DEVELOPMENT OF A DAMPED A-10 ENGINE AIR INLET RING

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ABSTRACT

A modern turbofan engine generates an intense acoustic environment which results in durability problems for the surrounding aircraft structure. Acoustic fatigue caused by jet engine noise is the principal origin of structural failures of A-10 engine air inlet extension rings. Many of these components exhibit failures in as few as a couple of hundred flight hours. This paper outlines the environments which cause these failures and presents the development of a damped A-10 inlet ring. The durability, cost, and weight of the re-designed component are compared to the baseline A-10 inlet ring. These comparisons demonstrate a significant improvement in the durability, weight, and life cycle cost through the incorporation of damping into an advanced inlet ring design.

INTRODUCTION

Many of the failures of secondary aircraft structures may be attributed to acoustic fatigue generated by modern turbofan engines. Engine inlets, nacelles, cowl doors, and surrounding structure are especially prone to these failures. While the failures themselves may not be catastrophic from the standpoint of an individual secondary component, potential foreign object damage to the turbofan engine could have a detrimental effect on the flight worthiness of the aircraft. Frequently recurring maintenance and repair of these structures adversely affects aircraft availability and operational costs. Recent Department of Defense directives rate operational availability equivalent to operational performance for the design of new aircraft. As a consequence, managers of future military system programs must incorporate advanced structural design and manufacturing technologies into those systems to ensure their reliability. The application of structural damping and careful structural design practices in areas subjected to high intensity acoustic excitation can reduce or eliminate the problems associated with the aforementioned secondary aircraft structures. LTV has established the viability of this technology through the re-design and manufacture of A-7 center section leading edge flaps, F-111 outboard spoilers, and A-10 engine air inlet rings.

This paper discusses the development and re-design of an inlet extension ring used on an A-10 attack aircraft. Work on this project was performed under the Structural Improvement of Operational Aircraft Program, Air Force Contract Number F33615-81-C-3219. The goals of this program were to develop advanced structural design and manufacturing technologies which would increase the durability and decrease the life cycle cost of secondary aircraft structures. These objectives were to be attained without a performance or weight penalty as compared to the baseline component. In pursuit of these goals, the failures plaguing the baseline inlet ring were identified and the causes established through a series of tests and analyses. An advanced inlet ring was then developed based on these design criteria, and its durability validated through the same analysis and laboratory test procedures used for the baseline inlet ring.

A schematic representation of the baseline inlet ring cross-section and its installation is depicted in Figure 1. This structure provides an aerodynamically smooth interface between the inner nacelle lip of the aircraft and the fan shroud of a TF34-GE-100 engine. The baseline inlet ring is approximately 42 inches in diameter and 9.25 inches wide. The materials used in its construction are conventional 2024 and 6061 aluminum alloys in various product forms and tempers. A laminated skin, composed of three 0.025" layers of aluminum, bonded with 3M's AF-126 modified epoxy film adhesive, is formed in 180° sections, and spliced in two locations to form the body of the baseline inlet ring. Aluminum angle stiffeners are employed at the forward and aft ends of the skin to add rigidity to the structure and provide attachment points for installation on the aircraft. The forward angle stiffener supports a floating forward flange which is attached via 24 discrete spring elements. This spring-loaded flange provides a flexible interface between the inlet ring and the inner nacelle lip of the aircraft. The adaptive nature of this interface ensures the ability to remove a damaged engine and/or inlet ring and replace it with an undamaged spare in a minimum amount of time. Figure 2 illustrates each of

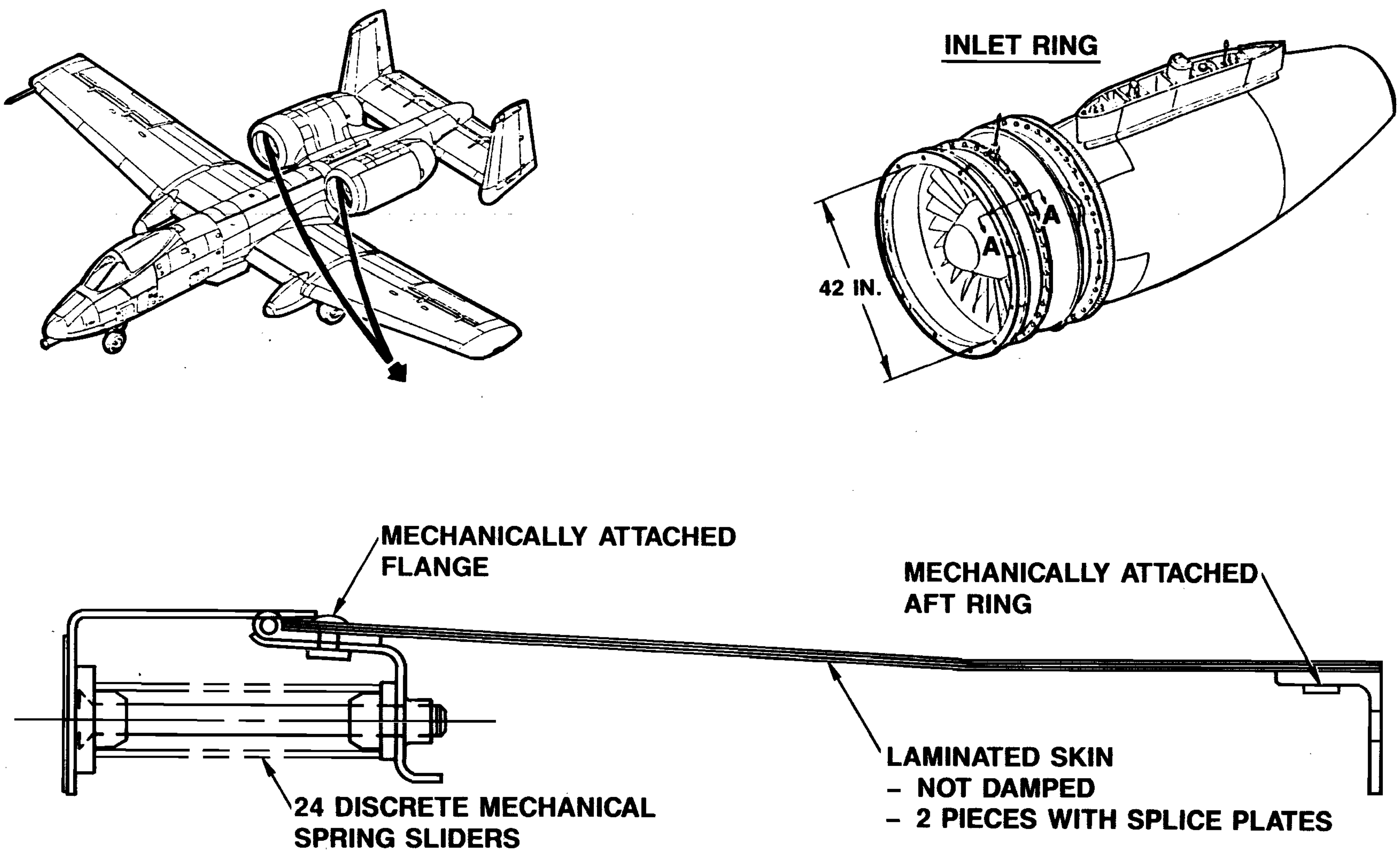

Figure 1 - Baseline Inlet Ring Cross-Section and Installation

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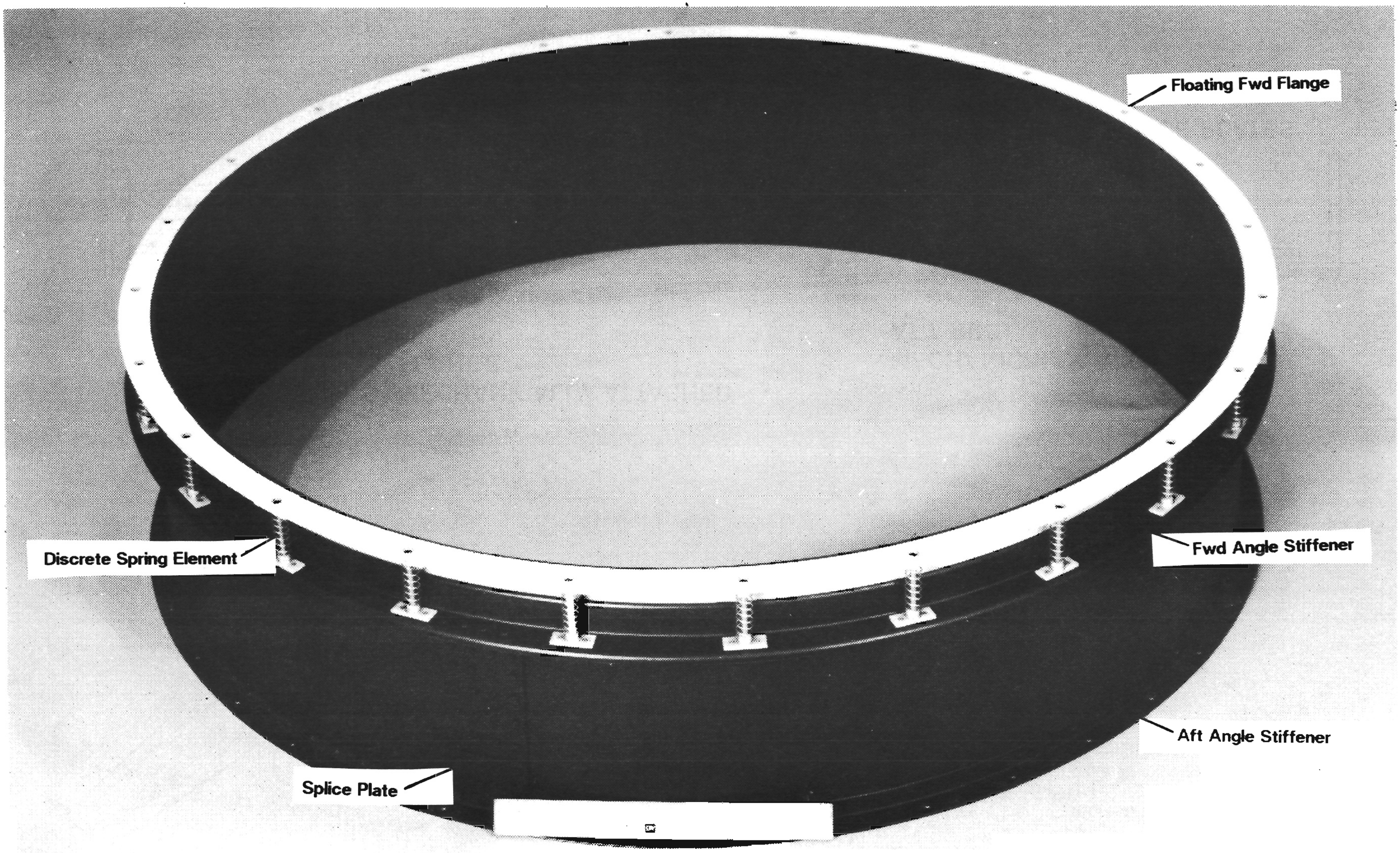

Figure 2 - Baseline A-10 Engine Air Inlet Extension Ring

the previously described elements of the baseline inlet ring and Figure 3 demonstrates how this component interfaces with the surrounding structure when installed in an aircraft.

A survey of baseline inlet rings in service identified a number of design shortcomings which induce unacceptable mean time between failure intervals for the component. The elements which exhibit durability problems include the rivets that attach the forward angle stiffener to the inlet skin, and the splice plates and splice angles which join the individual 180° segments of the inlet ring skin and angle stiffeners. Rivet failures occur at the forward angle stiffener in as few as 200 flight hours, with rivet head ingestion into the engine transpiring as a consequence of the failure. The deterioration of the rivet integrity may be attributed to an open shank condition which exists in the interface between the angle stiffener and the inlet skin. This situation is caused by the presence of an elastomeric seal between the skin and forward ring as illustrated in Figure 1. The lack of rigidity of the attachment at this interface is aggravated by an intense acoustic environment which produces circumferential bending and rocking modes of the forward ring. The discontinuous load application created by the discrete spring elements also enhances the severity of the problem. These effects contribute to the high cycle bending fatigue and eventual failure of the aluminum rivets. The failures associated with the splice plates and splice angles may be attributed to an abrupt change in the bending stiffness of the structure at these locations. When subjected to an acoustic environment, the inlet skin tends to deform about these stress raisers and the ensuing bending causes cracking of the splice plates. Finally, the flexible interface, at the forward end of the baseline inlet ring, provides little or no sealing to prevent blow-by and reduction of inlet ram pressure. This condition does not precipitate any structural failures, yet it prevents the inlet ring from completely and efficiently performing the function for which it was designed.

DESIGN CRITERIA

In order to effectively solve the problems associated with the baseline inlet ring, the reasons for the failures had to be identified. The establishment of the design criteria involved identifying the environments that the inlet ring encounters and verifying the failure mechanisms through analysis and laboratory test. Due to the inlet ring's proximity to the TF-34 engine, sonic fatigue caused by jet engine noise was surmised to be the principal cause of the baseline inlet ring failures. Acoustic fatigue of aircraft structures in the vicinity of modern jet engines is a well known phenomenon discussed extensively in the literature[1,2,3,4].

Predicated on these hypotheses, an engine ground run test was performed using an instrumented baseline inlet ring. The instrumentation included two microphones to monitor the sound pressure level at the interior of the inlet ring, and six accelerometers to assess the inlet ring response to the acoustic environment identified. Figures 4 and 5 illustrate the maximum sound pressure levels witnessed at the forward and aft ends of the inlet ring in a frequency range from 0 to 5000 Hertz. The most severe environments, based on maximum sound pressure level, occur in a

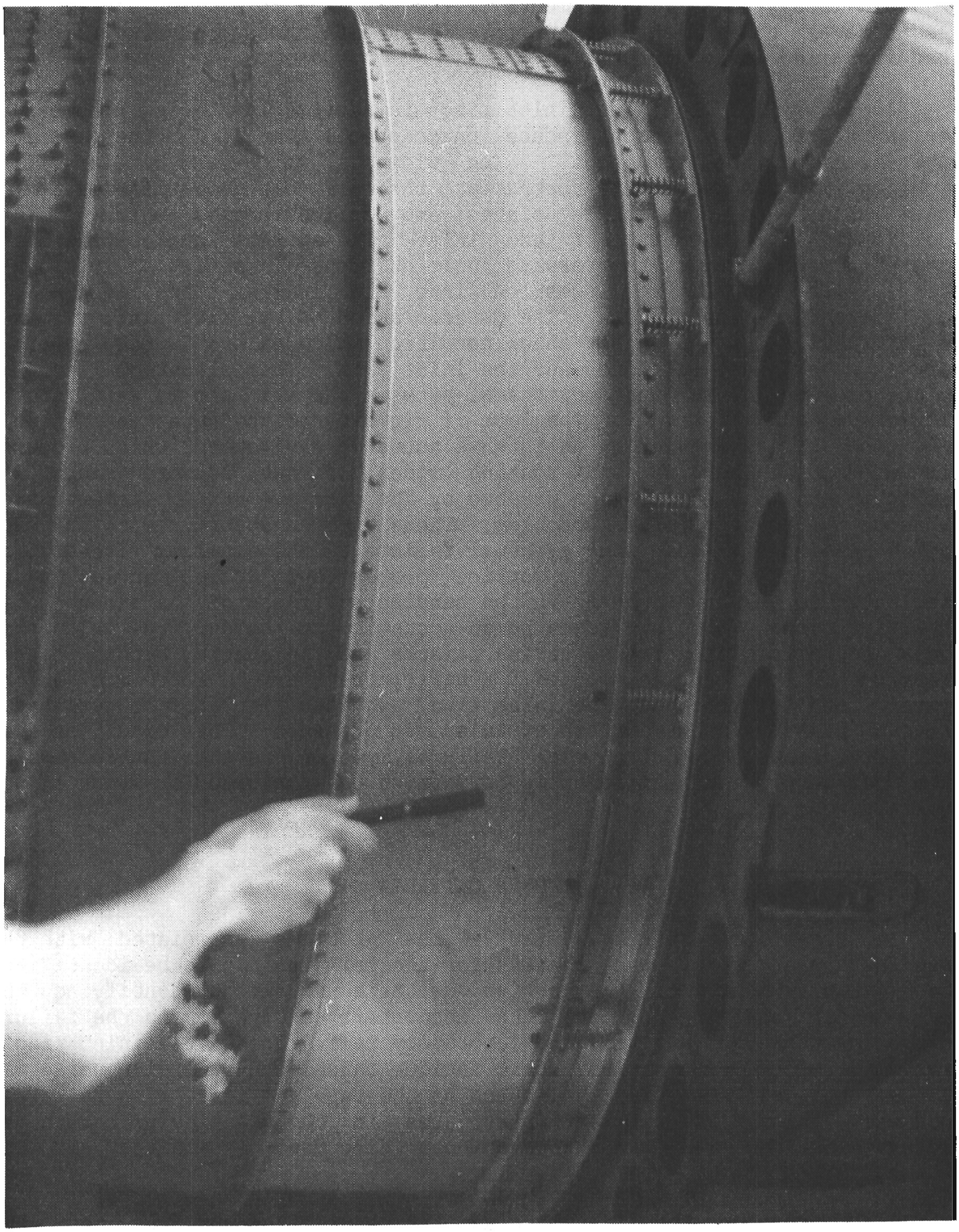

Figure 3 - Baseline A-10 Inlet Ring Installed in an Aircraft

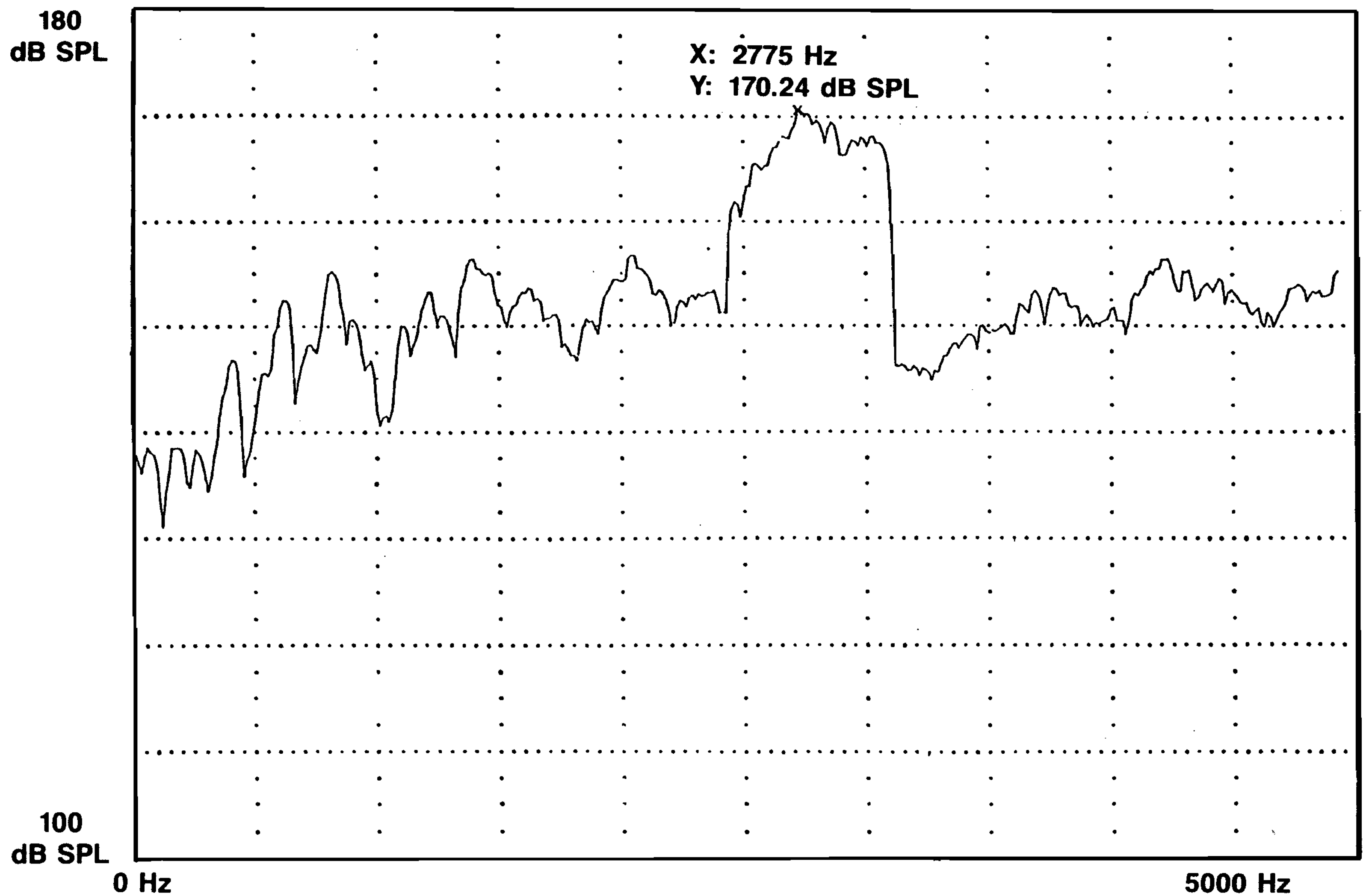

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Figure 4 - Peak Hold Sound Pressure Level Data From Aft Mounted Microphone

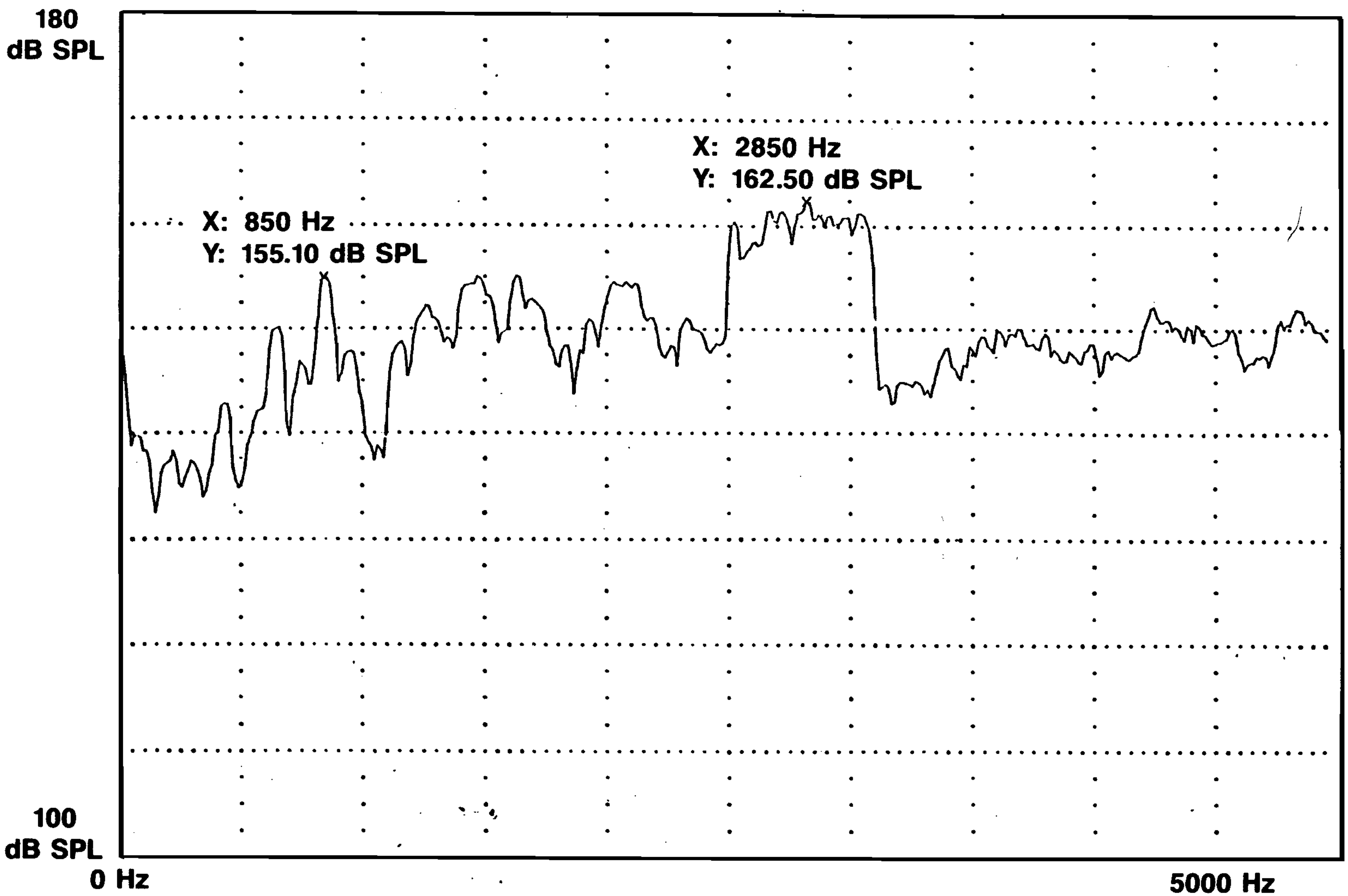

Figure 5 - Peak Hold Sound Pressure Level Data From Forward Mounted Microphone

range of frequencies from 800 to 1500 Hertz and 2500 to 3000 Hertz. The 2500 to 3000 Hertz regime is the result of fan blade passage and generates acoustic levels in excess of 170 dB (ref. 20 μPa). The other frequency range of interest, 800 to 1500 Hertz, produces maximum sound pressure levels of approximately 155 dB (ref. 20 μPa) in a range of engine speeds from 75 to 100 percent of maximum fan RPM. This multiple pure tone, or combination tone excitation, is caused by geometric and aeroelastic differences between successive fan blades which produces shock waves forward of the fan face. Phenomenon such as these have been characterized by various authors[1,3,4], and shown by Hancock[2] to be the cause of structural failures in another TF-34 installation.

With the environment information obtained in the literature and confirmed through engine ground run test, determining the amount of time that the inlet ring experiences this severe excitation was the only task that remained. It must first be realized that those environments identified through ground run testing will vary with atmospheric pressure and air density, and thus can change dramatically in flight. To assess these effects, an analysis of the the variation of sound pressure levels with climatic conditions and altitude was performed. Standard atmospheric conditions, outlined in MIL-STD-210A, were used for the purposes of this analysis. The study concluded that the multiple pure tone sound pressure levels remain significant to altitudes up to 8000 feet and the blade passage sound pressure levels remain meaningful to 12,000 feet. Using these altitude criteria and examining the A-10 mission profiles, the percentage of total flight time the aircraft operates within the severe excitation range of the two environments was determined. For the multiple pure tone excitation, the duty cycle equated to 10.2 percent of the total flight time, whereas the blade passage regime duty cycle was 22.9 percent of total flight time. The effects of these environments and duty cycles were further explored through finite element analysis and laboratory testing of the baseline structure.

An MSC/NASTRAN finite element model of the baseline design inlet ring was developed to determine the normal modes and response of the baseline structure. The two frequency regimes identified through the engine ground run test provided the bounds for this analysis. However, the frequency ranges used for analysis were somewhat narrower than the ranges over which maximum sound pressure levels were identified during the engine ground run test. Accelerometers mounted on the forward angle stiffener during this test showed significant response of this region between 800 and 1200 Hertz and also between 2800 and 3000 Hertz. Since this vibration was surmised to be the primary cause of the structural failures, the bandwidths used for analysis were decreased accordingly. Typical deformed shapes of this structure in the multiple pure tone and blade passage frequency bands are shown in Figures 6 and 7 respectively. Examination of these plots reveals the rocking and bending of the forward angle stiffener which causes rivet failure in this region. Because the excitation environments span the frequency ranges of 800-1200 Hertz and 2800-3000 Hertz, simply determining the stress associated with the inlet ring response at a single frequency does not fully characterize the stresses developed in the structure. In order to assess the stress generated by the random response of the inlet ring, Baranek[5] suggests the use of a root sum squared combination of the stresses determined from each individual mode. The difference in bandwidths of the two frequency regimes was taken into account by using an

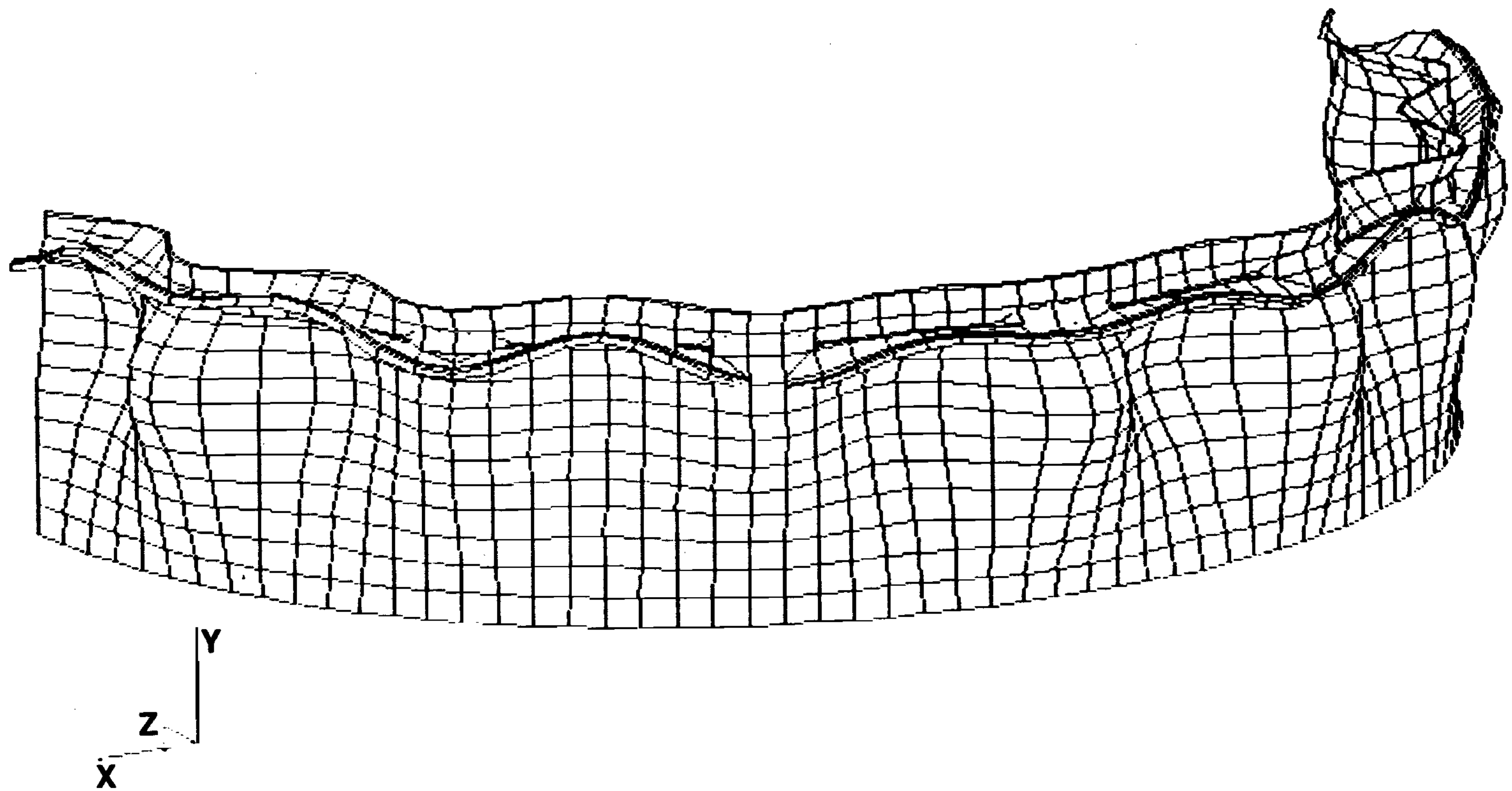

Figure 6 - Typical Deformed Shape Plot of the Baseline Finite Element Model in an 800-1200 Hz Environment

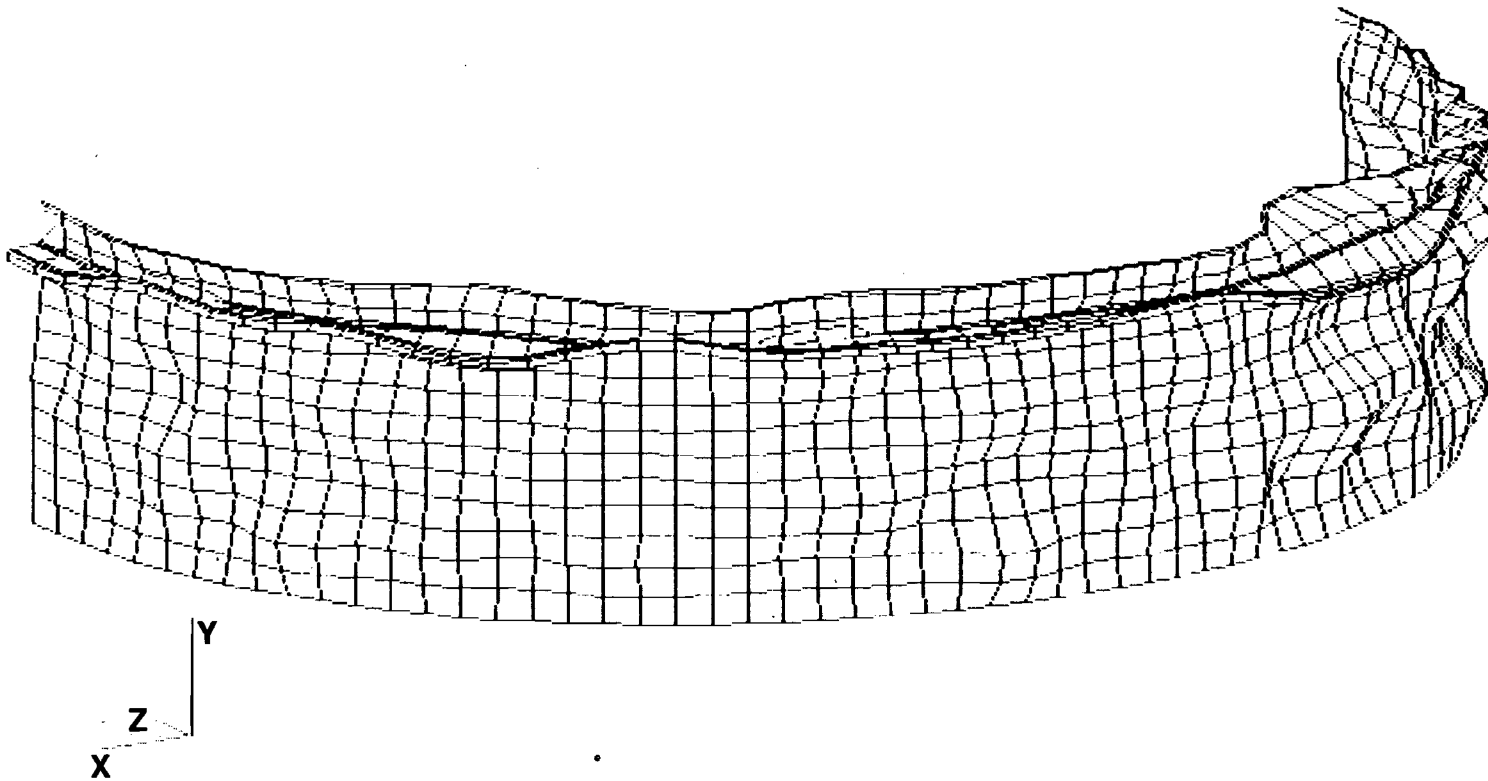

Figure 7 - Typical Deformed Shape Plot of the Baseline Finite Element Model in a 2800-3000 Hz Environment

equal number of the most severe modes from each bandwidth in this calculation. Upon calculating an equivalent stress for the frequency range, a constitutive relationship, derived from reference 6 for high cycle fatigue of monolithic aluminum, was applied to determine the life of various discrete structural elements of the baseline inlet ring. Applying the duty cycle information obtained previously yielded theoretical flight times to failure.

The results of the sonic stress analysis identified the rivets attaching the forward angle stiffener to the inlet skin as the most highly stressed region of the baseline inlet ring. Subsequent fatigue analysis, using the high cycle stress-life relationship described previously and Miner's Rule of cumulative damage, established a rivet life of 21.6 flight hours with the multiple pure tone environment contributing 99.8 percent of the fatigue damage. The significance of the multiple pure tone contribution based on analysis, coupled with the magnitude of the response witnessed during the engine ground run test, combine to substantiate this environment as the dominant fatigue mechanism. A good correlation between measured inlet ring response, and the response obtained through finite element analysis, served to further reinforce this hypothesis.

To substantiate the importance of the multiple pure tone regime in contributing to the failure of the baseline component, a series of laboratory tests were initiated. A modal analysis was performed on the baseline inlet ring to determine the modes of the actual structure and evaluate how these modes compare with those determined though finite element analysis. The inlet ring was mounted in a progressive wave tube and subjected to burst random excitation generated by two electro-pneumatic transducers attached to the front of the wave tube. This test setup is shown in Figure 8. A roving accelerometer was used to evaluate the response of the inlet ring at various points around its circumference. The data recorded from the roving accelerometer was then fed into a fast Fourier modal analyzer to determine the resonant modes of the structure. The structural modes of the baseline inlet ring were in good agreement with those established in the finite element analysis. Upon completion of the modal analysis testing, a sine sweep was performed. Since the duplication of the multiple pure tone environment required the use of a random excitation, and because the electro-pneumatic transducers could not produce this environment at sufficient sound pressure levels to duplicate the levels realized in service, a 45° section of the inlet ring was removed and mounted to an electro-dynamic shaker. Figure 9 illustrates this installation. A 45° segment was chosen as a result of the mode shapes of the structure identified from modal analysis. This segment provided a minimum of two wave lengths at the lowest frequencies, thus eliminating any adverse effects to the local structural response due to the clamped boundaries.

Sine sweeps of the segment confirmed the correlation of the response between the segment and the complete inlet ring. Validation of the similarity of the response led the way for the initiation of fatigue testing which duplicated the multiple pure tone environment. Dwell fatigue testing was initiated at 40g RMS in a bandwidth from 800-1500 Hz. The first rivet failure occurred after approximately 20 minutes of dwell testing. Total failure of the segment forward angle stiffener to skin joint was accomplished after 11 hours of dwell. When extrapolated to

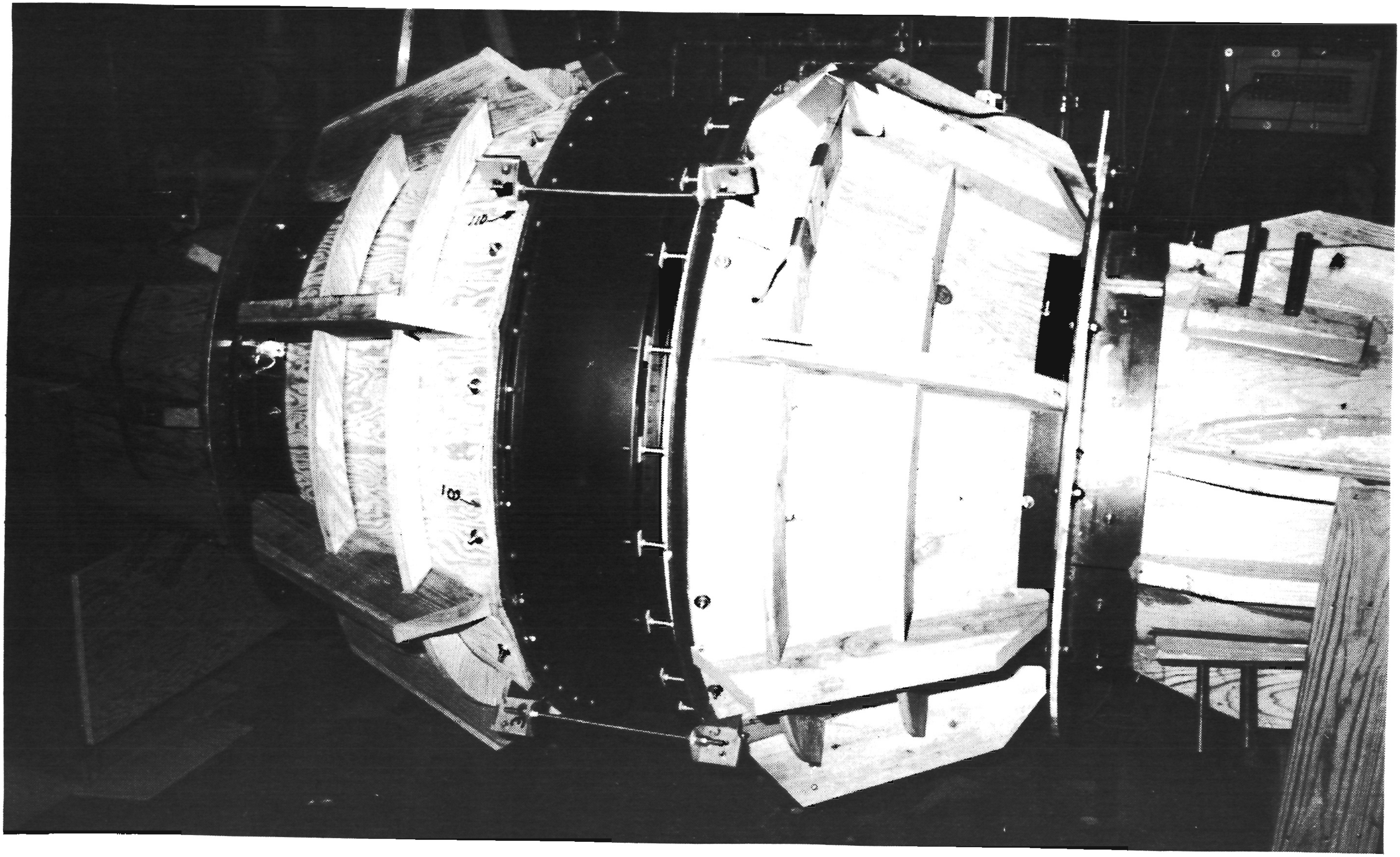

Figure 8 - Baseline Inlet Ring Installed in a Progressive Wave Tube

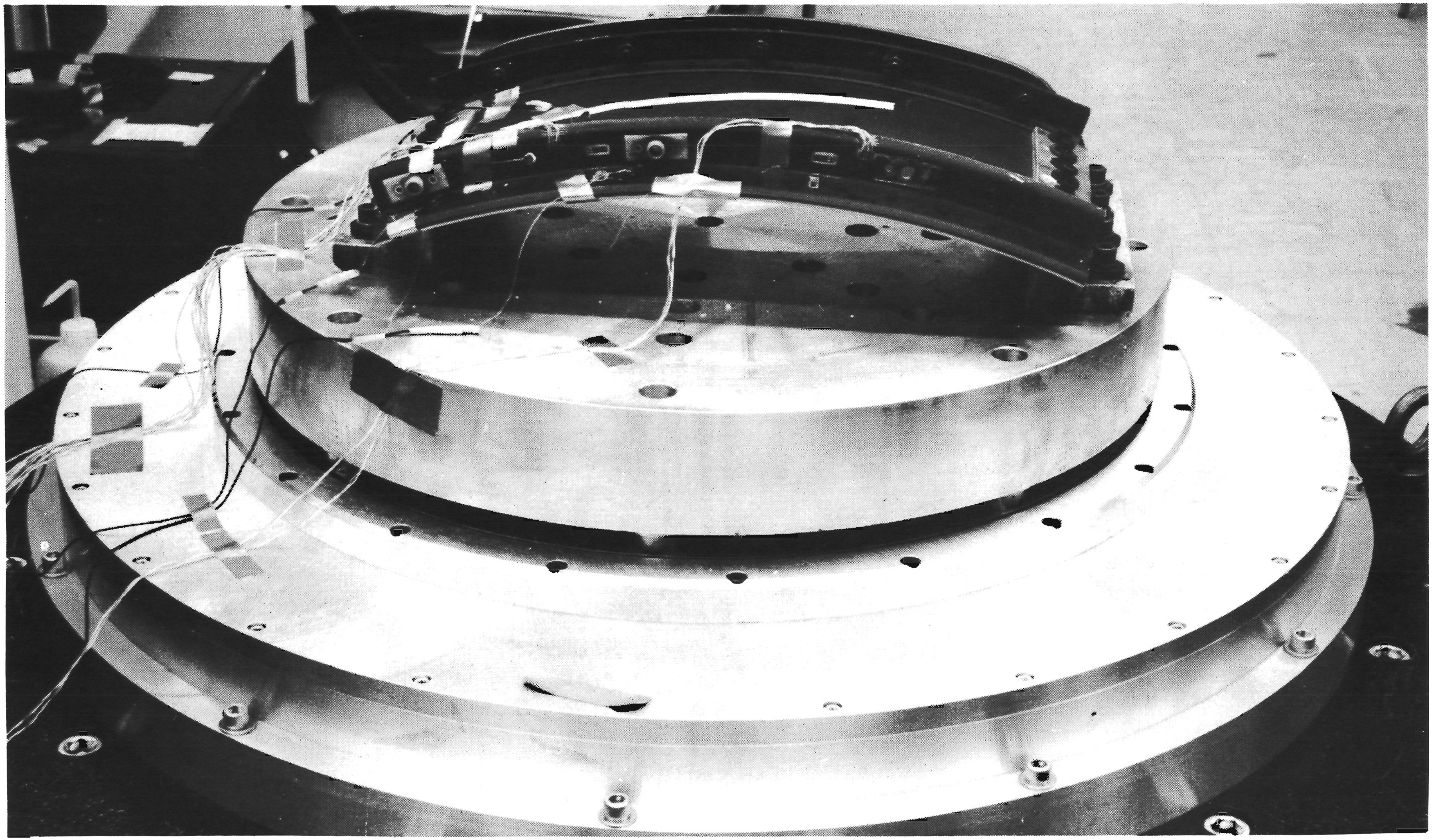

Figure 9 - Baseline Inlet Ring Segment Mounted to an Electro-Dynamic Shaker

flight times based on duty cycle, the failures that occurred in the laboratory testing were within the range of the failure times reported by Air Force maintenance personnel. By establishing the correlation between analysis, testing, and service experience, the foundation had been established for the design criteria, as well as providing a direct standard of comparison between the baseline and advanced designs during both analysis and test.

DESIGN DEVELOPMENT

Based on the environments identified when establishing the design criteria, the advanced inlet ring had to be designed to withstand a severe acoustic excitation. Guidelines utilized in the design of a structure subjected to high intensity acoustic excitation include providing continuous load paths, avoiding stiffness discontinuities, and incorporating structural damping where necessary. Many of the failures of the baseline inlet ring were the result of not adhering to these basic acoustic fatigue design principals. Therefore, other than the dimensional envelope dictated by the installation, the advanced inlet ring required a complete re-design. Some add-on fixes are available to provide acoustic fatigue resistance, but none of these treatments could remedy the inherent deficiencies of the baseline inlet ring. The elements of the baseline design which were eliminated from the advanced inlet ring include: 1) the riveted forward ring attachment, 2) the discontinuous splice configuration, and 3) the discrete spring elements. Improvements were also necessary in the area which forms a seal with the nacelle lip at the flexible forward interface. The design configuration created to satisfy these criteria is depicted in Figure 10.

Examining this cross-section reveals the elimination of the of the rivets at the forward flange by incorporating this element into the inlet skin. The discrete spring elements were replaced by a continuous elastomer spring which serves to evenly distribute the compression load when installed in an aircraft, as well as effecting a seal around the circumference. Figure 11 illustrates that by forming the nine individual skin plies simultaneously, and staggering the location at which each ply terminates, a continuous, spliceless skin can be produced. The laminated skin also serves as a method by which damping can be incorporated into the design. 3M's AF-32, a viscoelastic, nitrile phenolic adhesive, with proven damping properties, was used in this manner. Additionally, while no problems were recognized with the aft angle stiffener, its attachment method was modified to incorporate a rivet-bond procedure. The adhesive bond in this interface serves to provide a continuous path for load transfer and effectively reduces the stress concentration normally associated with a conventional riveted joint. This characteristic has proven to be especially advantageous on previous LTV programs, for detail attachment in structures subjected to severe acoustic excitation. Since the adhesive is the primary load carrying component of the joint, the number of rivets used in the aft ring attachment were reduced from the quantity used in the baseline inlet ring.

Upon completing the design development based upon the acoustic fatigue design practices outlined previously, analysis of the advanced inlet ring was initiated. The establishment of the baseline finite element model,

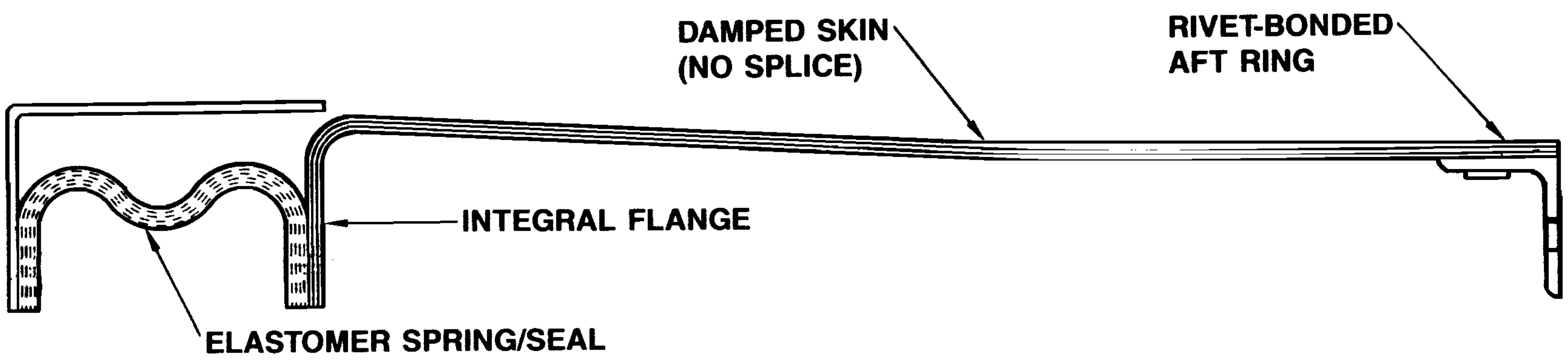

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Figure 10 - Advanced Design Inlet Ring Cross-Section

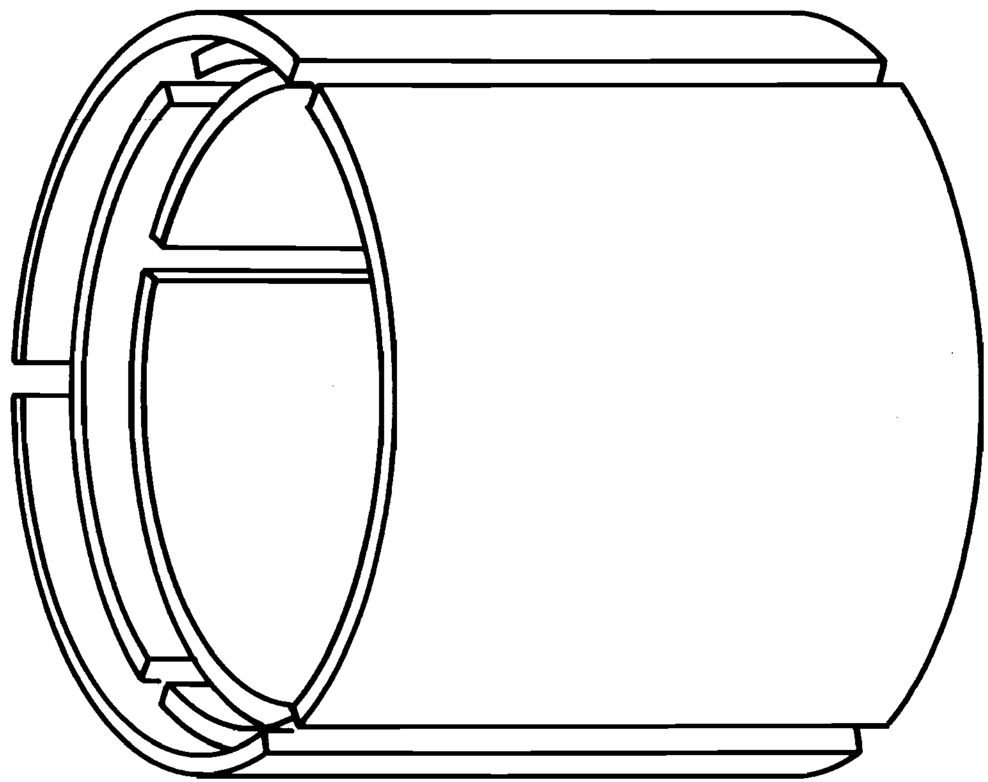

Figure 11 - Schematic of the Ply Nesting used in Production of the Advanced Inlet Ring Skin

with the results substantiated through laboratory and field test, provided the ground work for an advanced design finite element model which utilized similar assumptions. Consequently, the relative durabilities of the two components could be assessed prior to hardware production. An MSC/NASTRAN finite element model was constructed to evaluate the effects of the acoustic environment on the advanced inlet ring. Normal modes and response analyses were performed. Figure 12 illustrates a typical structural mode in the multiple pure tone frequency range and Figure 13 is indicative of modes occurring in the blade passage environment. Circumferential bending modes are also evident at the integral forward flange similar to those identified in the baseline inlet ring; however, the incorporation of damping reduces the stresses in this region to acceptable levels. The stress results from the frequency response analysis at discrete frequencies within the bandwidths of interest were combined using the same root sum squared procedure described for the baseline design analysis. The stresses which were identified in the various regions of the advanced inlet ring were, in all cases, much lower than those observed for the baseline design. Applying the same stress life relationship and duty cycle information utilized in the baseline design analysis, the projected total life, and life in flight hours based on duty cycle were obtained. This sonic fatigue analysis predicted a life greater than 6.9×10^5 flight hours for the advanced component.

The design development and analysis procedures were confirmed through segment and element testing of portions of the baseline and advanced design components. These tests provided a one-to-one durability comparison between the elements of each design before the advanced design inlet ring configuration was finalized and a full scale component produced. The tests also served to confirm analysis techniques and provide data where published data and analysis procedures were inadequate. The first of these series of tests compared the forward sections of each inlet ring design. Small straight sections representative of the forward ring area of both the baseline and advanced configurations were tested on an electro-dynamic shaker. The baseline segment exhibited rivet failure in three hours of dwell which was similar to those failures observed on the full scale baseline inlet ring. The advanced configuration was tested for the equivalent of 25 times that of the baseline segment, without failure, before the test was terminated. Acoustic test panels were used to confirm the advanced skin lap joint durability and compare that with the durability of the discrete splice plates used in the baseline design. The baseline panel, when mounted in a progressive wave tube and subjected to an acoustic environment, failed in four hours in a manner similar to that observed in inlet rings in service. The advanced panel was tested more than ten hours under the same environmental conditions without failure before testing was terminated. Other elements of the advanced design were tested simply to prove the proposed fabrication concept without a relevant comparison to the baseline inlet ring. These tests included the static and fatigue evaluation of the elastomer attachment method to the forward flange, and an abrasive wear test of a Teflon coating used to prevent metal-to-metal abrasion in the inlet skin radius.

The positive conclusions drawn from the development and analysis, combined with the confirmation of the design elements through segment and element testing, led the way for production of a full scale test component. The advanced inlet ring test article is shown in Figure 14. This inlet

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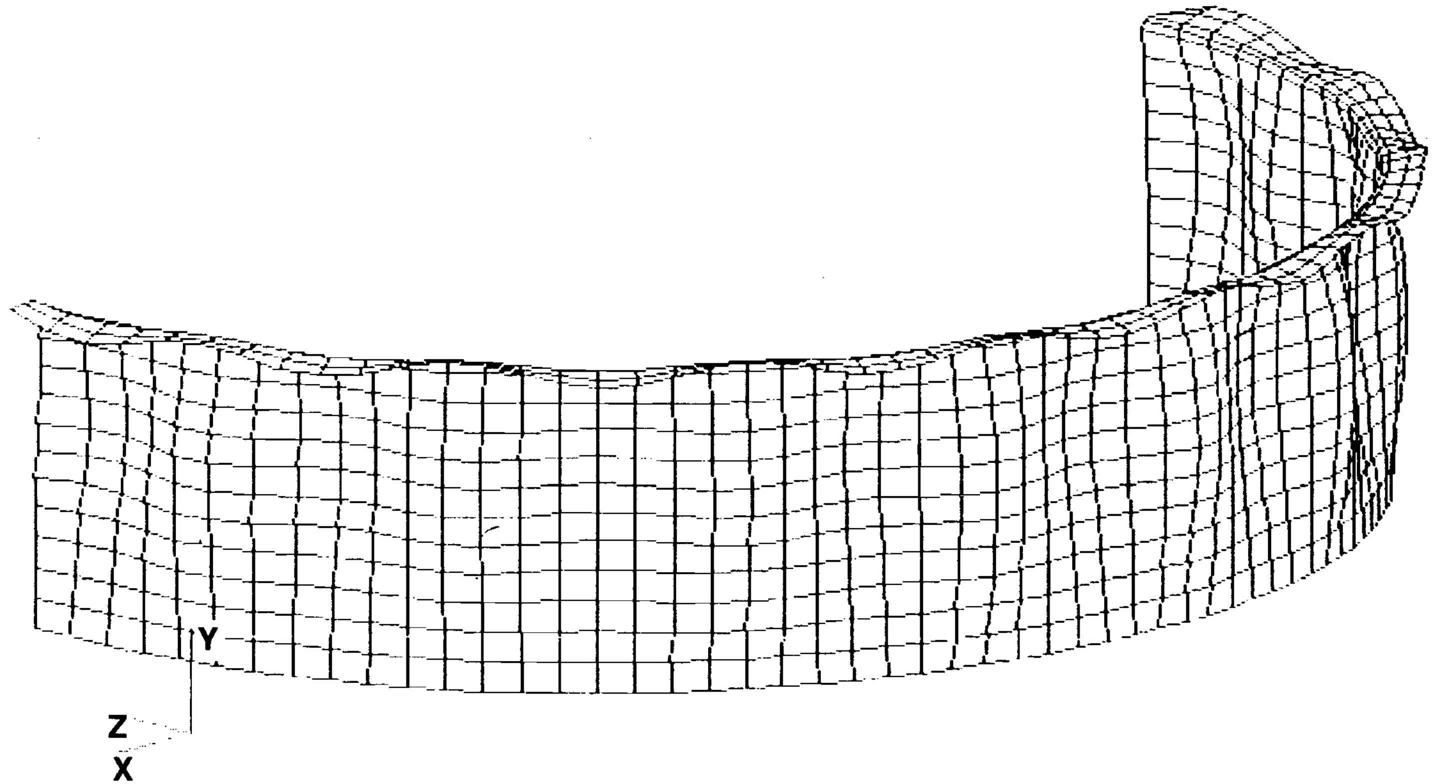

Figure 12 - Typical Deformed Shape Plot of the Advanced Finite Element Model in an 800-1200 Hz Environment

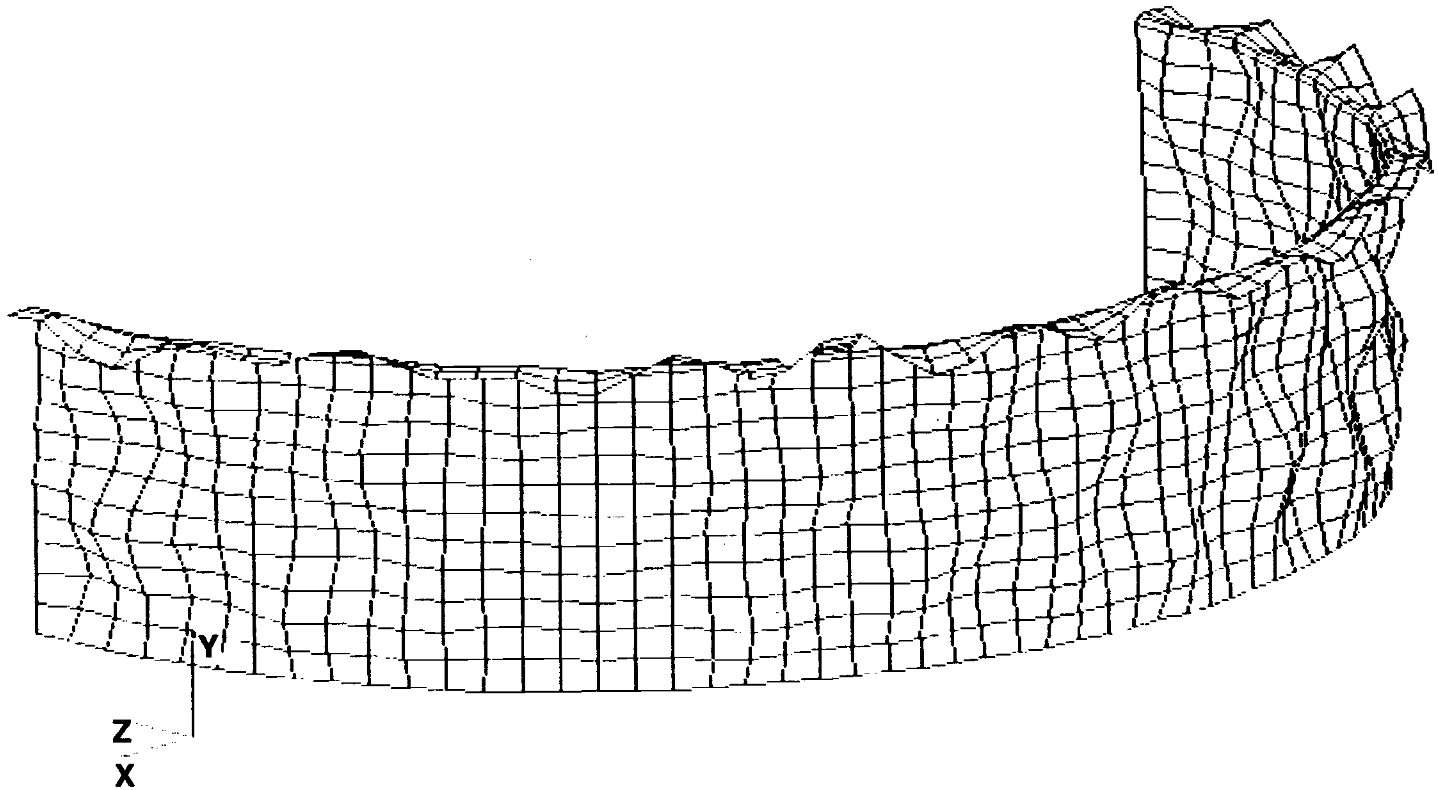

Figure 13 - Typical Deformed Shape Plot of the Advanced Finite Element Model in a 2800-3000 Hz Environment

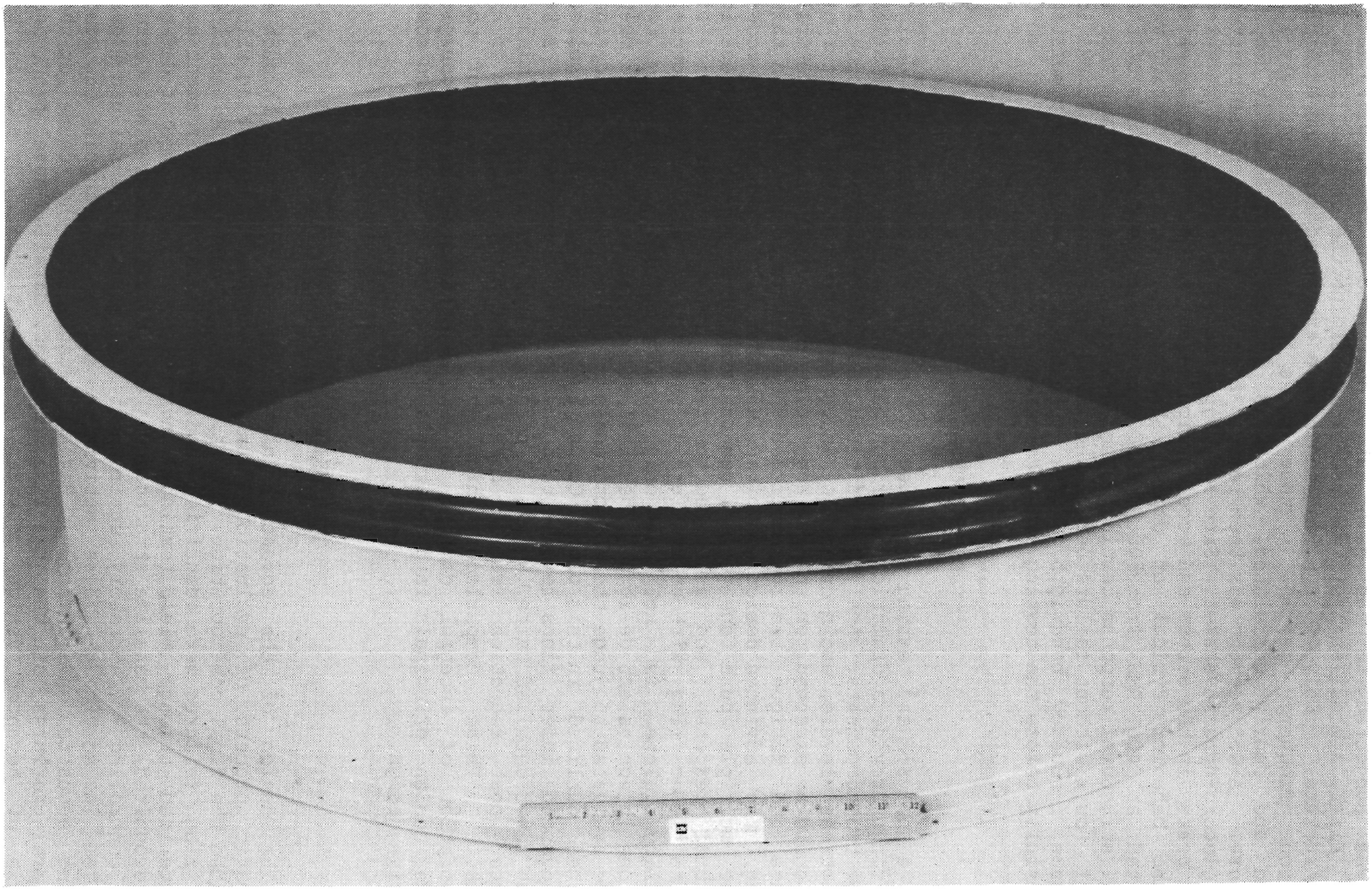

Figure 14 - Advanced Design Inlet Ring Test Article

ring was subjected to the same testing performed on the baseline inlet ring. First, a modal analysis was used to determine the resonant modes of the structure. Only four normal modes were extracted from the multiple pure tone frequency regime. Those modes that were obtained were ill defined and poorly correlated, which is indicative of a highly damped structure. A 45° segment was then removed from the inlet ring and mounted on an electro-dynamic shaker. Sine sweeps performed on this panel revealed broad peaks in the stress and acceleration versus frequency domain, which is also behavior typical of damped structure. Fatigue testing was initiated at 40g RMS from 800 to 1500 Hertz after the completion of the initial structural response testing. The advanced configuration was tested for 31 hours without failure before the level was increased to 50g RMS in the same frequency bandwidth. Six more hours of dwell were completed successfully before the testing was terminated.

DESIGN COMPARISON

The analysis and testing performed on the baseline and advanced design inlet rings provide a dramatic comparison between the relative durabilities of the two components. Analysis indicated that an 80 percent reduction in peak stress levels, and a durability increase of greater than a factor of 1000 could be expected for the advanced inlet ring. Full scale structural response and fatigue testing confirmed these predictions. Based on this testing, the advanced design exhibited less than half the number of modes in the multiple pure tone regime, demonstrated an 80 percent decrease in structural response, and was tested to greater than 500 times the life of baseline inlet ring without failure. As with any aircraft structure, durability alone is not the only consideration in assessing two functionally equivalent designs. The final structural weight and cost must also be evaluated to judge the effectiveness of the acoustic fatigue design practices outlined in this paper. Comparing these aspects of the baseline and advanced inlet rings reveals that the advanced component contains 86 percent fewer detailed parts, weighs 15 percent less, and has a preliminary projected cost reduction from the baseline inlet ring on the order of 25 percent. These comparisons highlight the effectiveness of the incorporation of integral damping as well as other other basic acoustic fatigue design principals in generating a lighter, more durable, and cost effective design.

CONCLUSION

The design of the advanced inlet ring was achieved through a systematic process of evaluation, analysis, design, and testing which validated the final configuration. First, potential causes of the baseline inlet ring failures were identified, and the installation environment was characterized through field testing. Once the potential causes of damage were recognized, the baseline structure was analytically modeled and tested in a controlled laboratory environment to confirm the failure modes exhibited in service. These activities served to pinpoint the most damaging acoustic environment. Having established the cause of the structural failures of the baseline component, detailed development and analysis of advanced design concepts were initiated. By adhering to acoustic fatigue design practices which suggest providing continuous load paths, avoiding stiffness discontinuities, and incorporating damping, a final advanced design configuration was achieved. The final step of the process involved applying the same testing used for the baseline design to the advanced inlet ring. Extensive laboratory testing validated the development and analysis of the final advanced inlet ring configuration. Using this approach, an inlet ring which has demonstrated durabilities in excess of 500 times greater than the baseline component while also reducing overall detailed part count and total structural weight was achieved. These factors are expected to contribute to a decrease in the life cycle cost, and an improvement in operational availability of Air Force fleet aircraft. Demonstrating this technology on smaller secondary structure should also lead to the realization that this technology is a viable alternative for application to larger primary aircraft structures subjected to high intensity acoustic environments.

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