage of sound waves, one or more layers of honeycomb separated by perforated sandwich, and a sealing back panel. The resulting structure is a series of Helmholtz resonators [1]. Advanced composite material application technology could make the acoustic liner have the advantages of light weight and good fatigue resistance, which is the key technology for low noise design on aeroengine. Based on the structure and noise characteristics of high bypass ratio turbofan aeroengine, three kinds of acoustic liners distributed in bypass duct were designed, which includes the inlet acoustic liner, the fan rear acoustic liner and the short cabin acoustic liner [2]. The inlet acoustic liner is used to reduce the forward fan noise, the fan rearward acoustic liner is used to reduce the rearward fan noise, and the short cabin acoustic liner is mainly used to reduce the fan / OGV (Outlet Guide Vanes) interference noise, as shown in figure 1. The inlet acoustic liner allows noise reduction measurements to be performed in full anechoic laboratory, by installing liner section between engine and the inlet duct. The fan rearward acoustic liner and short cabin acoustic liner could use flat sample for noise reduction performance measurements in flow tube, as shown in Figure 1. According to the structure and process characteristic, composite acoustic liner could be divided into segmented liner and zero splice liner. Zero splice acoustic liner has the advantage of full-surface sound absorption, no sound reflective boundary, and better noise reduction effect than segmented acoustic liner. Jointless is the development trend in fan acoustic liner field.

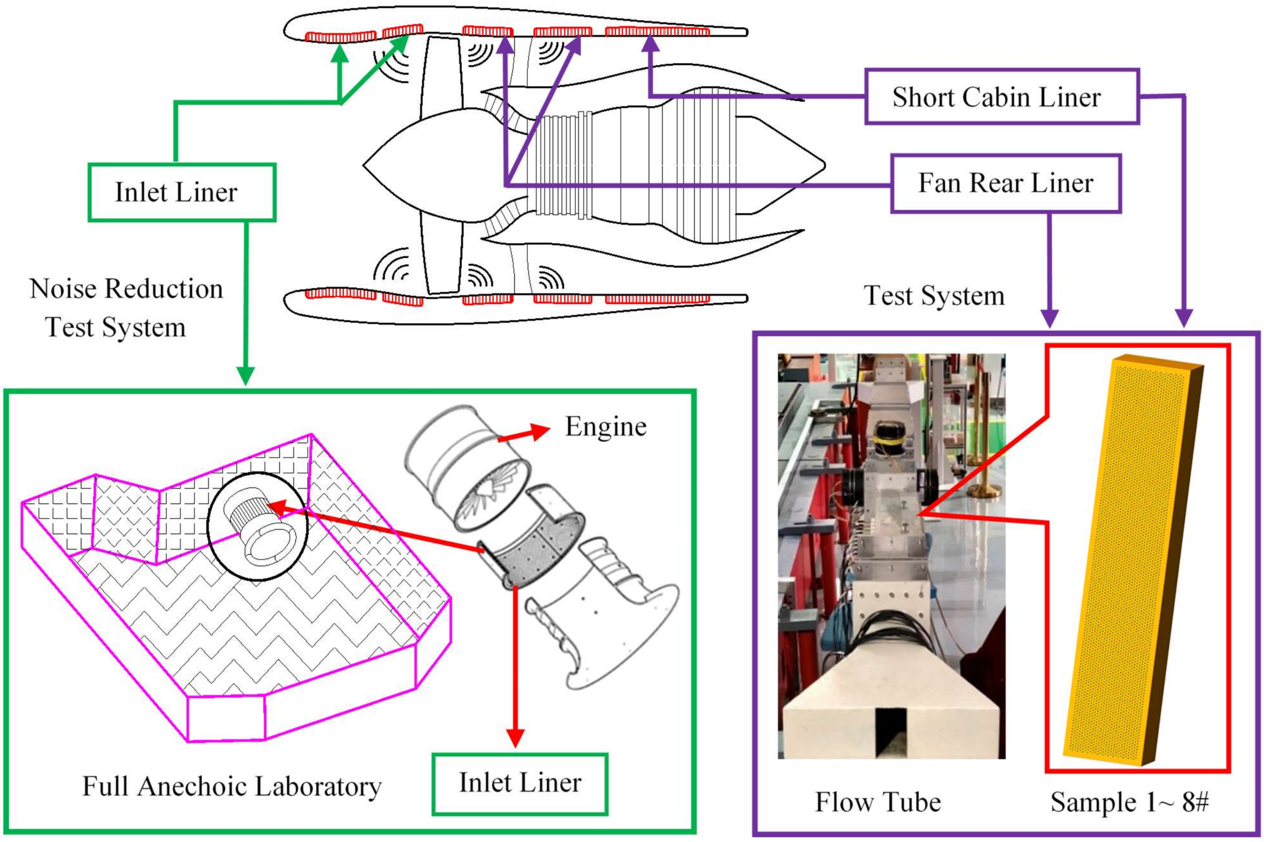


Figure 1 – Liner of Aeroengine and Test System

Parameter of “Sample 1~8#” Shown in Figure 8 and Table 1 as Below

2. Aerodynamic / Acoustic Integration Design of Acoustic Liner

Based on the fan speed of aeroengine, incoming flow speed and fan noise as the background, the parameters (Perforation Rate of face sheet or sandwich sheet, Thickness of Perforated Sheet and Height of Honeycomb) of the acoustic liner are obtained through the impedance, as shown in formula (1) and Figure 1. Geometric parameters of liner relate to the fan speed, as shown in Figure 2. The acoustic optimization of liner has been performed through aerodynamic / acoustic integration design, by matching the optimum duct impedance at the fan speeds representative of the engine certification flight conditions (Taking off, Climbing, Landing, or Other Conditions of Aircraft). For fan BPF (Blade Passing Frequency) correlation to the noise was much strong, the resonance frequency and noise reduction frequency bandwidth of liner should be controlled within first order of BPF.

$$Z = \frac{\sqrt{8\nu\omega}}{\sigma c}\left(1 + \frac{t}{d}\right) + \frac{1-\sigma^2}{\sigma}\left(M_o + kM_g\right) \tag{1}$$

Z = Impedance at Certain Frequency
t = Thickness of Perforated Sheet
d = Diameter of Silencing Hole / Perforated Hole on sheet
ω = Angular Frequency
M_0 = $|u_o|/c$
$|u_o|$ = Amplitude of Incident Velocity
M_g = V/c
V = Average Velocity
c = Sound Speed
ν = Velocity
k = Constant Coefficient
σ = Perforation Rate Shown in Figure 2

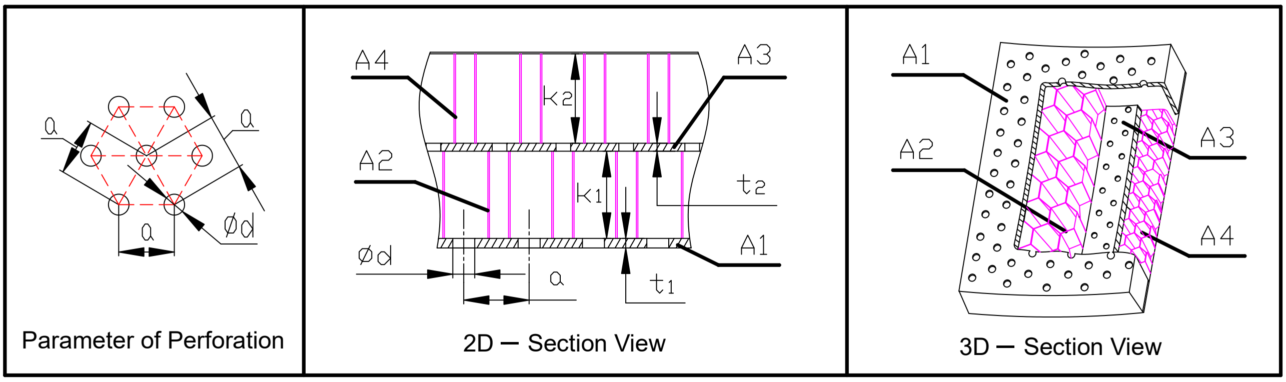


Figure 2 – Parameter of Double Layer Composite Acoustic Liner

σ = Perforation Rate of A1 （5%~8%）and A3（15%~30%）
a = Distance of Perforated Hole on A1 and A3
d = Diameter of Perforated Hole（1.5~3mm）
t_1 = Thickness of Perforated Sheet I (A1)
A1 = Perforation Sheet I = Face Sheet (Material: Fiber / Resin Composite)
t_2 = Thickness of Perforated Sheet II (A3)
A3 = Perforation Sheet II = Sandwich Sheet (Material: Same to A1)
k_1 = Height of Honeycomb I (A2)； A2 = Honeycomb I (Material: fiber with resin)
k_2 = Height of Honeycomb II (A4)； A4 = Honeycomb II (Material: Same to A2)

3. Structure / Process Integration Design of Composite Acoustic Liner

The composite acoustic liner is based on the method of structure / process integration design, which includes the design of composite layer, bonding of heterosexual materials, the assembly mode of fan case housing liners, and the thermoplastic forming mode of composite liner. Structure / process integration design mode of composite sandwich components breaks the information island between design, process and manufacture, and adopts parallel research mode in workflow. From structural design to process, all of which could be controlled by designer throughout the technological process.

The single layer acoustic liner is mainly composed of perforated face sheet, honeycomb and back panel. The double layer acoustic liner is composed of perforated face sheet, two layers honeycomb, perforated sandwich sheet and back panel. The mainly material of liner is carbon / epoxy or aramid / epoxy composite, which should have the ability of waterproof, impact resistance, airstream resistance and ageing resistance. Taking the double layer liner configuration design as example, the liner structure parameters (such as L1, L2, K_1, K_2, DI, SD, θ_1) are planned and designed to meet noise reduction performance and assembly structure, and the bolt hole + splice surface area ratio should be less than 10%, as shown in Figure 3.

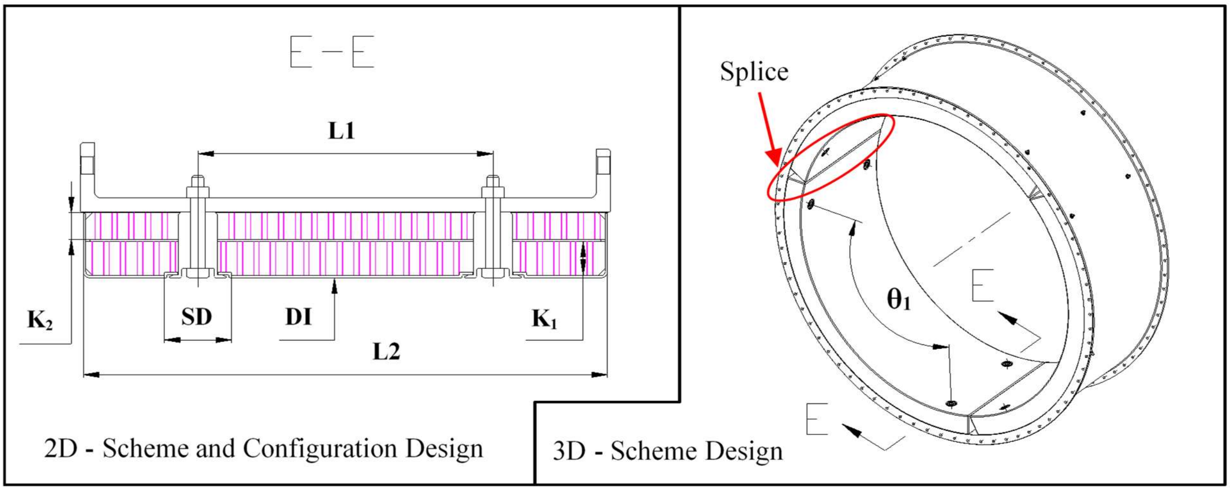


Figure 3 – Configuration and Scheme Design of Segment Liner

L1 = Axial Distance of Bolt Hole
L2 = Axial Distance of Liner
K_1 = Height of Honeycomb I
K_2 = Height of Honeycomb II
DI = Diameter of The Liner Flow Surface
SD = Surface Area of Bolt Hole
θ_1 = Circular Angle of Bolt Hole

3.1 Structural Design of Segmented Liner

The segmented acoustic liner could be divided into 4 sections, 3 sections or 2 sections as a whole circle. The advantage of segmented liner is that which is easy to assemble and decompose, as shown in Figure 3. The liner is fixed with fan case by bolts, and the metal bushing is embedded in bolt hole. the method of bonding of heterosexual materials is adopted to connect the honeycomb, perforated face sheet, perforated sandwich sheet, back panel and the bushing, so as to improve the anti-extrusion ability and rigidity of liner. Two perforated sheets, honeycomb and back panel are solidified after bonding, and the bushing is bonded with the liner through the hanging arm structure, which plays a role of bearing and transmitting force, as shown of “Adhesion Design” and “Hot Pressure Forming” process in Figure 4. Main design process: liner and case configuration design (segment and splice design) → liner structural design (including component bonding design and process route design) → perforation design (ensure maximum integrity of fibers on layers) → composite layer design (for the perforation to choose the best paving route).

The perforated sheet, back panel and perforated sandwich sheet are respectively made of satin weave fabric layer. The number of fabric layers is determined by the thickness of the sheet and panel. As shown in Figure 4, the designed direction is from right to left. If the back panel is only composed of fabric layer and resin, which is called “Acoustically Rigid Wall” or “Rigid Wall”.

The technological process of “Structure / Process Integration Design” is as follow: the laying process of weave fabric → solid of face sheet, sandwich sheet and back panel → perforation of face sheet I and sandwich sheet (sheet II) → liner assembly as a whole → molding and forming of composite liner → surface spraying of liner. As shown in Figure 4, the process direction is from left to right.

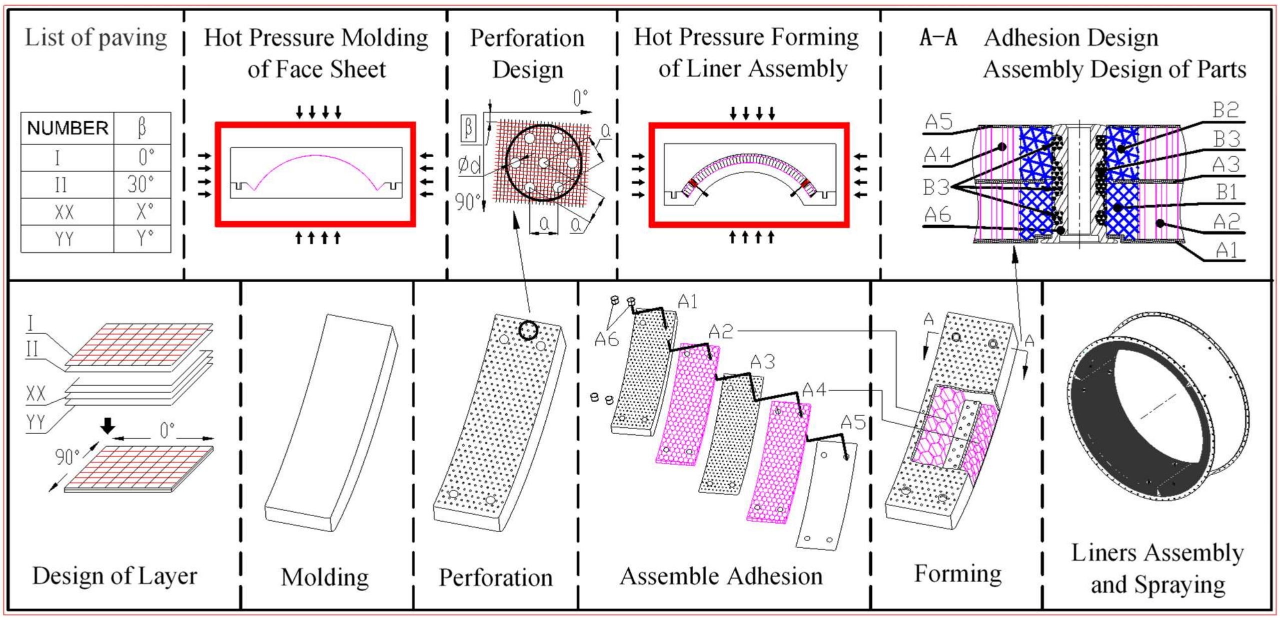


Figure 4 – Composite Liner-Structure / process Integration Design Workflow

I, II, …, XX, YY = Paving Sequence and Layer Number
β = Paving Angle of Layer Shown in Figure 5
“ a, d ” = Shown in Figure 2
A1~A4 = Shown in Figure 2

A5 = Back Panel Composed of Glass Fiber / Resin Composite (Rigid Wall)
A6 = Bushing Made in Metal
B1 = Sealant Composed of Medium Temperature Curing Adhesive
B3 = Handing Arm of Solid Sealant (Material Same to B1)

Fiber-reinforced composite only has the capacity of bearing function with intact fiber, and fibers integrity of meridian and parallel at different angle should be taken into consideration, as shown in Figure 4 and Figure 5. Due to the complex force of perforated sheet, load-bearing fibers are required in all direction, and the angle between layers should follow the list of paving in Figure 4. The integrity of the β=0°/ ±60° parallels is shown of formula (2), and the meridian integrity is shown of formula (3). The integrity of the β=90°/ ±30° parallels is shown of formula (3), and the meridian integrity is shown in formula (2). The maximum integrity of each paved meridian and parallel should be no less than 50%, which could meet the basic safety reserve.

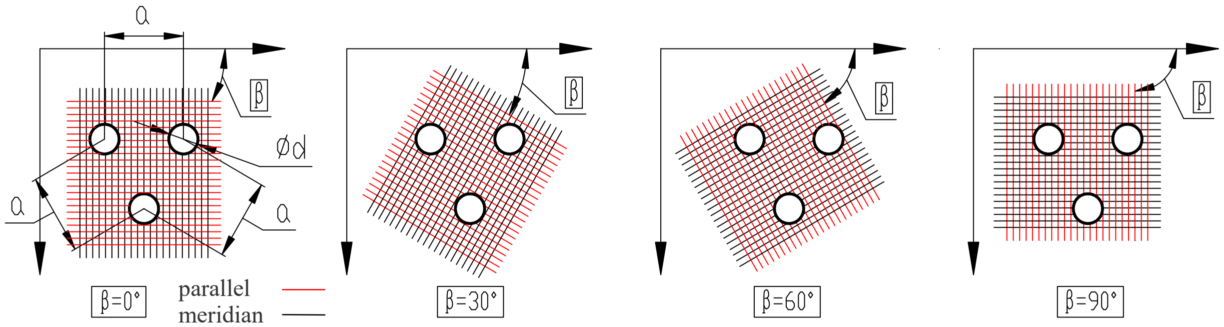


Figure 5 – The Paving Angle of Layer and The Integrity of Fibers

β = Paving Angle of Layer (Other Paving Angle Could Be Designed as Needing)
" a, d " = Shown in Figure 2

$$(\sin 60° \cdot a - d)/(\sin 60° \cdot a) \tag{2}$$

$$(a - 2d)/a \tag{3}$$

3.2 Structural Design of Zero Splice Composite Acoustic Liner

On segmented acoustic liner surface, the joints and bolt holes area can't absorb noise, which will reduce the noise absorption ability, or even produce secondary noise. The smaller joints of the acoustic liner, the better effect of noise absorption. With no joint and bolt hole, zero splice composite acoustic liner could absorb noise on completely surface [3], as shown in Figure 6 and Figure 3.

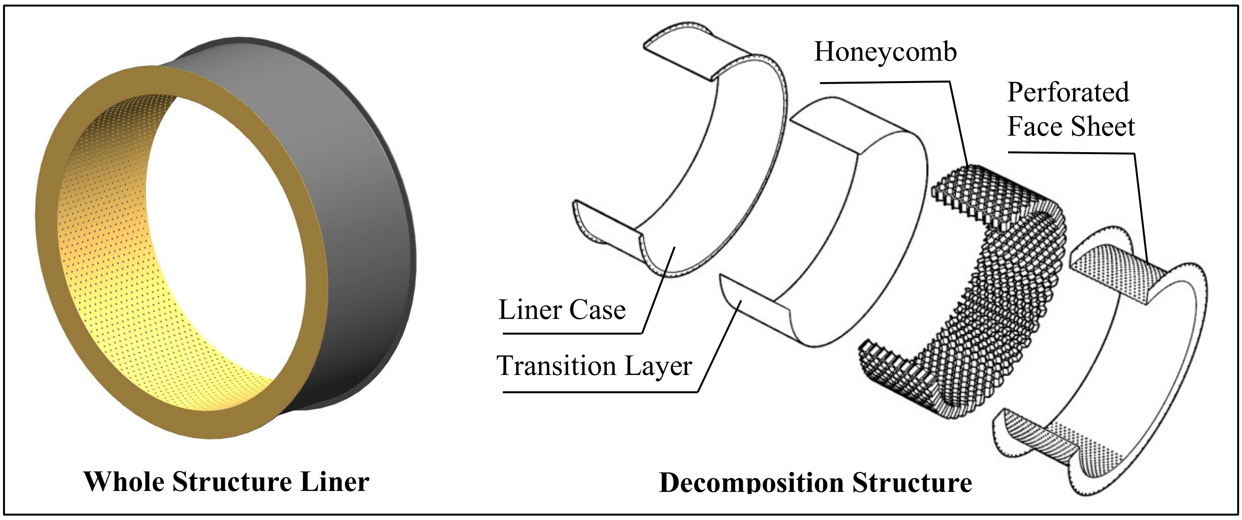


Figure 6 – Zero Splice Composite Liner Structure

The zero splice liner with single layer (single honeycomb) is composed of ring perforated face sheet, transition layer, honeycomb and composite liner case. The zero splice acoustic liner with double layer (double honeycomb) is composed of perforated face sheet, honeycomb I, perforated sandwich sheet, honeycomb II and liner case. The perforated face sheet could be laying structure, which is the same to the sheet of single layer liner. In order to improve the intensity of the acoustic liner, the perforated face sheet could be an integral winding structure. The forming method of the zero splice acoustic liner with single layer is as follow: forming the integral ring face sheet → perforation of the ring sheet → bonding the honeycomb with the perforated ring face sheet → winding the liner case with layer.

Compared with segmented acoustic liner, the zero splice acoustic liner has better noise reduction and weight reduction effect, which is the trend of lower noise design on aeroengine.

3.3 Noise Reduction Test of Composite Acoustic Liner

In the full anechoic laboratory, the fan of aeroengine is used for the noise source to test the noise reduction of liner. The experiment was carried out in two stages “Replacement Section Measurement” and “Acoustic Liner Section Measurement”, and the data under the same operating conditions in the two stages were compared to obtain noise reduction parameters such as the insertion loss of liner, as shown in Figure 7.

- First stage (Replacement Section Measurement)
  After the completion of data acquisition, the replacement case is divided.
- Second stage (Acoustic Liner Section Measurement)
  Using acoustic liner section to replace the replacement case, in the same operating condition.

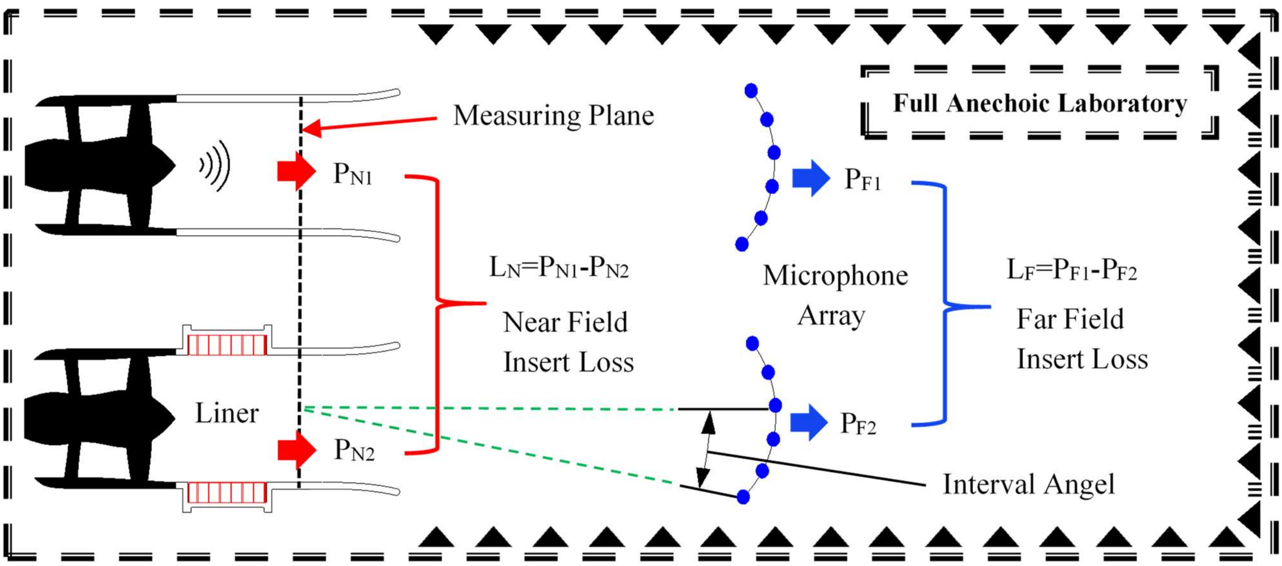


Figure 7– Measurement in Full Anechoic Laboratory

Noise reduction performance of liner is reflected by insertion loss, so as to the difference of the SPL in the full anechoic laboratory of “Replacement Section Measurement” and the “Acoustic Liner Section Measurement” test. Near field insertion loss L_N, as shown in formula (4).

$$L_N = P_{N1} - P_{N2} \tag{4}$$

P_{N1} = SPL of the “Replacement Section Measurement” test.

P_{N2} = SPL of the “Acoustic Liner Section Measurement” test.

Far field insertion loss L_F, as shown in formula (5).

$$L_F = P_{F1} - P_{F2} \tag{5}$$

P_{F1} = SPL of the “Replacement Section Measurement” test.

P_{F2} = SPL of the “Acoustic Liner Section Measurement” test.

4. Structural Design of Composite Flat Sample

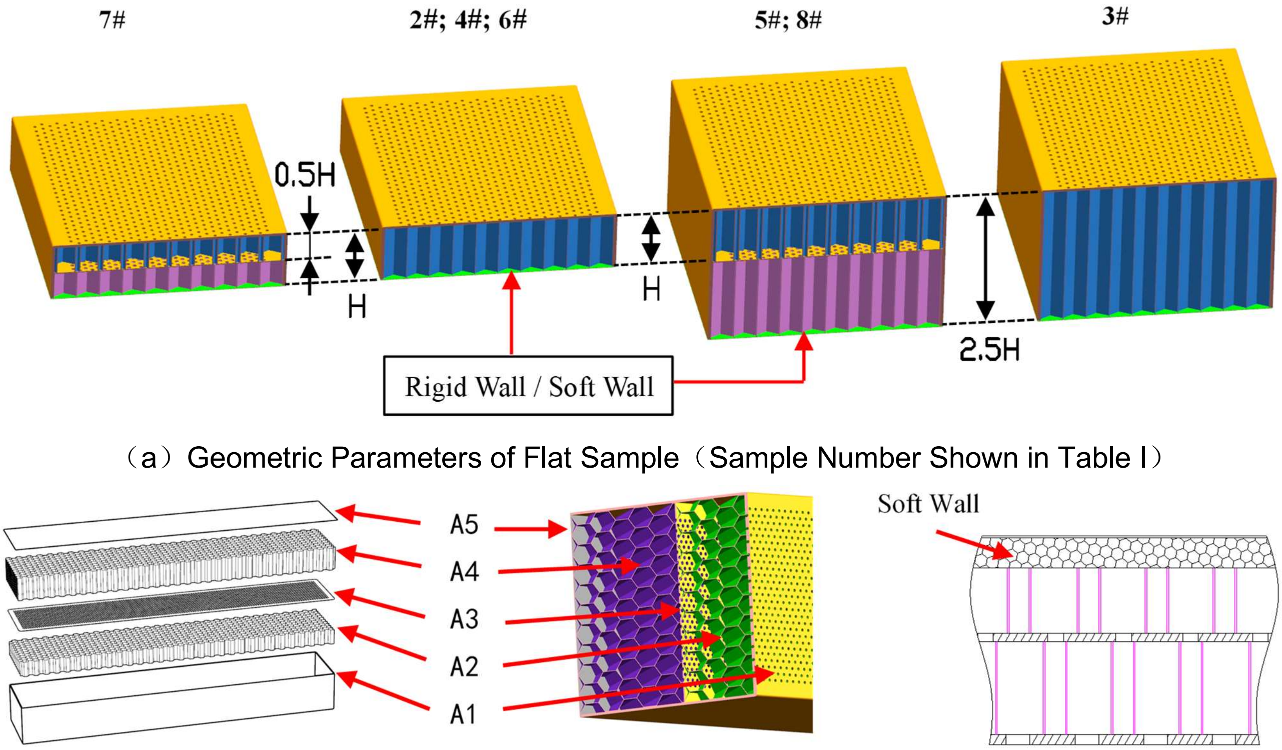
The Due to the difficulty and long period of the acoustic experiment on aeroengine, the flat sample of scale liner is used for the comparative conversion study. The noise reduction test of flat sample is carried out in subsonic flow tube. The study of flat sample not only provided data and parameters for composite acoustic liner, but also for the study of low noise design on aeroengine.

4.1 Single Layer Flat Sample Design

The single layer sample is used to verify the influence of parameters (perforation rate and honeycomb thickness of acoustic liner), and verify reduction frequency bandwidth and noise absorption. From the study of composite flat sample, the noise reduction effect of comparing and converting with liner could be carried out. The single layer flat sample is box structure, which consists of perforated face sheet, back panel and honeycomb. The flat sample is solidified and formed after bonding, as shown in Figure 8. The paving structure of perforated sheet and back panel is the same to Figure 4.

4.2 Double Layer Flat Sample Design

The single layer liner is a narrow bandwidth muffler. Compared with single layer liner, double layer liner could widen the noise absorption bandwidth in frequency domain, and improve the noise reduction ability. The double layer flat sample is also box structure, which consists of perforated sheet I, perforated sheet II, back panel and two layers of honeycomb, as shown in Figure 8. The paving structure of perforated sheet and back panel is shown as Figure 4. The back panel contains rigid and soft wall, as shown in figure 4 and figure 8 (c).



（a）Geometric Parameters of Flat Sample（Sample Number Shown in Table I）

（b） Explosion View - Double Layer Liner （c） Structure of Soft Wall

Figure 8 – Flat Sample Structure of Composite Acoustic Liner

A1~ A6 = Shown in Figure 2 and Figure 4

H = Hight of Liner, Shown in Table 1

4.3 Acoustic Test and Noise Reduction Capacity of Flat Sample

The acoustic test of the flat sample was carried out in flow tube, which was the scaled model of liner. The acoustic liner sample was installed on the single wall surface of flow tube, as shown in Figure 9. Acoustic measuring points T102 and T104 were installed upstream and downstream of the installation groove. The calculation method of insertion loss with flat sample is consistent with the acoustic liner on aeroengine, and the face sheet of 1 # sample is no perforation structure, which is the replacing box for comparison. The test condition is as follow: flow rate 0.25~0.5Ma, SPL 110~150dB, noise frequency bandwidth 0~6000Hz.

Table 1. List of Liner Sample Parameters

Number	Perforation of Sheet I or Sheet II	Height of Honeycomb I or Honeycomb II	Hole Diameter	Type of Structure
1 #	I=0	H	0	Comparison Sample for Data Analysis
2 #	I=σ	H	a	Single layer, Rigid wall
3 #	I=σ	2.5H	a	Single layer, Rigid wall
4 #	I=2σ	H	0.75a	Single layer, Rigid wall
5 #	I=2σ；II=3σ	I=H； II=1.5H	0.75a	Double layer, Rigid wall
6 #	I=2σ	H	0.75a	Single layer, Soft wall
7 #	I=2σ；II=3σ	I=0.5H；II=0.5H	0.75a	Double layer, Rigid wall
8 #	I=2σ；II=3σ	I=H； II=1.5H	0.75a	Double layer, Soft wall

The insertion loss of the liner sample is measured by the four-transmitter method, and the sound impedance is obtained by the push-back technology, which has been verified by NASA (National Aeronautics and Space) Langley GIT flow tube. 8 groups acoustical test were carried out, including 5 single layer samples and 3 double layer samples. The parameters of samples are shown in Table 1, and the insertion loss curve is shown in Figure 11. 6# and 8# are acoustically soft walls, between the back panel and the honeycomb is polyimide foam. Hard wall refers to acoustical total reflection wall, with surface wall normal velocity of wave is zero. Polyimide foam acoustically soft wall, using the spherical reflection of the foam surface and sound absorption performance to improve the noise reduction performance of Helmholtz resonators (cells of liner).

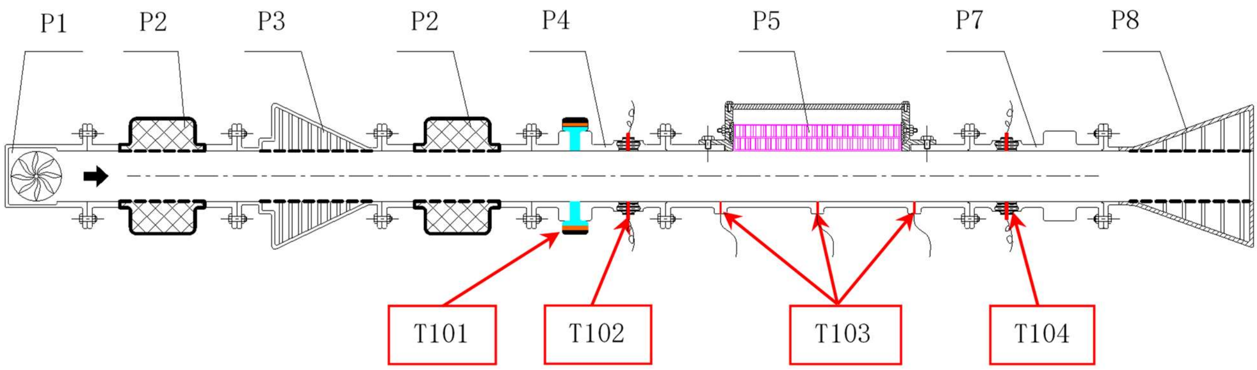


Figure 9 – Flow Tube Test System of Flat Sample

P1 = High Speed Gas Source
P2 = Regular Muffler
P3 = Expand Cavity Muffler
P4 = The Measuring Section with Noise Source
P5 = Composite Flat Sample Section (Test Assembly Structure of Acoustic Liner)
P7 = The measuring Section
P8 = Exhaust Section
T101 = Noise Source from 0 to 6000 Hz
T102 = SPL Test Point Upstream of Composite Liner Sample
T104 = SPL Test Point Downstream of Composite Liner Sample
T103 = Air Flow Velocity

5. Analysis of Noise Reduction Performance with Different Liner

Through simulation, design and acoustic test of the whole aeroengine and sample level, the following analysis results are obtained.

a) At far and near field of aeroengine, the effective insertion loss of single layer liner is in a narrow bandwidth, as shown in Figure 10.

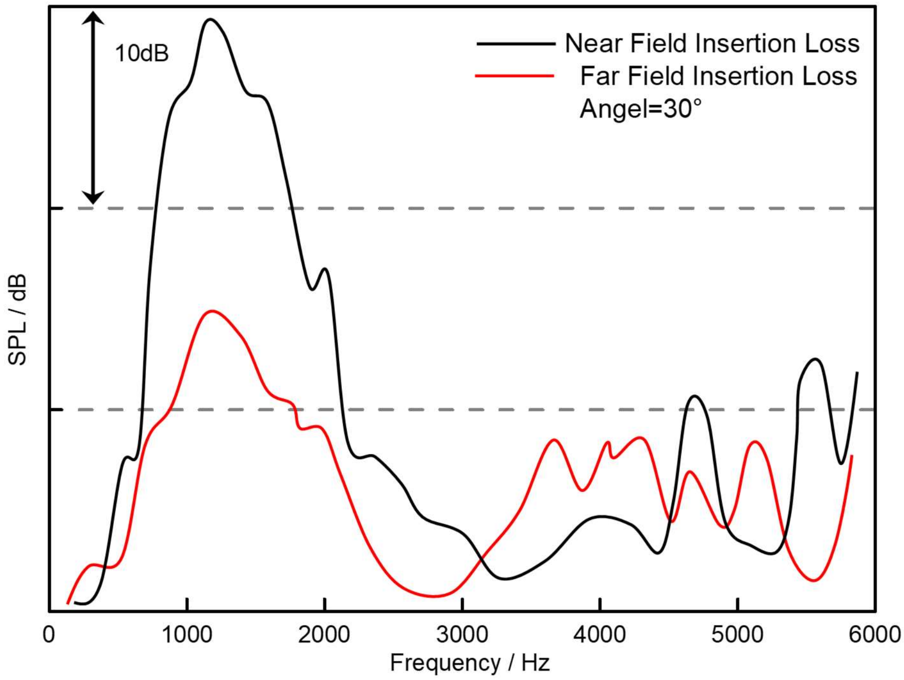
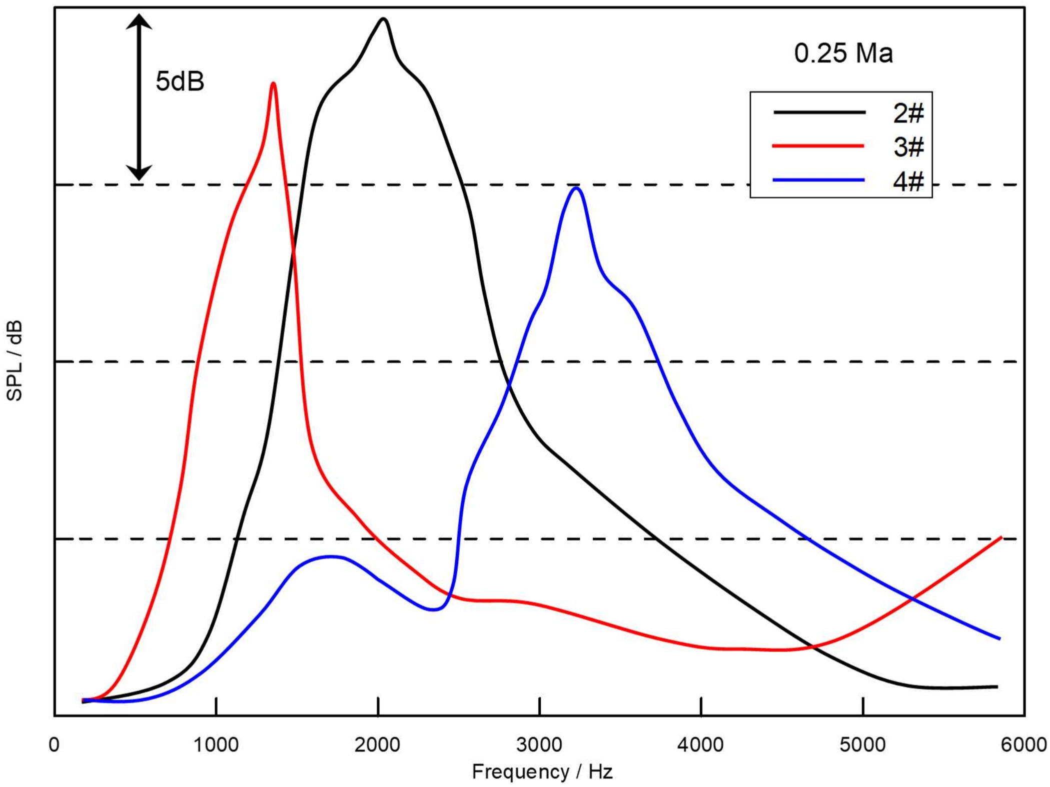


Figure 10 – The Near and Far Field Insertion Loss of Single Layer Inlet Liner on Aeroengine

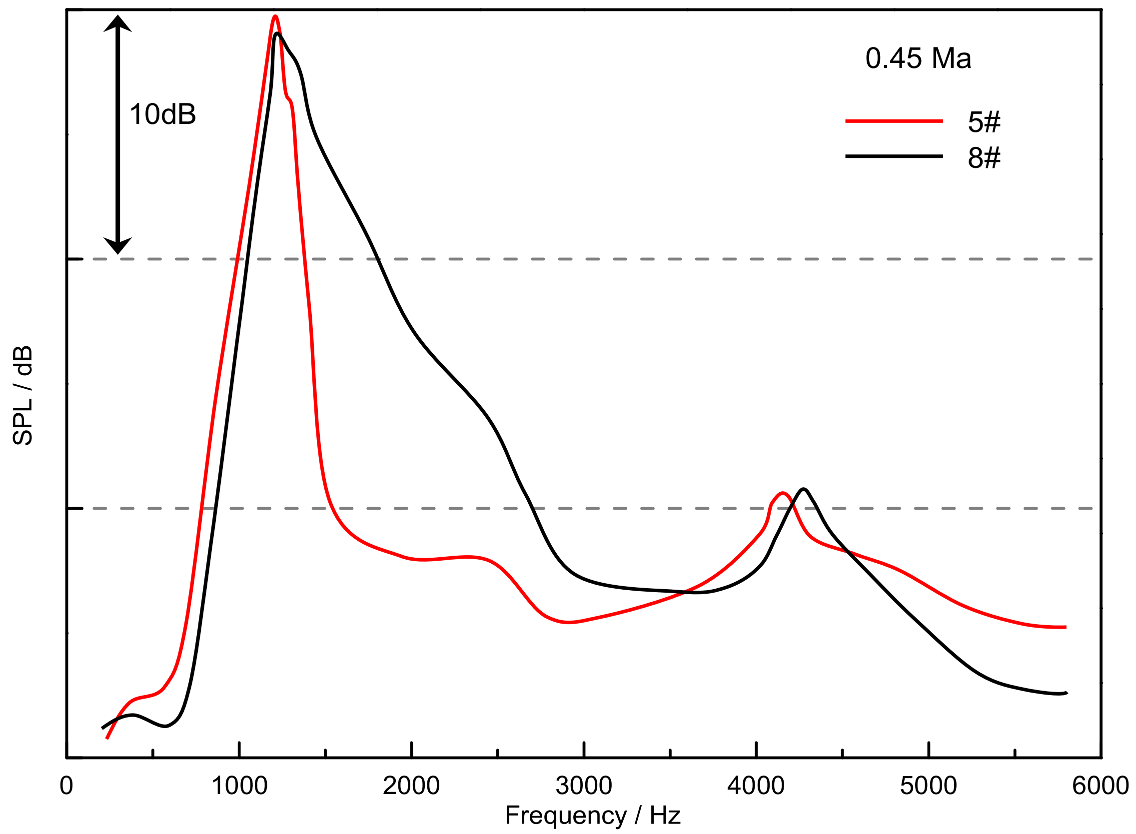
b) With the increasing of flow speed, noise reduction performance of single layer acoustic liner declined significantly. Compared with single layer acoustic liner, the noise reduction performance of double layer acoustic liner declined more slowly, as shown in Figure 11(a) and Figure 11(c).

c) If double layer liner designed reasonably, it could have two resonant peaks, and has a wide noise reduction frequency bandwidth, as shown in Figure 11(b) and Figure 11(c).

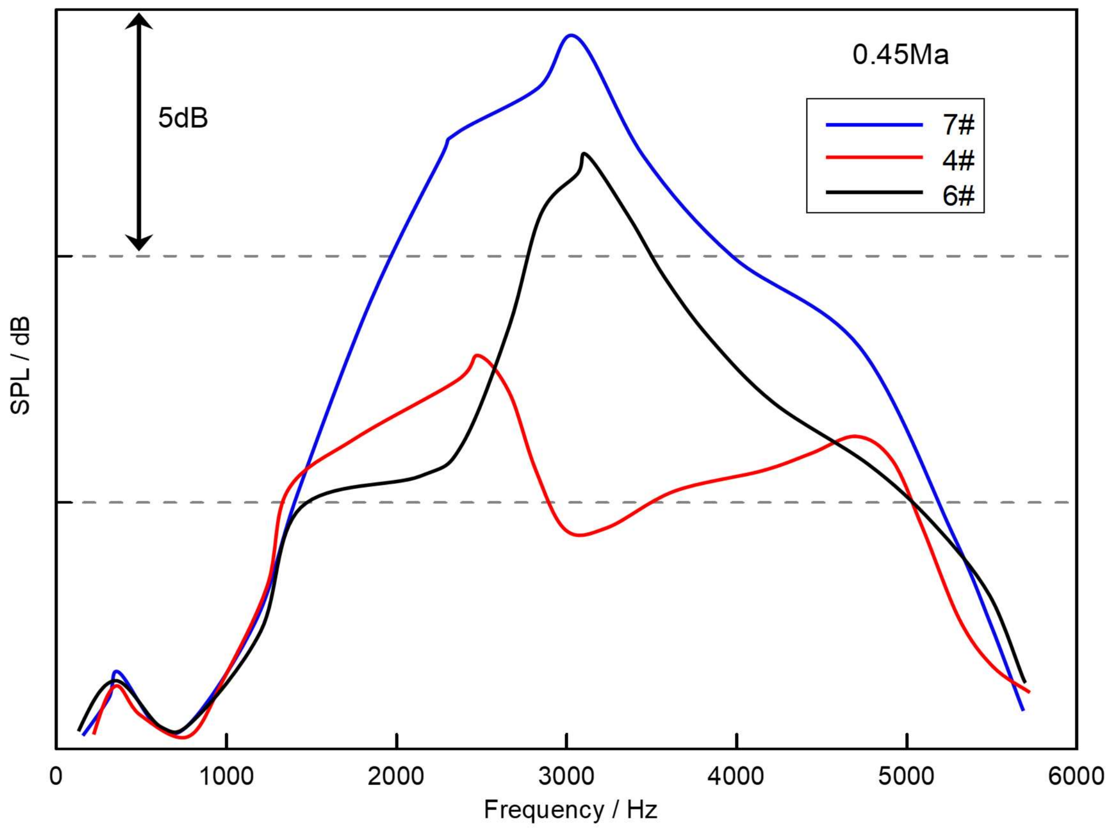
d) Soft wall liner with polyimide foam could not only raise resonance peak, but also widen the noise reduction bandwidth near the peak, as shown in Figure 11(b).



（a） Different Parameters Insertion Loss of Single Layer Liner



（b） Contrast of Rigid and Soft Wall (Double Layer Sample)



（c） Contrast of Double Layer and Single Layer Sample

Figure 11 – Insertion Loss of Composite Flat Sample in Flow Tube System

6. Conclusion

Lightweight, composite and high reliability are the future trends of acoustic liner and the mechanism of aeroengine. This paper introduces the design of performance parameter, structural design, and acoustic experimental research of the composite acoustic liner. The structural design and acoustic experimental research of the composite flat sample were carried out, and the noise reduction characteristics of the sample under different parameters (perforation rate, thickness, single and double layers) were gotten. In this paper, the selection method of acoustic liner parameters is explained from the aerodynamic / acoustic integration design processing. The design and forming method of composite acoustic liner were introduced from the structure / process integration design. The comparative conversion study was carried through the acoustic experiments of composite acoustic liners and flat samples. This paper not only builds a platform for structural design of composite acoustic liners, but also builds a data platform for noise reduction performance. Providing 5~10dB of noise reduction technology reserve for low noise research on aeroengine, the conclusion was gotten as follow.

- Taking the layer design of perforated sheet, perforation and fiber integrity design as example, the structure / process integration design of is demonstrated, which provides reference and experience for the design of composite sandwich components for aeroengine. A reasonable design concept not only improves design and productivity, but also benefits the product throughout its life cycle.
- In order to raise the noise reduction capacity and frequency bandwidth, fan liner should develop to no splicing, multilayer and acoustically soft wall structure, and structural design with technological process should be considered in parallel.
- According to the working condition of the fan liner, noise reduction scheme was designed, and the whole engine and the sample level noise reduction test were carried out simultaneously. The parameters such as insertion loss and sound impedance are compared, and the noise reduction characteristics from different test were obtained.

7. Contact Author Email Address

Email: houpeng2749@sina.com

8. Copyright Statement

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