ICAS-92-5.4.4

RESEARCHES ON SONIC FATIGUE OF THE AIR-INLET DUCT OF XX AIRCRAFT

Yao, Q.H., Ge, S., Guo, D.W., Shao, Ch., Bai, J.J.
Aircraft Strength Research Institute, P.R. of China
Zhang, X.Y.
Shenyang Aircraft Research Institute, P.R. of China

Abstract

An extensive collaboration research program has been conducted by the Aircraft Strength Research Institute (ASRI) and Shenyang Aircraft Research Institute (SARI), in order to solve the sonic fatigue failure problem of the inner-wall panel of the air-inlet duct of XX aircraft, which aimed at obtaining the acoustic loads to which the panel subjected and the response and the sonic fatigue characteristics of the panel, and utilizing the the induced noise loading spectrum from actual aerial measurements to perform sonic fatigue tests for the air-inlet duct model simulating the real structure, in combination with both theoretical and experimental analysis. The main objectives of this program are to provide reliable data and analysis motheds for the determination of sonic fatigue life of the air-inlet duct of the same types of aircraft on active service and for the sonic fatigue life design techniques for new types of structures.

In this paper, a brief introduction to the theoretical and experimental analysis is given describing mainly the following

- Sonic fatigue prediction.
- Sonic fatigue test of the panels simulating the inner-wall structure.
- Actual aerial measurements for acoustic loads
- Inducing the acoustic loads from actual aerial measurement results to get damage-equivalent loads spectrum.
- Verification sonic fatigue test.

I. Introduction

Certain modes of sonic fatigue damage problems were found occuring in some areas of the air-inlet duct of the original XX aircraft during its test flight, including the inner panel vibrating violently that consequently induces cracks in the skin and the rivet head being sheared.

The inner substructure was modified then, with stiffeners being put closer to reduce the dimension of the inner skin, so as to increase the stiffness avoiding the main excitation frequency. And this modification resulted in the sonic fatigue damage phenomena disappearing. But it was still uncertain whether the target life of three thousands flight hours would be met.

It was reported that the types of sonic fatigue problems existed in varying degrees in aircraft structures[1]. A kind of military aircraft, for instance, was found to have the similiar rivet damage and skin cracks in more than 60% of them during the maintenance after 500 flight hours. And it was believed that these damage were mainly induced by intense sonic loads[2].

In order to determine the sonic fatigue life of the air-inlet duct structures, a collaboration research program was drawn.

The program comprised the following phases:

1. Sonic fatigue prediction for the inner duct panels.
2. Sonic fatigue test of the panels simulating the inner-wall structure.
3. Aerial measurements for sound pressure level at the surface of the inner-wall.
4. Inducing the acoustic loads from actual aerial measurement results to get damage-equivalent load spectrum.
5. Verification sonic fatigue test.

II. Program Description

1. Sonic Fatigue Prediction

A lot of programs were conducted previously to develop sonic fatigue design methods for typical skin-frame-stringer aircraft structures.

As a result, considerable sonic fatigue design methodologies, principally based on semiempirical approaches, have been developed[3].

In China, the sonic fatigue research activities began in the 1970s. Most of them were concentrated on the theoretical analysis and experiments[4], noise environment measurements[5] and some put-on damping material treatments[6].

From the engineering application point of view, the sonic fatigue analysis and design method based on the semiempirical approaches is preferred compared with some large-scale finite element computation program, as the sonic fatigue problems have been characterized by a significant degree of inherent unpredictability that has so far made it almost impossible to carry out precise analysis, while most of the data used in a semiempirical approach had been the statistical results of sonic fatigue experiments and tests which takes into account the uncertainty of both noise excitation and the structure response characteristics. And it makes the prediction easier and more reliable.

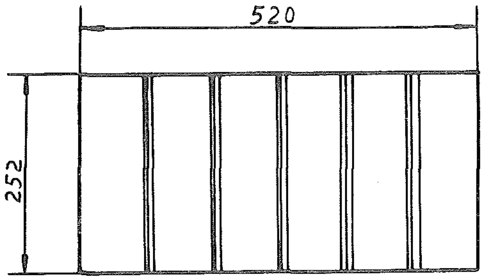
In this program, several sonic fatigue analysis method were surveyed which were collected from world wide literatures. Then four most commonly used semiempirical approaches were adopted. Detail researches on their characteristics, application range and limitations were made. And each method was computer programed on which sonic fatigue analysis program package was based. This program package can widely be used in the sonic fatigue design and analysis, the suitable analysis progarm can be selected by users in man-machine-dialogue way, according to the noise excitation type and the characteristics of the structure to be analysed[7].

In order to solve the sonic fatigue of the inner duct wall, the calculation model (as well as the sonic fatigue test panel) were designed, which were partitioned by the frames and longerons, shown in Fig.1.

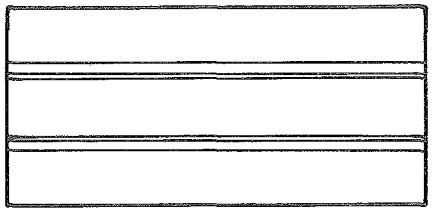
2. Sonic Fatigue Test

Test Specimen

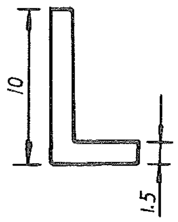
Both vertical stiffened and longitudinal stiffened panels were designed and manufactured, simulating the forepart and rearpart of the duct respectively, with skin thickness, distance between two stringers and the material being the same with the real air-inlet duct configuration.



(a) Vertical Stiffened Panel



(b) Longitudinal Stiffened Panel



(c) Stringer

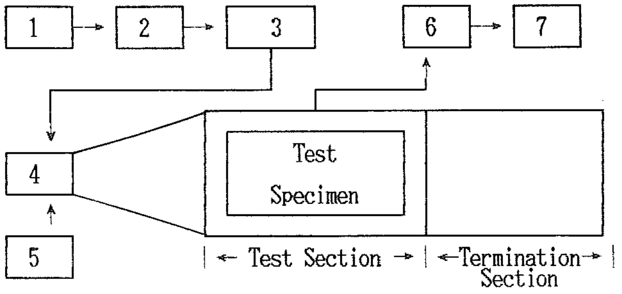
Fig.1 Calculation and Test Panel Configuration

Test Objectives

Sonic fatigue test was performed in a progressive-wave-tube with the panels being subjected to broad band random acoustic loading at grazing incidence. The test set up is shown in Fig.2.

The main objectives of the test were to provide scientific basis for the determination of the sonic fatigue life of the air-inlet duct structure and to get reliable experiment data of this configuration, as later on the slope of the " S-N " curve obtained from test would be used as an important parameter in inducing the damage-equivalent sonic loads spectrum.

The panels were instrumented with strain gauges, and data were taken under sound pressure levels of 156dB,



1 — Sine-random Signal Generator
2 — Filter
3 — Power Amplifier
4 — Electro-pneumatic Transducer
5 — Air Supply
6 — Strain and Acceleration Measurement
7 — Recorder, Analyzer

Fig.2 Progressive-wave-tube Test Set Up

158dB, 159dB, 160dB, and 162dB.

Finally, the regression curves of the sound levels VS. sonic fatigue life (number of circles) were obtained for vertical stiffened panel:

$$\log N = 42.18991 - 0.2262657\ SPL \quad (1)$$

for longitudinal stiffened panel:

$$\log N = 36.97394 - 0.1943298\ SPL \quad (2)$$

where N — Sonic fatigue life, number of circles to failure.
SPL — Sound pressure level, dB.

Comparison

The sonic fatigue life of the panels from test and calculation program package was compared as shown in Table 1.

3. Aerial Measurement

Sonic loads spectrum is of key importance in sonic fatigue analysis since the structure response and consequently the failure mode are greatly dependent on it. In order to get accurate sonic loads spetrum inside the air-inlet duct on the surface of the panels, the aerial measurement was performed.

Three microphones were installed in the left-hand-side air-inlet duct, at the fore, middle and rear part respectively, as shown in Fig.3.

Twenty-four flight states were chosen including take-off and climbing and other stunt and conventional states as listed in Table 2. And for each state, both the relevant parameters such as height and Mach number and the sound signals were recorded by airborne tape recorder. The duration time for each state was statistically given.

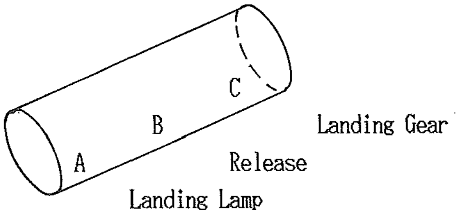


Fig.3 Measuring Points

The overall sound pressure level and the spectrum in one-third octave band were obtained for each state, and a typical spectrum is shown in Table 3.

4. Damage-equivalent Loads Spectrum

As mentioned previously, during a typical take-off and landing route, 24 characterized flight states were chosen and the sound pressure spectra in one-third octave band were measured for each flight state. Those sound loads were the main excitations that the inner wall panel of the air-inlet duct subjected during a typical flight route. The sonic fatigue damage mainly caused by those excitation could be accumulated until the failure, such as cracks or some modes of sonic fatigue appeared. The well-known Miner's accumulated damage theory could be used to calculate the total damage by linearly superposing all the sonic fatigue damage induced by all of the sound loads in each state.

But under some circumstances, the laboratorial test in special, those state-time sound pressure level spectra should be induced into a unified sonic fatigue loads spectrum.

In this program the methodology was researched on which the damage-equivalent loads spectrum was based.

From the sonic fatigue damage point of view, the fatigue damage caused by the reduced loads spectrum is equal to the total accumulated damages caused by each sound excitation in each states.

The principle and the main reduce procedures are as follows.

Sonic Fatigue Characteristics of Structure

In a bi-logarithmic coordinate system, the tested "S-N curve" of the structure could be expressed approaximately by least squares method as

$$W^{B}T = C \qquad (3)$$

where W — sound pressure
T — sonic fatigue life time
C — constant
B — the negtive reciprocal value of the slope of the "S-N curve" in bi-logarithmic coordinate system.

The equation (3) means that the spectrum sound pressure value and the sonic fatigue life time under sound loads follows the relationship:

$$(W_1/W_2)^{B} = T_2/T_1 \qquad (4)$$

that is to say, different sound pressure values and fatigue times could be equivalent in the sense of damage-equivalent.

In this program, both the vertical and longitudinal stiffened panels were tested under broad band random sound pressure excitation, and the regression " S-N curves" were obtained as shown in equation (1) and (2). The B values could be calculated from those two equations.

Reduce Pressure Data in All States

As shown in Table 3, the measured sound loads in totally 24 states could all be expressed in the forms of one-third octave band spectra. The frequency ranged between 1.6 to 10KHz, could be divided into several segments. In this program, the segments were chosen the same as the one-third octave band division.

A. The measured one-third octave band sound pressure level spectra for each state were converted into sound pressure load, referred as W_{ij}
where $i=1,2,\cdots,N$, designates state number
$j=1,2,\cdots,M$, designates frequency band segment number
and the duration time for each state was referred as T_i.

B. For a specified frequency band segment (one of the one-third octave band) j, the maximum sound pressure load among 24 states was chosen as the basic value

$$\overline{W}_j = \mathrm{Max}(W_{ij}) \qquad (i=1,2,\cdots,N)$$

and the corresponding time could be calculated according to equation (4):

$$\overline{T}_j = \sum_{i=1}^{n} (W_{ij}/\overline{W}_j)^{B}T_i \qquad (5)$$

therefore, for the jth frequency band, the sound pressure load was determined as $\overline{W}_j$ and the corresponding duration time $\overline{T}_j$. then let j equals to 1,2,⋯, M repeatedly, and follow the calculation steps mentioned above, the sound pressure loads and duration times for each one of all the one-third octave band were determined.

C. A specific duration time corresponding to a specific frequency band where the fundamental frequency of the structure was located was chosen as the unified duration time for the induced spectrum, referred as T, and then the sound pressure for each one-third octave band was modified:

$$W_j = (\overline{T}_j/T)^{-B} \cdot \overline{W}_j \qquad (6)$$

D. Converting Wj into sound pressure level, the one-third spectrum was obtained, with unified duration time being T.

The one-third octave band spectrum derived A. through D. was damage-equivalent to the aerial measured sound pressure level spectra of 24 states. And it is convenient to use in test and calculation.

This reduction procedure was computer programed so as to increase the data processing efficiency. Typical reduced damage-equivalent one-third spectra for vertical and longitudinal stiffened panels are shown in Fig.4 and Fig.5, respectively.

5. Verification Sonic Fatigue Test

Specimen

In the verification sonic fatigue test, the specimen were the same as shown in Fig.1, which were vertical and longitudinal stiffened simulating the air-inlet duct inner panel configuration partitioned by frames and longerons at different positions, respectively. And they had been made by aircraft manufacturing company in order to ensure the similarities in material and technological process with real structures.

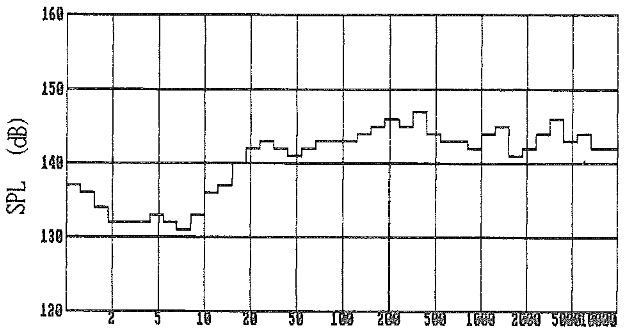
Excitation Spectrum

Test was conduted in the progressive-wave-tube (PWT) test facility where the sound wave exerted excitation on the specimen at grazing incidence. The excitation spectrum inside the PWT in the test section was controled with microphone installed in the test section and the measured signal was feedback through the multi-channel equilizer to the controling computer to adjust the excitation spectrum to the required damage-equivalent spectrum. First of all, a driving spectrum was generated by a PC 286 computer which was led into the band-pass filters and the amplifier to drive the electro-pneumatic transducer generating sound excitation inside the PWT. Then the sound spectrum in the test section was measured and analysed by spectrum analyzer. And the measured spectrum was compared with the required spectrum, which gives a reference to adjust the driving spectrum in the computer. Repeating the procedure above, the required damage-equivalent spectrum could be achived. To shorten

```
  TET=   .718440E+02

  CF..HZ   EWMAX..DB           CF..HZ   EWMAX..DB

     1.60 .13765E+03             2.00 .13686E+03
     2.50 .13499E+03             3.15 .13299E+03
     4.00 .13265E+03             5.00 .13295E+03
     6.30 .13318E+03             8.00 .13247E+03
    10.00 .13155E+03            12.50 .13399E+03
    16.00 .13616E+03            20.00 .13789E+03
    25.00 .14066E+03            31.50 .14296E+03
    40.00 .14357E+03            50.00 .14286E+03
    63.00 .14187E+03            80.00 .14228E+03
   100.00 .14306E+03           125.00 .14346E+03
   160.00 .14366E+03           200.00 .14407E+03
   250.00 .14538E+03           315.00 .14610E+03
   400.00 .14542E+03           500.00 .14712E+03
   630.00 .14479E+03           800.00 .14355E+03
  1000.00 .14309E+03          1250.00 .14293E+03
  1600.00 .14490E+03          2000.00 .14501E+03
  2500.00 .14137E+03          3150.00 .14219E+03
  4000.00 .14445E+03          5000.00 .14635E+03
  6300.00 .14307E+03          8000.00 .14465E+03
 10000.00 .14271E+03
```



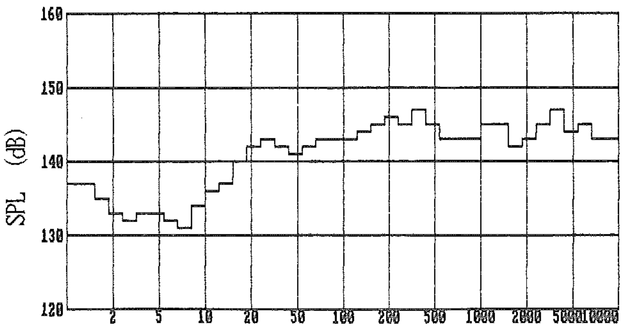
1/3 Octave Center Frequency (Hz)

Fig.4 Reduced Spectrum for Vertical Stiffened Panel

```
  TET=   .711669E+02

  CF..HZ   EWMAX..DB           CF..HZ   EWMAX..DB

     1.60 .13799E+03             2.00 .13746E+03
     2.50 .13553E+03             3.15 .13340E+03
     4.00 .13281E+03             5.00 .13321E+03
     6.30 .13350E+03             8.00 .13263E+03
    10.00 .13182E+03            12.50 .13406E+03
    16.00 .13620E+03            20.00 .13795E+03
    25.00 .14069E+03            31.50 .14298E+03
    40.00 .14360E+03            50.00 .14290E+03
    63.00 .14193E+03            80.00 .14235E+03
   100.00 .14309E+03           125.00 .14350E+03
   160.00 .14370E+03           200.00 .14411E+03
   250.00 .14544E+03           315.00 .14620E+03
   400.00 .14554E+03           500.00 .14725E+03
   630.00 .14513E+03           800.00 .14384E+03
  1000.00 .14374E+03          1250.00 .14376E+03
  1600.00 .14577E+03          2000.00 .14580E+03
  2500.00 .14242E+03          3150.00 .14333E+03
  4000.00 .14557E+03          5000.00 .14716E+03
  6300.00 .14421E+03          8000.00 .14546E+03
 10000.00 .14378E+03
```



1/3 Octave Center Frequency (Hz)

Fig.5 Reduced Spectrum for Longitudinal Stiffened Panel the test time, the speed-up factor was taken into account in the excitation spectra according to the criteria ISO 2671, with

$$L_{p.acc} = L_{p.equ} + (20/\gamma)\log(T_s/T_{acc}) \qquad (7)$$

where $L_{p.acc}$ — sound pressure level (SPL) after acceleration, in dB;
$L_{p.equ}$ — equivalent SPL, in dB;
T_s — life time of the tested structure, in hour
T_{acc} — acceleration test time, in hours;
γ — fatigue damage accumulation ratio, generally $\gamma = 6$.

Test Procedure

A. Mode Test

The vertical and longitudinal stiffened panels were mounted on sidewall of the PWT which were excited by a random excitation and then the response of the panels were used to determine the mode parameters.

The mode test result were shown in table 4.

B. Sonic Fatigue Test

The vertical and longitudinal stiffened panels were mounted on the two sidewalls of the PWT respectively. The sound excitation spectra were the reduced damage-equivalent one-third octave band sound pressure level spectra with acceleration factor taken into account.

The test lasted 5 hours which equivalent to three-thousand flight hours of target life time of the air-inlet duct. During the 5 hours sonic fatigue test no cracks on the panel skin were found and neither were the sonic damage in the rivet head.

III. Conclusions

In this collaboration research program, which began in 1988 and ended in 1991, lots of research work in combination with both theoretical and experimental analysis had been completed within nearly four years. Beginning with the engineering sonic fatigue prediction methods, a series of research activities were conducted including the aerial measurement for sound excitation loads inside the duct, reduction of the measured sound spectra, sonic fatigue test for "S-N curves" and the verification sonic fatigue test under the reduced sound spectra. After that the sonic fatigue life time of air-inlet duct of the XX aircraft was certain and the conclusion for this structure could be given: the structure configuration of the duct after modification is reasonable and it is certain that under the sound excitation the structure satisfies the required three-thousand flight hours of target life time and it would not suffer the sonic fatigue failure encountered before.

Furthermore, through the research activities involved in this program, the sonic fatigue analysis and anti-sonic fatigue design techniques and the test methods have been set up. The sonic fatigue analysis computer program package, for instance, provides a quick and convenient analysis and calculation method to the panel structure sonic fatigue problems. Some other sonic fatigue damage problems have been occured in the XX series aircraft, and in other types of military aircraft. The analysis and computation and test methodologies developed in this program is hopefully applicable to those problems. And this will promote the aircraft dynamic design technology.

References

1. Zhou Zhilun, Hu Binxiang, "Aircraft Noise and Sonic Fatigue Problem", Technique Report, 2nd Department, Aircraft Strength Research Institute, P. R. China, August 1979.

2. Liu Mingyuan, "Sonic Fatigue Induced Rivet Failure and Skin Cracks in Aircraft Strctures", Technique Report, Xi'an Aircraft Company, P.R.China, March 1980.

3. Rudder, F.F.Jr. and Plumblee, H.E.Jr., "Sonic Fatigue Design Guide for Military Aircraft", Air Force Flight Dynamics Laboratory, AFFDL-TR-74-112, May 1975.

4. Ge Sen, " Investigation on Sonic Fatigue Characteristics of Aircraft Panels", MS thesis, Aircraft Strength Research Institute, P.R.China, August 1984.

5. "Noise Measurement on Fuselage and horizontal Tail for XX Aircraft", Xi'an Aircraft Company, P.R.China, October 1973.

6. Hao Lianying, " The Application of Visco-elastic Damping Material ", Technique Report, 2nd department, Aircraft Strength Research Institute, P.R.China, June 1983.

7. Shao Chuang, "Sonic Fatigue Analysis Computer Program Package", Technique Report, 2nd Department, Aircraft Strength Research Institute, P.R.China, July 1991.

Table 1 Comparison of Test and Calculation Results

	OSPL (dB)	Life Time (min.)	
		Calculation	Test
VERTICAL STIFFENED	156	257.0	180.0
	158	103.0	62.7
	159	72.4	72.7
	160	32.5	34.7
	162	10.0	6.5
LONGITUDINAL STIFFENED	156	223.0	236.0
	158	54.8	35.7
	159	30.9	42.8
	160	15.8	18.1
	162	3.7	15.0

Table 2 Flight States

No.	Flight States	Height (m)	Mach No.	Duration Time
1	taxi, take-off	262	0.27	30"
2	climbing	1403	0.59	8'40"
3	transonic level flight	5696	0.983	3'10"
4	right transverse roll	5805	1.23	20"
5	large air-velocity pressure level right turn	6203	1.36	40"
6	decelerating	6336	1.29	2'10"
7	level speed up	6356	1.35	1'30"
8	rise right turn	3400	0.92	40"
9	level flight	5465	1.25	8'10"
10	leftside glide	5559	1.24	1'20"
11	rightside circling	5516	1.21	1'10"
12	abrupt rise	6360	1.38	40"
13	transonic level flight	10476	1.03	8'10"
14	right transverse roll	10446	1.55	10"
15	large air-velocity pressure level right turn	10472	1.70	40"
16	decelerating	11795	1.66	2'10"
17	level speed up	9874	1.68	50"
18	rise right turn	8149	1.40	40"
19	level flight	10340	1.70	8'10"
20	leftside glide	10251	1.74	10"
21	rightside circling	10690	1.77	1'10"
22	dive and rise	5392	1.18	50"
23	descending	2461	0.63	3'40"
24	release landing gear	962	0.43	2'20"

Table 3 1/3 Octave Band SPL Spectrum

Frequency Band Number	Measurement Point			Frequency Band Number	Measurement Point		
	Point A	Point B	Point C		Point A	Point B	Point C
1				21	120.0	124.0	122.3
2	111.7	116.7	112.7	22	122.4	125.7	122.6
3	111.7	113.6	109.5	23	127.1	127.6	123.7
4	109.3	108.4	113.4	24	127.4	126.9	126.0
5	109.0	113.0	110.6	25	128.8	127.6	127.3
6	112.4	115.9	112.5	26	129.1	129.2	129.2
7	108.11	114.5	113.1	27	131.4	129.9	129.2
8	111.5	115.3	113.4	28	130.4	130.3	133.1
9	111.4	115.4	114.8	29	131.9	130.9	132.9
10	109.7	113.4	115.0	30	133.4	131.7	132.9
11	111.1	116.0	117.8	31	130.9	131.9	133.0
12	111.1	116.8	117.0	32	134.9	136.9	136.5
13	113.6	119.1	116.1	33	138.4	138.8	139.7
14	116.6	118.9	116.6	34	133.4	134.9	138.7
15	117.2	118.7	118.3	35	133.1	134.9	137.9
16	120.0	119.6	119.2	36	134.2	137.7	143.0
17	119.0	122.0	121.0	37	135.3	140.0	144.8
18	118.5	122.1	120.9	38	135.3	139.0	142.3
19	118.6	122.7	121.6	39	134.2	137.1	141.3
20	119.1	123.3	121.6	40	134.1	137.3	140.6

Table 4 Mode Test Results

	Longitudinal Stiffened Panels		Vertical Stiffened Panels	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	135.0	0.08333	182.5	0.07534
2	182.0	0.08108	257.0	0.05820
3	217.5	0.04598	437.5	
4	430.0		540.0	
5	545.0		620.0	