Turbofan-Engine Noise Suppression

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An interim status report is presented of a continuing program to reduce the perceived noise levels (PNL's) on the ground below the takeoff and landing approach paths of turbofan-powered commercial transports. Since the PNL is dominated by the discrete-frequency noise radiated from the fan, the program has been directed principally toward the development of fan-inlet and exhaust ducts incorporating acoustically absorptive linings. Ground and flight tests have been performed on an experimental design evolved by incorporating acoustic linings within the basic "short" fan-discharge duct design of a contemporary transport. The ground tests indicated a small loss in thrust and a corresponding increase in cruise fuel consumption. Flyover noise tests showed a modest reduction in PNL under the landing approach path, but the particular lining configuration was unsatisfactory in terms of durability. Improved lining designs are needed to provide acceptable service life. Summaries of experimental and analytical studies conducted concurrent with the design, fabrication, and testing of the experimental ducts are also presented. These studies include 1) model duct transmission-loss tests of various duct lining treatments, 2) development of a flyover noise data reduction system using digital techniques to determine effective PNL's, 3) static strength tests, and 4) sonic fatigue tests.

Introduction

NOISE produced by commercial jet transport engines around airport communities is a contemporary problem of international concern. The problem of aircraft flyover noise can be alleviated by many techniques, e.g., the following: 1) Modify the engines to reduce the noise output at the source. 2) Modify the nacelle installation on the airplane to reduce the noise radiated from the engine. 3) Change the basic airplane design to reduce the thrust required to stay on the glide slope during landing approach or to improve the capability of the airplane to climb after takeoff. 4) Vary operational techniques to minimize the noise exposure to airport communities. 5) Plan for the use of the land around airports in noise-sensitive areas to avoid high levels of noise exposure. 6) Improve the acoustical insulation of residential dwellings in the vicinity of the airport.

A solution to the problem will probably involve some combination of the preceding techniques. However, an airframe manufacturer can only influence directly either the modification of engine installation on the airplane or modification of the basic airplane design.

Early jet transports were powered by turbojet engines. Noise generated by the jet exhaust dominated the noise perceived on the ground during an aircraft flyover. The noise from this source was partially controlled by jet exhaust noise suppressors.[1–3] The advent of the turbofan engine helped[4] by reducing the velocity of the jet exhaust, since jet exhaust noise varies approximately as the eighth power of the jet velocity. However, the total noisiness perceived by a listener under the airplane flight path was not greatly reduced because of the annoyance produced by the discrete-frequency tones (1600–6300 Hz) associated with the fan-rotor stages.

The subject of this paper is the reduction of discrete-frequency fan noise through the installation of acoustically absorptive materials in the fan-discharge and fan-inlet ducts. Studies have so far emphasized duct problems and have been limited to installations of the Pratt & Whitney Aircraft Company (P&WA) JT3D turbofan engine in the DC-8 airplanes using "short" fan-discharge ducts. This paper presents the design of a set of experimental short fan-discharge ducts that incorporated acoustical treatment on both the inner and outer duct walls, and gives the results of engine performance and flyover noise tests. The absorptive surfaces consisted of porous-metal facing sheets with impervious backing sheets separated by cavities.

The paper is divided into the following three major sections: 1) a review of the preliminary studies that provided the acoustic and aerodynamic guidelines for the design of the treated ducts, 2) a discussion of the practical constraints on the design of the treated ducts, the results of the noise and performance testing, and a description of the failures that occurred in the duct-lining facing material, and 3) a discussion of some of the supporting studies conducted concurrently with the design, fabrication, and testing of the experimental ducts.

Review of Preliminary Duct-Lining Studies

Preliminary acoustic and aerodynamic studies[5] provided pertinent background material for the development of the experimental fan-discharge ducts. The requirements for the design of the duct lining were derived from information provided by 1) flow-resistance and standing-wave-tube tests, 2) measurement of the sound pressure levels (SPL's) at the wall of the engine-inlet and fan-discharge ducts on a JT3D turbofan engine, 3) model duct transmission-loss tests, and 4) tests of the duct-wall friction, which determined recommendations for methods to control circulation losses.

Flow Resistance and Standing-Wave-Tube Tests

The investigation of various duct lining techniques concentrated on the use of porous metal surfaces made of fibermetal.

Presented as Paper 67-389 at the AIAA Commercial Aircraft Design and Operation Meeting, Los Angeles, Calif., June 12–14, 1967; submitted July 28, 1967; revision received December 22, 1967. Preliminary development studies were supported in part by the NASA Langley Research Center under Contract NAS1-5256, while development of the full-scale acoustically treated experimental ducts was supported solely by Douglas Independent Research and Development funds.

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Laboratory studies of the acoustical properties of materials showed that the flow resistance of fibermetal increases nonlinearly for through-airflow rates greater than about 15 cm/sec. For airflow rates less than 10 cm/sec, the flow resistance of fibermetal appears to be determined by the viscous friction associated with laminar flow through the interstices of the mat of fibers. For flow rates greater than 20 cm/sec, additional losses due to turbulence and acoustic streaming phenomena occur, and the flow resistance of a given sample of material increases rapidly above the laminar flow value as the flow rate increases. The increase in resistance for a typical sample of fibermetal might be from a laminar flow value of 13-cgs rayls at 10 cm/sec to a turbulent-flow value of 40 rayls at 500 cm/sec. (Assuming an equivalence between a steady airflow rate and an acoustic particle velocity, a flow rate of 500 cm/sec corresponds to an SPL of 160 db, re 0.0002 μbar, for a plane wave in free space. The 10-cm/sec flow rate corresponds to about 126 db.)

Standing-wave-tube tests were conducted to determine the resistive and reactive components of the specific acoustic impedance and also the acoustic absorption coefficients associated with various duct-lining designs. These tests were run with normal-incidence sound for frequencies between 1250 and 6300 Hz at SPL's of about 110 db. These tests showed that absorption coefficients greater than 0.85 could be obtained with a bandwidth of about 2000 Hz, providing the flow resistance of the surface material, the depth of the backing cavity, and the material in the cavity were properly chosen.

Duct-Wall Sound-Pressure Level Measurements

SPL measurements were made with $\frac{1}{4}$-in.-diam capacitor microphones flush-mounted on a bifurcated fan duct and on an inlet duct of a JT3D engine on a test strand. Narrow-band spectral analyses showed discrete-frequency components at the fundamental blade-passage frequencies associated with the product of the number of blades on the first or second fan rotor stages and the fan rotational speed. Fundamental blade-passage frequencies varied from about 2300 Hz at a landing power setting to 3700 Hz during takeoff. These duct wall SPL measurements showed the following:

1) Acoustical treatment applied to the wall of these ducts would be exposed to levels as high as 161 db at fundamental blade-passage frequencies corresponding to high engine power settings. This high SPL indicated the need for considerable allowance for the nonlinear increase in flow resistance under actual operating conditions.

2) Considerable energy was present at harmonics of the fundamental frequencies up to the third harmonic.

A spectrum for an equivalent acoustic loading for sonic-fatigue testing of various duct-lining construction techniques was also derived from these measurements. The spectrum had an over-all SPL (for the frequency range 35.5–1120 Hz) of 150 db with pressure spectrum levels varying from 123 db at 40 Hz to 117 db at 1000 Hz. (Pressure spectrum levels are in decibels re 0.0002 μbar for a 1-Hz bandwidth.)

Model Duct Transmission-Loss Tests

Although laboratory studies are useful in studying the basic acoustical properties of materials, it is essential to conduct tests with airflow over the duct-lining surface and with incident sound pressure levels, in the frequency range of interest (1600–6300 Hz), as close as possible to the actual values encountered in an engine. The impedance of the duct-lining materials varies with the level of the sound impinging on it, the angle of incidence, and the speed and direction of the air flowing over the surface. Since the duct's geometry determines the airflow velocity and the angle with which an incident sound wave impinges on a porous surface, the duct's actual dimensional relationships must be preserved.

To accomplish these goals, model tests were conducted using a dual-reverberant chamber test facility located in East Hartford, Conn., at P&WA. These tests determined the transmission loss (TL) of sound propagating through various model ducts at various airflow rates. The model ducts were all segments of the full-scale fan-discharge or inlet ducts. Subscale modeling was avoided because of the difficulties involved in attempting to scale the acoustical absorptivity of a lined duct with airflow through the duct. Typical SPL's for the tests ranged between 138 and 133 db in the frequency range between 1600 and 6300 Hz. The fan-discharge duct shape was that of the standard bifurcated production short duct. The inlets had either the shape of the standard JT3D cowl for the DC-8 airplane or new shapes with light-bulb-shaped centerbodies that provided channels with smaller cross dimensions and increased area for installation of acoustical treatment.

For a given value of maximum obtainable duct velocity, the throat area of the model ducts was determined by the available capacity of the airflow system of the dual-reverberant chamber test facility. Once the throat area was fixed, the maximum test velocity depended upon the amount and effectiveness of the acoustically treated area and upon the maximum signal-to-noise ratio in the receiver chamber.

Figure 1 shows a test duct installed between the two reverberant chambers. A semidiffuse sound field was created either by a pulse jet or by electro-pneumatic transducers in the source chamber The pulse jet in the upstream chamber was the source for the fan-discharge duct tests; the electro-pneumatic transducers in the downstream chamber were the source for the inlet duct tests. A semidiffuse field was used to obtain better correlation of model duct test results with full-scale test results, based on the previous experience of P&WA.

The attenuation produced by various duct-lining configurations was determined as a function of frequency for various duct velocities. Attenuation was defined as the difference in decibels between the transmission loss produced by a hard-walled duct and by a duct with an acoustically absorptive lining. The results for both the inlet and exhaust ducts showed that 1) significant attenuation could be produced by porous fibermetal surfaces backed by air-filled cavities, with the attenuation increasing as the backing depth was increased from 0.25 to 1.0 in.; 2) flow resistance of the porous liner should be about 40-cgs rayls at the operating conditions in the engine; and 3) for a given duct lining configuration, the attenuation achieved varied as 20 $\log_{10}[A_2/A_1]$, where A_2 and A_1 are two different areas associated with a given treatment in a given duct.

Duct-Wall Friction Tests

In addition to the preliminary acoustical studies described previously, preliminary tests were also conducted in a low-speed wind tunnel to determine the relative magnitude of the increase in frictional resistance that a porous duct-lining material would present to air flowing over the surface, as compared to that of aluminum sheet.

This increase is caused by losses due to surface roughness and to secondary flow circulation through the porous wall. Circulation occurs as a result of the static pressure gradients impressed on the duct walls by duct cross-sectional area changes and wall curvature. Air flows into the acoustical cavities at zones of increased pressure and out at zones of reduced pressure and, therefore, sustains total pressure losses in passing through the porous wall. Wind-tunnel tests were performed to investigate the magnitude of the roughness and the circulation losses.

The test section of the wind tunnel used for the tests is rectangular, 38 in. × 54 in., and is approximately 10 ft long. The setup is shown in Fig. 2.

Several test lining configurations were installed on one surface of the airfoil mounted in the two-dimensional flowfield at zero angle of attack. The adjacent pivoting flat plate was used to impress positive or negative longitudinal pressure gradients on the test linings. The pivoting plate, airfoil, and end plates formed a two-dimensional duct of variable effusor or diffusor angles α (Fig. 2).

The effect of the test panels on wall friction was measured by the momentum deficit in the boundary layer at the downstream edge of the panels. This deficit was expressed in terms of the boundary-layer momentum thickness, which was determined with the use of the total- and static-pressure survey rakes.

Two different fibermetal surfaces (with nominal flow resistances of 10 and 25 rayls) were tested with several different cavity schemes. The results are shown in Fig. 3. The effects of flow circulation through the fibermetal are shown by the curves for the 0.75-in.-deep, air-filled cavity. In this case, the flow through the test panels could communicate throughout the full length of the unpartitioned cavity (24 in.). Large increases in the boundary-layer momentum losses were noted over the tested range of duct angles, which are representative of those that occur in practical duct design. The incremental losses were approximately the same for both the 10- and 25-rayl surfaces.

Several schemes to reduce circulation losses were evaluated. As a baseline against which to measure the effectiveness of these schemes, momentum surveys were made with the back side of the porous walls sealed with tape. As would be expected, the momentum loss ratio was unaffected by duct angle when the porous surface was sealed with tape. The data for the blocked case also confirmed the absence of circulation losses for an air-backed porous wall without a pressure gradient, i.e., the test data at zero duct angle agreed with those of the sealed wall.

Circulation losses were also essentially eliminated by the installation of either fiberglass or compressed open-cell polyurethane foam in the backing cavity. In addition, compartmentation by an egg-crate divider of 1.5-in. cell size was equally effective. Type AA fiberglass was used (fiber diam-4×10^{-5} in.) with a density of 0.8 lb/ft^3 in the 0.75-in.-deep cavity; the compressed polyurethane foam had a density of 5.4 lb/ft^3.

Experimental Full-Scale Fan-Discharge Ducts

Design

The results of the aforementioned preliminary studies were applied to the design of experimental acoustically treated, short fan-discharge ducts. Each duct makes an offset S-bend in arriving at the fan exhaust nozzle on the sides of the nacelle. It was required that the treated ducts terminate in the same nozzle shape to avoid changes to the fan thrust reversers and external cowling. Also, the ducts were required to mount on the same fan-discharge flange as the standard hard-walled production ducts.

Since changing the internal aerodynamic contours would have introduced new problems, it was required that the porous walls conform to the existing inner lines. The four flow-splitters that divide the ducts into separate channels were also retained in their same locations. Outside of the porous surfaces, all available space was provided for the acoustic backing cavities by relocating some of the equipment that surrounds the duct. Provision was made for as much cavity depth as possible behind the porous surface because of the favorable trends observed in the preliminary model duct transmission-loss tests described previously. However, the treatment area was limited by the requirement that only equipment installed by Douglas (e.g., electrical, hydraulic, and pneumatic systems) were to be relocated.

Within these practical constraints, a total of 2800 sq. in. per engine of exhaust duct surface was available for installation of absorptive linings. On the basis of laboratory acoustical tests and dual-reverberant chamber measurements, a 10-rayl fibermetal was selected for the lining facing material. (Fibermetal with a nominal 10-rayl laminar flow resistance was expected to behave approximately as 40-rayl material when installed in the engine because of the 160 db incident SPL and the high airflow rates over the surface of the lining.) The facing material was riveted to Z-shaped frames, which, in turn, were riveted to a solid aluminum backing sheet. The cavity depth varied from 0 to 1.5 in. and from 0 to 3.5 in. on the outer and inner sides of the ducts, respectively. These cavities were filled with 1.2-lb/ft^3 type AA fiberglass to prevent the circulation losses indicated in Fig. 3. Photographs of experimental test ducts are shown in Fig. 4.

Test Results

Prior to flyover noise tests, the acoustically lined experimental ducts were installed on an engine test stand to adjust their nozzle area and to measure their effect on engine performance. Figure 5 is an aerial photograph of the test stand. A JT3D engine is mounted on a simulated inboard pylon suspended from a section of a simulated DC-8 left wing. The

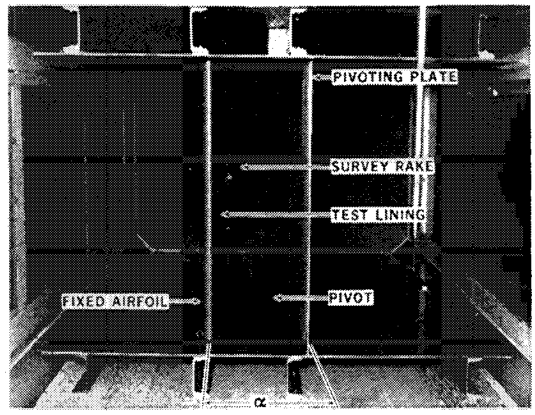

Fig. 2 Duct-wall friction test (view looking downstream).

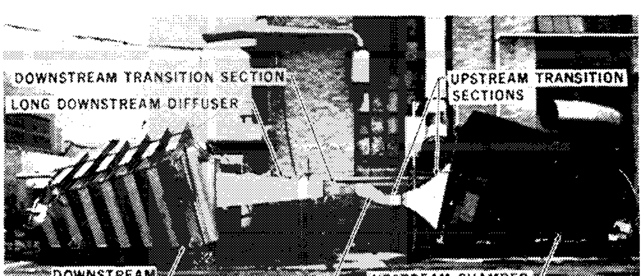

Fig. 1 Dual-reverberant-chamber test facility.

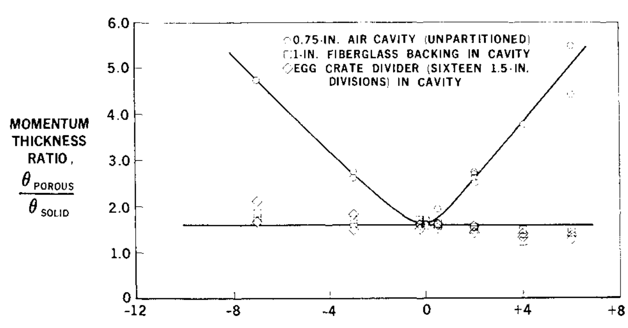

Fig. 3 Effects of lining configuration on wall friction (10-rayl fibermetal).

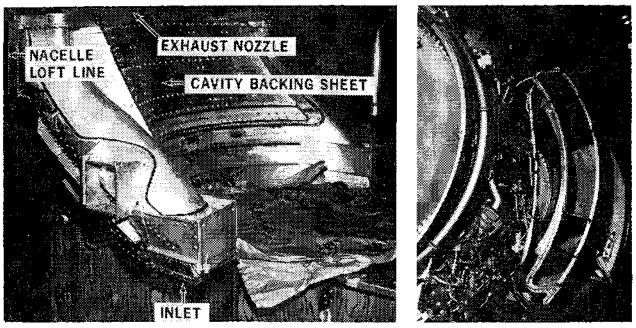

Fig. 4 Acoustically treated duct.

wing section extends 10 ft on each side of the pylon. The facility is equipped for recording thrust, engine shaft speeds, fuel flow, various engine and duct pressures and temperatures, and atmospheric conditions.

Engine performance

The effect of the treated fan-exhaust ducts on static thrust is shown in Fig. 6, where a 0.75% thrust loss at takeoff power is indicated. This loss in static thrust corresponds to a cruise specific fuel consumption increment of about 2%. The loss in thrust is greater than that estimated from the wind-tunnel measurements of the wall-friction increase only because of the increased roughness of the duct surfaces (e.g., see Fig. 3 for an α of 0 deg). The fiberglass may not have been in intimate contact with all of the facing surface, permitting some flow circulation. The engine behavior was normal in all other respects, and the installation was approved for flight testing.

Flyover noise

All four nacelles of a test airplane were equipped with treated fan-exhaust ducts for flyover noise tests conducted in the vicinity of Long Beach Municipal Airport in California during October and November 1966. Noise measurements were made on the ground during takeoff and landing operations as the aircraft flew overhead at various altitudes and engine thrusts.

Data acquisition and reduction methods were as described in Ref. 6. The aircraft altitude was obtained from a photograph of the aircraft taken at the microphone position as the aircraft passed overhead, following the technique described in Ref. 7. Reference 8 contains additional details of the instrumentation used for recording aircraft flyover noise. Data were reduced by use of an octave-band analyzer with the meter set to give a damping equivalent to that of the precision sound level meter on the "slow" scale.[9,10] The peak SPL's obtained in each octave band during the flyover were used rather than the levels at any given instant of time.

A program for a digital computer was used to assist in analysis of the flyover noise data. The program adjusted the observed SPL's to standard day atmospheric conditions and fitted a curve as a function of altitude for each octave-band by the method of least squares. The curve-fitting assumed spherical divergence of sound and octave-band air absorption values.[11] PNL[12] and over-all SPL were then computed for various altitudes from the normalized octave-band SPL.

Results of the flyover noise tests with the treated ducts installed, and with standard production ducts installed, were compared to determine the reduction in flyover noise resulting from the acoustical treatment. Figure 7 indicates the effect of the treated exhaust ducts on the PNL's beneath an airplane flying overhead at an altitude of 1000 ft. Little reduction in PNL was achieved at full takeoff thrust. At reduced thrusts corresponding to noise abatement power cutbacks and landing approach power settings (of the order of 70 and 35% of maximum net thrust, respectively), the experimental ducts reduced the PNL's by about 1.5 to 2.5 PNdb. The lack of suppression at maximum thrust is probably the result of a reduction in effectiveness of the acoustic linings at high exhaust-duct velocities. A trend toward a decrease in duct-lining effectiveness with increasing duct velocity had been observed in the duct-model transmission-loss testing.

Duct-lining failures

Several failures of the fibermetal surfaces of the experimental ducts occurred during the flight-test program. With one minor exception, the failures occurred only in the extreme top and bottom channels of the discharge ducts on both the inner and outer surfaces. There were failures in each of the eight ducts; they occurred on the fibermetal surfaces between the supporting Z-stringers. None of the failures occurred on the sections with the large unsupported spans (about 7 × 20 in.); they occurred at a characteristic location in the duct on sections between the most closely spaced stringers (about 4 × 5 in.).

Concurrent and Continuing Studies

Concurrent with the design, fabrication, and testing of the experimental acoustically treated fan-discharge ducts described previously, several study programs were also conducted. Work on these programs is not yet complete, but sufficient progress has been made to warrant a discussion of recent results.

Model Duct Transmission-Loss Tests

Additional TL tests were conducted using a model of the center channel of one of the fan-discharge ducts. This duct model simulated the varying depth backing cavity design selected for the full-scale, experimental, acoustically treated ducts (Fig. 4). The original duct models used for the preliminary duct-lining studies had a 1-in.-deep cavity behind the porous surface material and accommodations for a con-

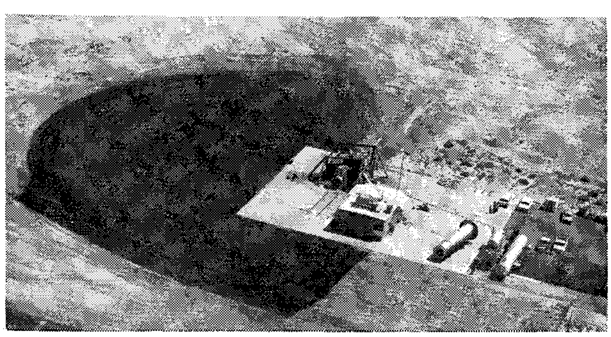

Fig. 5 Douglas engine test stand at Edwards Air Force Base.

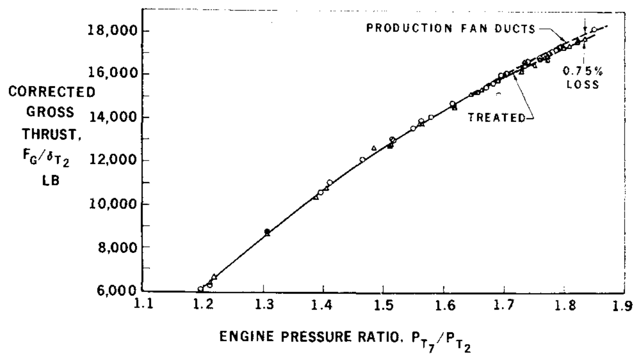

Fig. 6 Effect of treated fan-exhaust ducts on static thrust

siderably larger treated area. The depth of the cavity could be reduced to any desired value. For equal treated areas and equal duct cross-dimensions, these tests produced the following conclusions:

1) A constant depth, 1-in.-deep air-filled cavity should give more noise reduction in the frequency range between 1600 and 6300 Hz than the varying depth air-filled cavity when both cavities are faced with the same type of fibermetal.

2) For high duct velocities, attenuation produced by the model of the center channel of the fan-discharge duct is quite unlike that produced by the model of the end channels. The end channels have more curvature and twist than the center channel since the air has to make a quarter turn along an almost helical flow path in the end channels. The attenuation produced by a given duct-lining treatment was less in the end duct model than in the center duct model. Also, for velocities at the duct throat ranging from 100 to 600 fps, the attenuation produced by a given configuration decreased rapidly with increasing velocity through the end duct and only slightly with increasing velocity through the center duct. This result means that the total attenuation produced by a given treatment installed in a complete highly curved full-scale duct will be limited by that achieved with the duct channel producing the smallest amount of attenuation.

3) Acoustic liner configurations, consisting of two resistive layers separated by air-filled honeycomb cells, appear to produce larger attenuations than single-layer designs with air-filled backing cavities. This conclusion was also supported by standing-wave-tube measurements of absorption coefficients.

4) Filling the varying depth cavity behind the porous fibermetal surface with fiberglass made a reduction of 4 db in the attenuation on the average between 1600 and 6300 Hz. The fiberglass was the same type used in the flyover noise tests. Therefore, the aerodynamic requirement to fill the cavities with a material to reduce circulation losses may well be a partial explanation for the relatively small noise reductions achieved in the flyover noise tests.

Flyover Noise Digital Data-Reduction System

New procedures have been proposed recently[13] to evaluate the annoyance of aircraft flyover noise. The new techniques use a concept known as effective perceived noise level (EPNL), which incorporates corrections to account for the increased annoyance of long duration compared to short-duration sounds and of discrete-frequency tones compared to broadband sounds. The EPNL concept may be most useful in rating noise produced by turbofan-powered transport aircraft. A digital data-reduction system was developed to assist in determining EPNL's from tape recordings of aircraft flyover noise. This system generates punched paper cards that are used by a digital computer under program control to automatically produce machine-drawn plots of instantaneous PNL's, tone-corrected instantaneous PNL's, and over-all SPL's as functions of time during a flyover. Duration corrections are determined from the tone-corrected instantaneous PNL's and added to the peak value of the tone-corrected instantaneous PNL to obtain the EPNL. The procedure is repeated for several recordings to obtain EPNL's as a function of distance between airplane and a ground observer and of engine power setting.

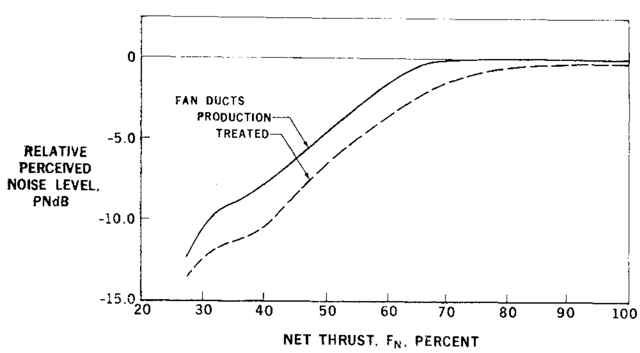

Fig. 7 Comparison of flyover PNL's—JT3D-3B engines (altitude 1000 ft).

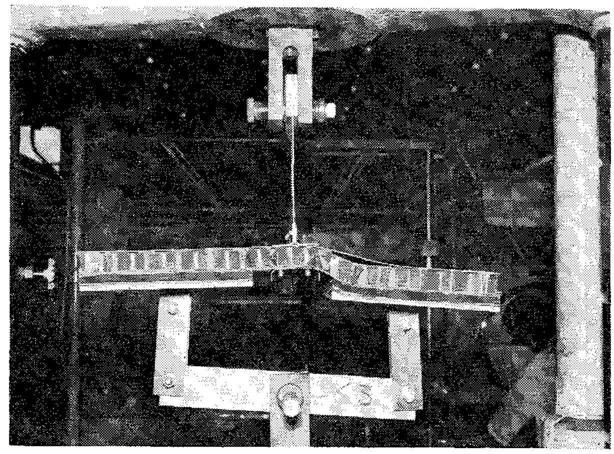

Fig. 8 Tensile testing apparatus—bending beam specimen.

Static Strength Tests

The task of providing adequate structural integrity is being emphasized in a continuing study of fundamental strength testing. A sandwich construction of a honeycomb core bonded between porous facing material and a solid backing sheet shows promise of providing the required integrity. The use of honeycomb materials with relatively small cells essentially eliminates circulation losses and, at the same time, provides improved structural support.

Two types of structural tests have evolved. Initially, the mechanical properties of basic materials, such as fibermetal and adhesive systems, are determined by simple tensile and lap-shear tests. Subsequently, as the materials are integrated into a sandwich design, the structural integrity of a composite panel is determined by bending beam tests (Fig. 8) where the specimen simulates a fan-discharge duct section at a splitter connection. The load, applied through rubber pads cemented to the backing sheet, simulates the duct internal pressure. None of the specimens tested so far has sustained the design loads, but structural weaknesses have been identified and corrective measures are being investigated. For example, improved methods of attaching the splitter to the lining are being developed. An early technique involving through-bolt fasteners proved unsatisfactory. Although spacer tubes were installed between the facing and backing sheets, dimensional control was not adequate to prevent local crushing and weakening of the honeycomb.

Sonic Fatigue Tests

Sonic fatigue tests on acoustically treated panel designs have been conducted using the high-intensity sound system shown in Fig. 9. This system uses a progressive-wave tube driven by up to ten electro-pneumatic transducers. Test panels were mounted on the side of the tube for grazing incidence. A total of nine flat fibermetal panel designs were tested; four panels were riveted skin- and rib-type construction and five were bonded honeycomb sandwich construction.

Some of the significant preliminary observations of these tests are summarized as follows: 1) For a riveted panel comprised of a 0.020-in.-thick fibermetal surface, failures occurred at attachment locations; for panels with 0.040-in.-thick fibermetal surfaces, failures were confined to areas near the

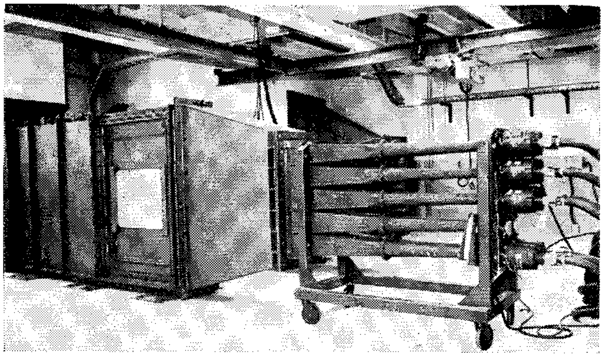

Fig. 9 High-intensity sound system.

center of the panel bays. 2) Varying the spacing of the rivets used to fabricate the test panels from 1.0 to 2.25 in. did not affect the fatigue life of the panels tested. 3) The primary cause of all bonded honeycomb panel failures could be attributed to insufficient strength in the core and adhesive bonding material. 4) For those panels that had no doublers attached around their perimeter, failures occurred near the panel edges; when a doubler was used, failure was confined to locations near the panel's center. 5) Honeycomb panel constructions were superior to skin and rib panel constructions in their ability to resist acoustically induced fatigue, although careful attention must be paid to the details of the bonding techniques.

Conclusions

1) The surface roughness of porous fibermetal facing materials resulted in a minor increase in duct total-pressure losses because of increased aerodynamic wall friction.

2) Large increases in duct total-pressure loss occurred in acoustic duct-lining configurations subjected to static-pressure gradients when there were no provisions for controlling secondary flow circulation through the porous facing.

3) The increased total-pressure losses due to circulation were essentially eliminated when the backing cavity was divided into suitably small partitions or was stuffed with acoustically absorptive filler materials.

4) The effect of the fiberglass filler material on noise attenuation was unfavorable in fan-exhaust ducts.

5) The total attenuation produced by a given duct-lining configuration was limited by that segment of the duct producing the smallest amount of attenuation.

6) As indicated by duct transmission-loss measurements, an improvement to the lining configuration, used in the experimental full-scale ducts, would incorporate an air-filled cavity 1-in. deep.

7) Tests with a JT3D engine on a ground test stand indicated a small loss of thrust due to the experimental acoustically lined fan-discharge ducts. A corresponding increase in cruise fuel consumption was calculated.

8) A modest reduction in flyover noise at landing approach power settings was measured beneath a DC-8 test airplane equipped with the treated fan-discharge ducts. Little reduction was measured at full takeoff power setting.

9) The duct lining design was unsatisfactory in terms of structural durability.

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