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EFFECTS OF AIRCRAFT NOISE ON FLIGHT AND GROUND STRUCTURES

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SUMMARY

Structural vibrations caused by aircraft noise can lead to damage of the structure or to transmission of noise and vibration that reduces the comfort of occupants. This paper discusses three examples involving structural response to aircraft noise. Acoustic loads measured on jet-powered STOL configurations are presented for externally blown and upper surface blown flap models ranging in size from a small laboratory model up to a full-scale aircraft model. The implications of the measured loads for potential acoustic fatigue and cabin noise are discussed. Noise transmission characteristics of light aircraft structures are presented. The relative importance of noise transmission paths, such as fuselage sidewall and primary structure, is estimated. Acceleration responses of a historic building and a residential home are presented for flyover noise from subsonic and supersonic aircraft. Possible effects on occupant comfort are assessed. The results from these three examples show that aircraft noise can induce structural responses that are large enough to require consideration in the design or operation of the aircraft.

INTRODUCTION

Noise generated by aircraft propagates into the aircraft itself and through the atmosphere to structures on the ground. In the aircraft, the noise can generate vibratory stresses that lead to acoustic fatigue, or can propagate through fuselage walls and cause uncomfortably high cabin noise levels. On the ground, aircraft noise can cause building vibrations that may lead to damage or to increased discomfort of the occupants. Penalties associated with noise effects on aircraft structures can take the form of excess weight required to prevent fatigue and to lower noise levels, of maintenance required to repair fatigue failures, or of passenger complaints of excessive noise. Penalties associated with noise effects on ground structures can range from unfavorable publicity to community actions (such as curfews) that restrict the use of airports. To minimize such penalties, it is important to assess possible noise effects early in the development of new aircraft types, especially those with increased performance, so that noise-reduction methods can be developed.

In this paper, examples of noise effects are discussed for three classes of aircraft for which increased performance is being sought. The topics discussed are: STOL aircraft acoustic loads, light aircraft noise transmission, and building response to aircraft noise. The emphasis of the discussion is on the response of the structure to the noise. Implications of the results for possible structural damage and occupant annoyance due to noise are discussed.

SYMBOLS

Measurements were made in U.S. Customary Units, and are presented in both the International System of Units (SI) and U.S. Customary Units.

d	diameter of nozzle exit
f	frequency, Hz
g	acceleration of gravity
p_{rms}	root mean square of the fluctuating component of pressure
q_0	dynamic pressure of the engine exhaust flow at the nozzle exit
U_0	velocity of the engine exhaust flow at the nozzle exit

Abbreviations:

AMST	advanced medium STOL transport
EBF	externally blown flap
FPL	fluctuating pressure level
OAFPL	overall fluctuating pressure level
rms	root mean square
SPL	sound pressure level
STOL	short (runway) take-off and landing
USB	upper surface blown

Reference level for FPL, OAFPL, and SPL is 20 μPa.

STOL AIRCRAFT ACOUSTIC LOADS

Configurations and Sources

In order to obtain STOL performance of jet aircraft using the powered-lift concept, a particular arrangement of the aircraft components has been developed. Some features are illustrated in figure 1. Powered lift is obtained by deflecting the engine exhaust flow downward using wing and flaps. To obtain such interaction, the engine must be located forward of the wing, either under the wing (externally blown) or over the wing (upper surface blown). In both cases, the direct impingement of the high velocity, turbulent, exhaust flow subjects the wing and flaps to intense fluctuating loads (in the presence of high static loads and temperatures) that may cause excessive acoustic fatigue. To minimize rotational moments when operating with an engine out, the STOL aircraft's engines are located nearer to the fuselage than are conventional aircraft engines. The location of the engines in a forward and inboard position exposes larger areas of the fuselage to more intense acoustic pressures than conventional locations. These high external acoustic pressures may cause excessive interior noise levels. In addition, the exterior noise of STOL aircraft when operating in the powered-lift mode (take-off and landing) is expected to be of extended duration as well as at high levels. These long durations at high levels increase the likelihood of unfavorable noise effects on the aircraft.

The two powered-lift systems currently under development (externally blown flap and upper surface blown flap) are fundamentally different from each other so that acoustic loads information on one system may not necessarily apply to the other. Therefore, parallel programs are underway on both EBF and USB systems to develop acoustic loads information through measurements on small-scale models, large-scale models, and full-scale aircraft in flight. The objectives of these programs are to develop methods for predicting acoustic loads on aircraft in flight (using model tests and scaling laws) and to provide acoustic loads data on actual aircraft for use in ongoing developments. Some results from these research programs are presented in the following discussion.

USB Flap Studies

Acoustic loads have been measured on USB configurations including small laboratory scale models, several 8.9-kN (2000-lb) thrust engine models, and a full size 220-kN (50 000-lb) thrust aircraft engine configuration. Preparations are underway to measure acoustic loads on the YC-14 AMST aircraft. Comparisons are presented in references 1 and 2 between results from small-scale models, using air jets to simulate engine exhaust, and from large-scale models having actual jet engines. In figure 2, results are shown from tests of a full-scale YC-14 ground test rig and a 1/4-scale model of that ground test. The full-scale YC-14 rig includes a CF6 engine and many systems that are to be flown on the aircraft; the test included checkout of several flight systems, including the flow-turning aerodynamic performance of the flap system and the fluctuating pressure measurement system. The scale model uses a 8.9-kN (2000-lb) thrust engine and was designed to geometrically scale the important features of the full-scale setup. The tests included aerodynamic measurements of flow turning and thrust, so the acoustic loads results shown were measured on models that were operating in a flight-type powered-lift condition. In figure 2, overall fluctuating pressure levels at three positions on the flap and fuselage are shown as a function of the average velocity of the exhaust jet at the nozzle exit. Full-scale data are taken from reference 2. Figure 2 shows that the levels of the acoustic loads are 135 to 160 dB on the fuselage (gages 7 and 20) and up to 165 dB on the wing (gage 34). These levels are high enough that substantial effort will be required to provide satisfactory acoustic fatigue life and interior noise environments. Full-scale results are about 3 dB higher than model results. The overall agreement between model and full-scale results shown in figure 2 is sufficiently good to give confidence that model results can be used to predict full-scale characteristics. Additional analyses of the results obtained on the 1/4-scale model tests are underway for comparison with the full-scale model results. Current plans include measurements of acoustic loads on the wing, flaps, and fuselage of the YC-14 AMST aircraft to determine actual flight levels and effects due to forward speed, and to obtain results for comparison with values predicted from ground tests.

EBF Studies

Acoustic loading information has been measured on the three EBF configurations shown in figure 3 (ref. 3). Data from the small-scale model and the TF34 model (using an 36-kN (8000-lb) thrust engine) are intended to be used with scaling laws to provide predictions of acoustic loads for full-scale flight situations. Measurements on the YC-15 AMST aircraft are intended to aid the development of the scaling law prediction technique, and to provide acoustic loads data in an aircraft flight situation for an EBF STOL configuration. Data from the small-scale model are compared with results from the TF34 model in figure 4.

In figure 4, values of the dimensionless fluctuating pressure level (FPL) are presented as a function of Strouhal number. Data for two flap settings are shown at two positions on the flaps. The data for the TF34 model include engine exhaust velocities ranging from a Mach number of 0.33 to 0.59. The fact that these data all fall within the narrow dotted region indicates that FPL and Strouhal number are appropriate dimensionless quantities to account for the effects of velocity on FPL and frequency. The figure shows that for three of the four conditions there is good agreement between the results from the small-scale model (nozzle diameter of 5.08 cm (2 in.)) and from the TF34 engine (nozzle diameter of 96.52 cm (38 in.)). This agreement suggests that acoustic loads can be scaled, at least over the range of variables represented by these two tests.

An indication of the magnitude of the acoustic loads on the EBF configuration is given in figure 5. In this figure, overall fluctuating pressure levels (OAFPL) are shown for seven transducers, two flap positions representing expected flight positions, and five engine exhaust velocities covering the range from low to full engine power. Examination of the table (note the four circled values) shows that the pressure levels range from 143 dB to 163 dB. Previous experience with acoustic fatigue of structures suggests that when levels are in the 140-dB range, some acoustic fatigue may be expected, and when the levels rise to the 160-dB range, substantial problems may be anticipated.

Estimates of the interior noise levels that might be expected on passenger-carrying versions of both the EBF and the USB aircraft have been made using data such as are shown in figures 2 and 5 and current sidewall noise reduction technology. These estimates suggest that new developments either in reduction of exterior noise levels or in improvement of fuselage sidewall noise reduction are needed to provide a satisfactory cabin noise environment.

LIGHT AIRCRAFT NOISE TRANSMISSION

Test Description

Flight measurements of interior noise in light aircraft (refs. 4 and 5) have shown that the levels are high enough that noise reduction efforts are needed to provide a noise environment that is comfortable and similar to the environment that passengers have come to expect from their experiences in modern jet aircraft. In order to carry out noise reduction, it is necessary to know the sources of the noise and the transmission properties of current aircraft structures. Studies on light aircraft (refs. 6 and 7) have suggested that propellers and engines are important noise sources, and that possible noise transmission paths include the exterior air and fuselage sidewall (referred to herein as the "airborne" path) and the primary structure (referred to herein as the "structureborne" path) through which interior noise is transmitted in the form of structural vibration that may originate, for example, in the engine. In order to study the characteristics of these two noise transmission paths, a light aircraft fuselage was set up and tested in the reverberation chamber of the Langley aircraft noise reduction laboratory, as shown in figure 6. A sound field was generated by speakers, and the chamber characteristics provided a reverberant uniform noise field over the complete exterior of the fuselage. Three microphones in the chamber (shown in fig. 6) were used to measure the noise field exterior to the fuselage. Readings from these three microphones during testing were nearly the same, indicating that the exterior noise field was uniform. Noise was measured inside the fuselage by the two microphones shown in figure 6 for the reverberant noise field to determine airborne noise. Noise transmitted through the structureborne path was determined by attaching a mechanical shaker to the engine support structure at the front of the aircraft and taking measurements with the two microphones inside the fuselage with no exterior noise field. A broadband spectrum, having nearly constant level over the frequency range from about 100 Hz to 1000 Hz for the mechanical input and from about 100 to 4000 Hz for the acoustic input, was used.

Airborne and Structureborne Transmission

Some results from these tests are shown in figure 7, where interior noise levels measured with exterior noise alone and with vibration input alone are shown. The data shown in figure 7 indicate that the interior noise level SPL varies with either exterior noise level or mechanical input in a linear trend with 45° slope. Based on the logarithmic scales used in these figures, this result indicates that the interior noise level is a linear function of either exterior noise or mechanical vibration input. This result was anticipated and indicates that analytical programs for prediction and control of interior noise can be based on tractable linear relations. The graph of interior noise as a function of exterior noise indicates that the interior levels are about 21 dB lower than the exterior levels, indicating that the fuselage is providing a significant overall noise reduction (averaged over frequency and the various transmitting structures such as windows and sidewall panels). Further reduction of the fuselage sidewall noise is desirable and might be accomplished by means of analytical methods to optimize the distribution of mass, stiffness, and damping while retaining minimum weight.

Figure 7 also shows that vibration inputs are an efficient mechanism of interior noise generation. For example, 8.9 N (2 lb) of vibration force input results in an interior noise level of about 82 dB. The exterior noise level required to induce 82 dB of interior noise is about 103 dB. This result suggests that interior noise resulting from vibrations transmitted through structural paths (from vibration sources in the engine, for example) can be significant. Control of such structureborne noise might be accomplished by use of vibration isolation devices such as shock mounts or integral damping treatments in the engine support structure.

RESPONSE OF BUILDINGS TO AIRCRAFT NOISE

Study Plan

The airport community noise problem has been a major concern of airport planners and the aircraft manufacturers and operators for many years. This concern was highlighted with the proposed introduction of the Concorde supersonic transport service into this country. A major public concern was expressed in the environmental impact statement (ref. 8) about the expected Concorde noise-induced vibratory response of historic buildings and homes near the airport in terms of structural damage and annoyance. As a result of this concern, measurements of noise-induced building vibrations have been conducted by Langley Research Center near the Dulles International Airport as part of the total Department of Transportation program of assessment of Concorde.

The approach to the assessment of Concorde noise-induced building vibrations involves the following steps: (1) measurement of vibratory response of windows, floors, and walls of selected buildings, including historical ones; (2) development of functional relationships ("signatures") between the vibration response of building elements and the range of outdoor and/or indoor noise levels associated with events of interest; (3) comparison of the Concorde-induced response with the response associated with other aircraft as well as with common domestic events and/or criteria. It should be noted that criteria are not well established particularly with respect to building damage.

Test Site Description

Figure 8 is a map of the Dulles International Airport and surrounding community areas. Also shown on the map are the nominal departure flight paths of Concorde and the locations of the test sites where structural response was measured. The test sites include one historic building (Sully Plantation) which is located on the airport boundary about 2.2 km (1.4 miles) from the end of the closest runway. Also monitored were three residential houses of families who had registered complaints concerned with building vibrations due to Concorde operations. These houses, located in Montgomery County, Maryland, range from about 21 to 32 km (13.1 to 19.9 miles) from the airport.

Window and Wall Response

Sample vibratory response data and associated outdoor noise levels are presented in figures 9 and 10. The functional relationship between the measured vibration response of a window and wall of Sully Plantation is shown in figure 9 for the range of outdoor SPL measured during take-off operations of Concorde and subsonic aircraft (refs. 9 and 10). The data cluster about a single line and show a linear relationship between response and noise level. Both the Concorde noise levels and induced responses exceed the levels due to subsonic aircraft by about 10 dB or a factor of 3. Also, the response of the wall is lower than the window which would be expected because of the larger mass and stiffness of the wall. Of particular significance is the fact that the vibratory response is a function of pressure amplitude and virtually independent of aircraft type. Thus, the inference of references 8 and 11 that Concorde-induced building response will be greater because of the low-frequency content of the Concorde spectrum is not supported by the data shown in figure 9.

Sample vibratory response data obtained in the residential communities of Montgomery County (ref. 12) are shown in figure 10 for both Concorde and subsonic take-off operations for test site 3. A functional relationship between the vibratory response and noise levels similar to those obtained at the Sully Plantation is again observed. Both the noise levels and vibration response due to Concorde are higher than the levels associated with subsonic aircraft operations. However, the difference between the maximum levels of noise and vibration for Concorde and for the subsonic aircraft is about 26 dB or a factor of 20. The reason for the greater difference between responses of Concorde and of subsonic aircraft at this location as compared with those measured closer to the airport at Sully Plantation is believed to be due to differences in aircraft operational procedures.

The linear response relationship observed in figures 9 and 10 is significant in that it not only gives the absolute response of the aircraft as recorded but enables extrapolation to other runway cases, flyover distances, or house locations if a noise data base is available. The acceleration levels induced by the aircraft are shown to be high enough to cause small objects to rattle, perhaps resulting in increased annoyance.

CONCLUDING REMARKS

This paper presents three examples of situations where structural responses are caused by aircraft noise. Acoustic loads measured on externally blown and upper surface blown flap STOL configurations are shown to be sufficiently high that acoustic fatigue and cabin noise require careful consideration for possible commercial applications. Laboratory studies of the noise transmission into a light aircraft fuselage indicate that interior noise can enter the fuselage through both the fuselage sidewall transmission path and the primary structure (vibration) transmission path. Accelerations measured on the windows and walls of a historic building and a residential home indicate that noise from a supersonic aircraft causes acceleration levels high enough to be perceptible by occupants, and that the noise and vibration levels due to the supersonic aircraft are higher than those due to subsonic aircraft by a large enough factor to present a clear contrast that draws attention to the supersonic aircraft.

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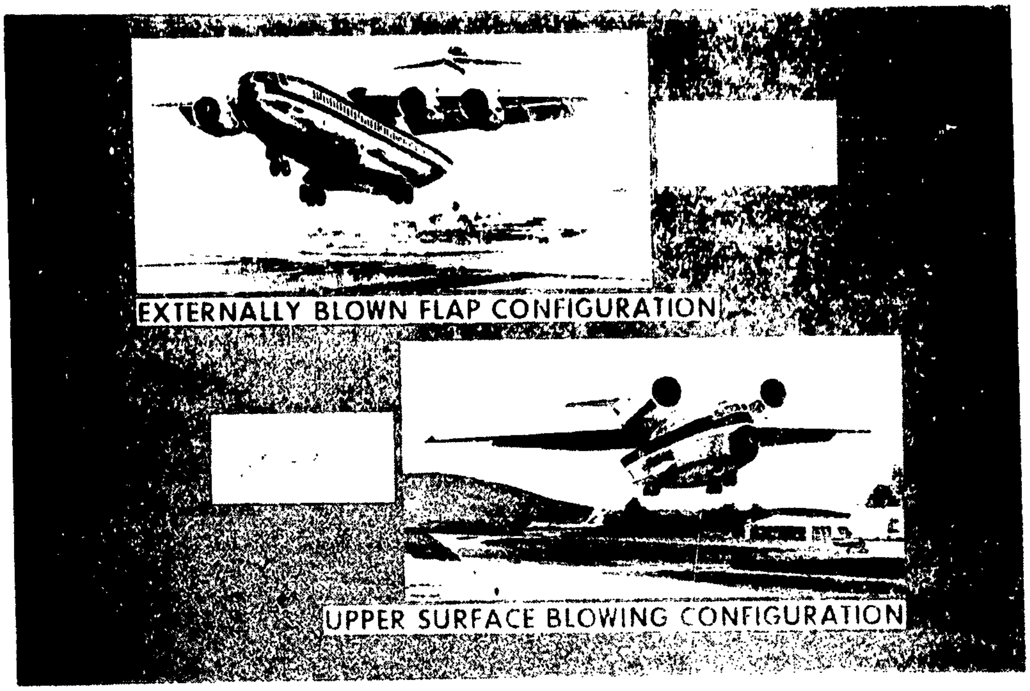


Figure 1.- Artist's concepts of commercial STOL transports using powered-lift systems.

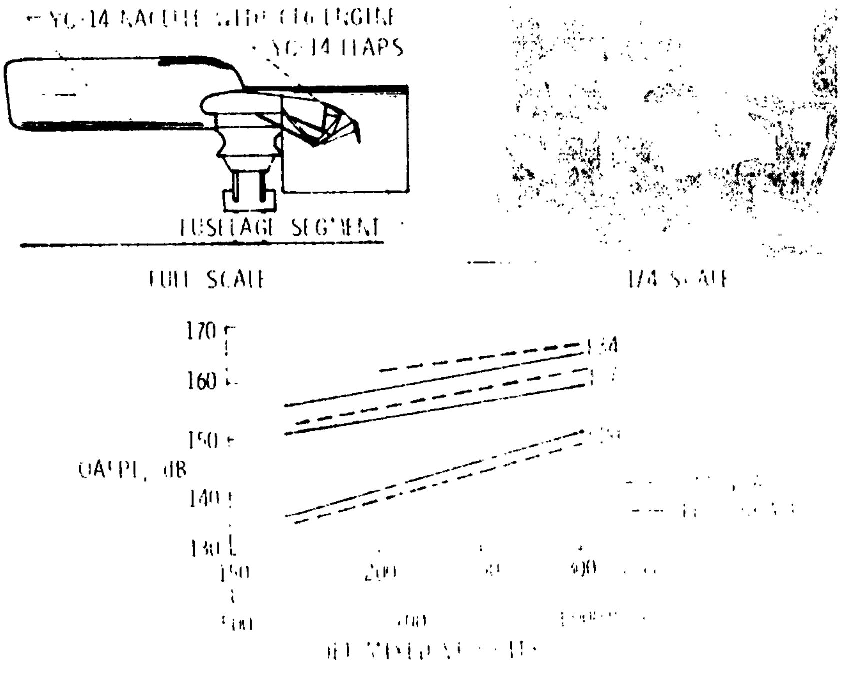


Figure 2.- Fluctuating pressures on USB models.

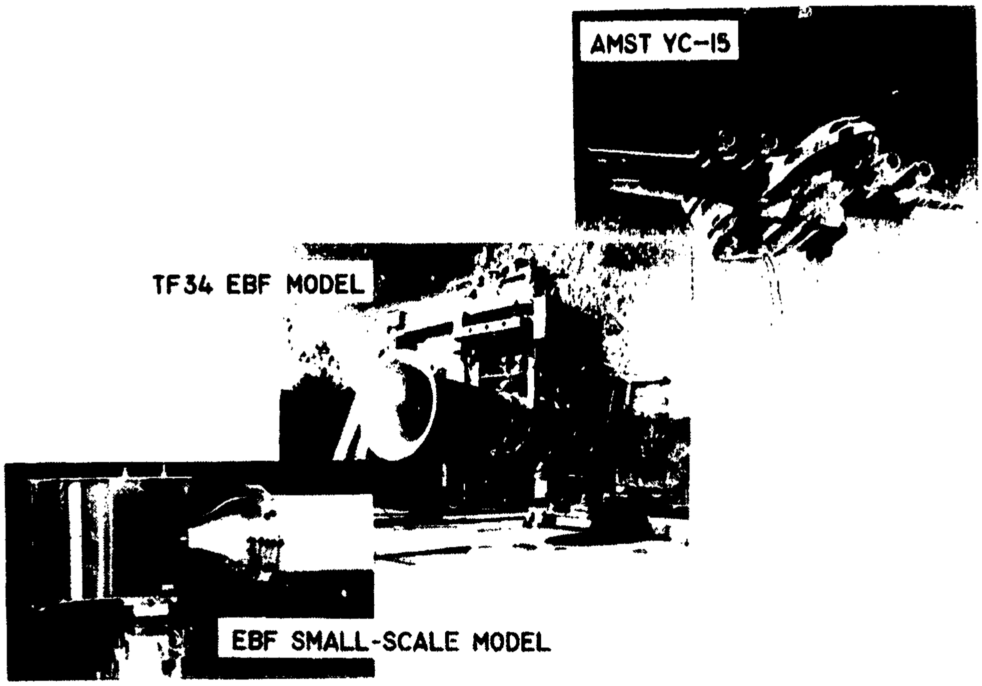


Figure 3.- Test configurations for EBF fluctuating loads studies.

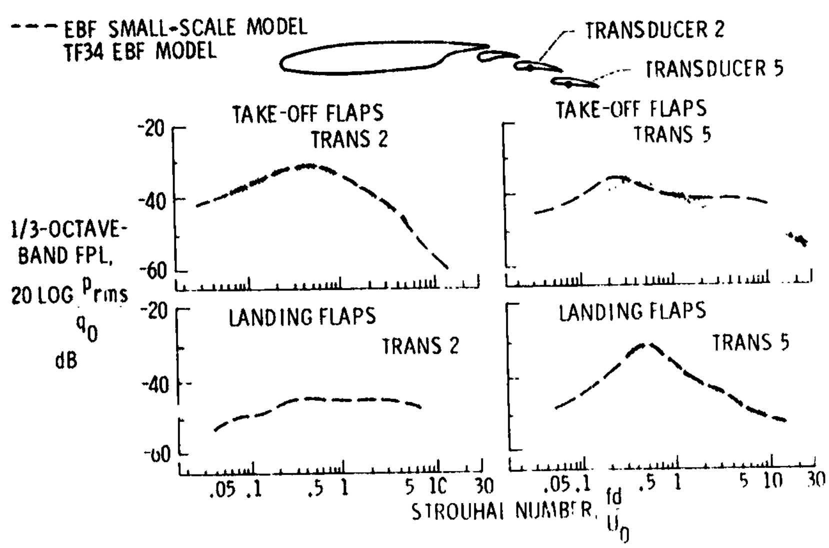
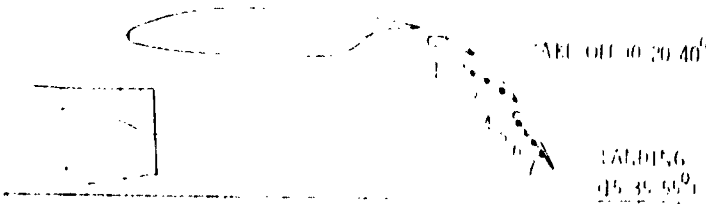


Figure 4.- Fluctuating pressures on large- and small-scale EBF models.



		OAFPL, dB									
		TAKE OFF (0 20 40°)					LANDING (15 35 55°)				
MACH NUMBER		0.33	0.45	0.51	0.57	0.59	0.33	0.44	0.49	0.55	0.59
TRANSDUCER	1	149	155	156	158	159	150	156	158	160	162
	2	151	157	159	160	161	148	154	156	159	160
	3	152	158	160	162	163	148	153	155	157	159
	4	149	154	156	159	160	146	152	153	156	157
	5	145	150	152	155	156	147	152	154	156	156
	6	143	143	150	152	153	148	154	155	156	157
	7	144	149	151	-	154	148	153	155	157	157

Figure 5.- Overall fluctuating surface pressure levels on TF34 EBF model.

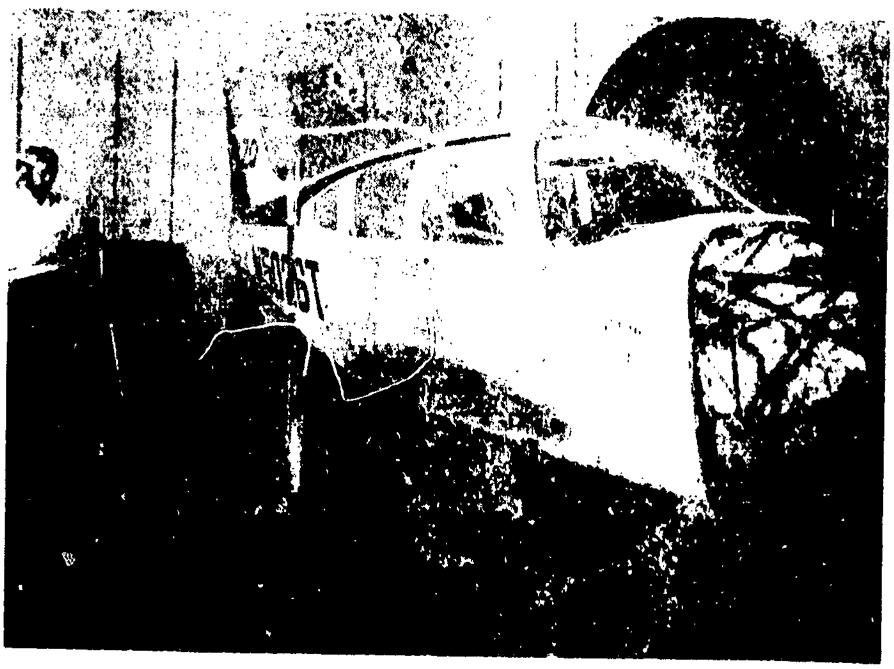


Figure 6.- Noise transmission test setup in reverberation chamber.

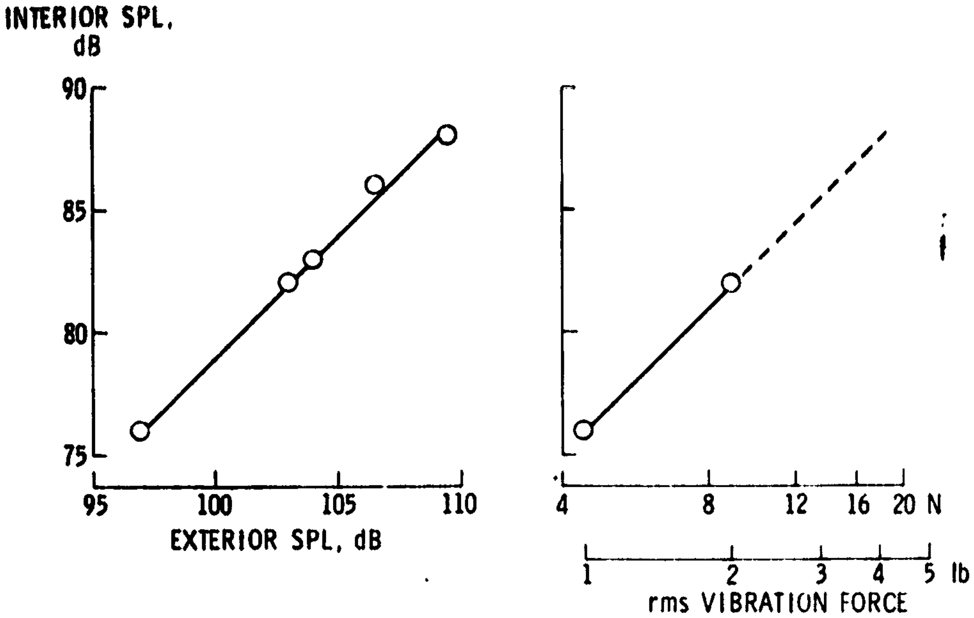


Figure 7.- Airborne and structureborne interior noise of light aircraft fuselage in reverberation chamber.

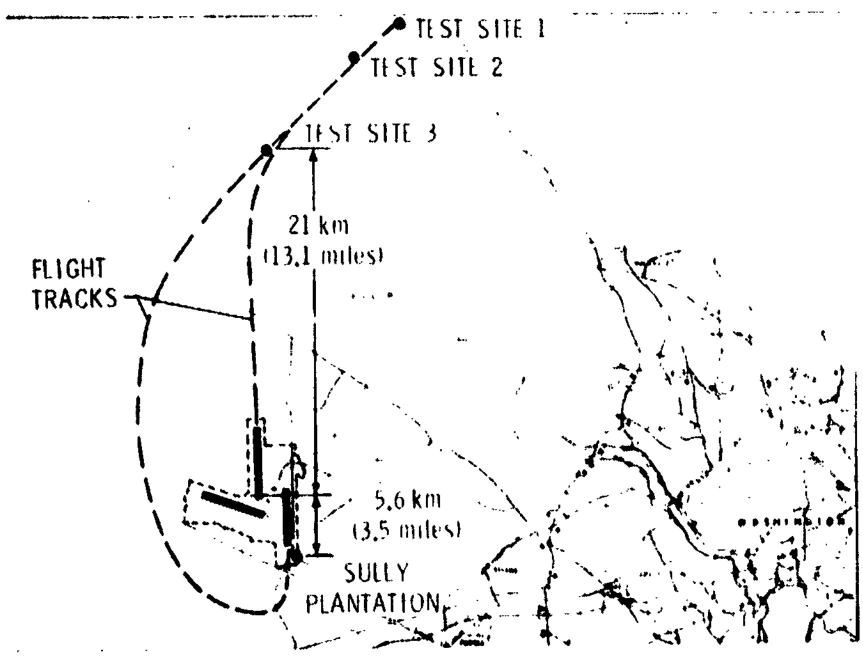


Figure 8.- Test sites for building response study.

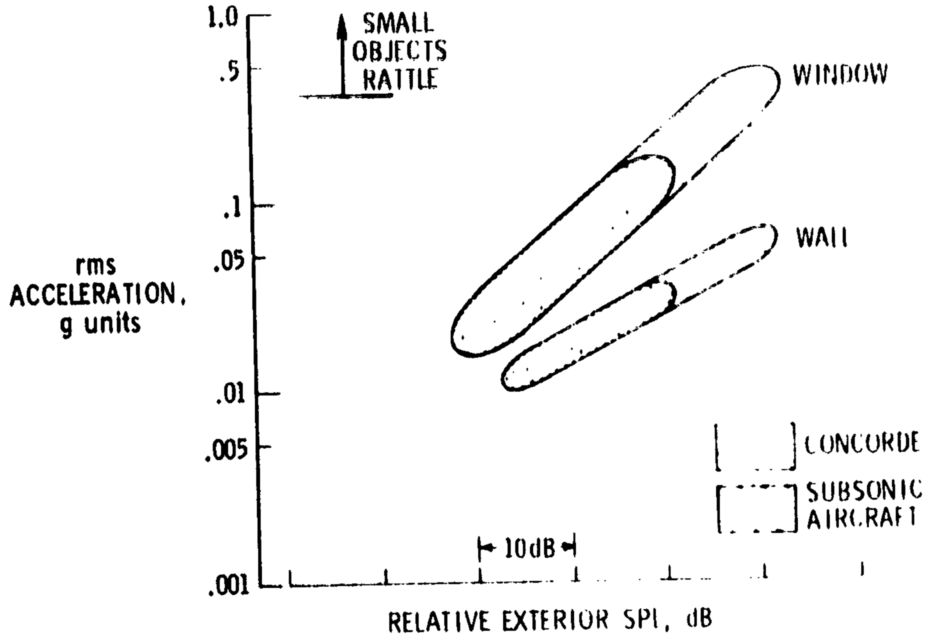


Figure 9.- Response of wall and window to aircraft noise at Sully Plantation.

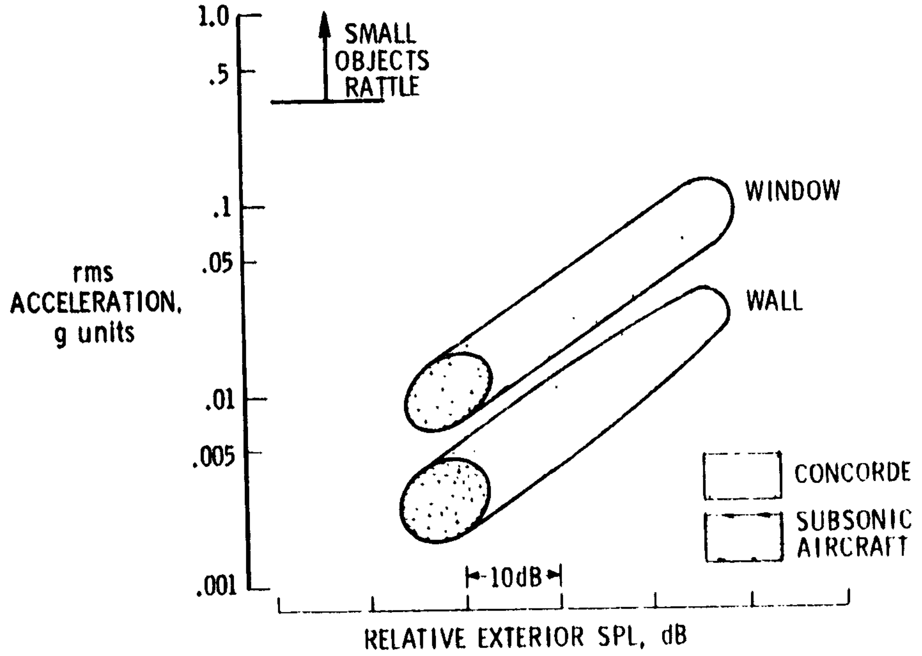


Figure 10.- Response of wall and window to aircraft noise at test site 3.