A Full-Scale Structural Fatigue Test Program

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Test methods are described for an experimental fatigue evaluation of a full-scale airplane structure. Specific reference is made to a fatigue test program conducted on the Lockheed P3A wing and gear. A flight-by-flight test loading spectrum comprising 7500 flight hours was constructed to represent the total service experience of the airplane. In the construction of the spectrum, emphasis is directed to the air-ground-air transitions that are provided during a flight-by-flight simulation. Previous studies have shown that these large transitions adversely affect fatigue life. Loads, preprogramed on magnetic tape, were applied to the specimen by hydraulic jacks through a closed-loop electrohydraulic servo system. The program employed 51 servo channels to control the force output of 105 jacks. The test methods devised for this program provided an automated loading system that faithfully duplicated service conditions on the specimen in a relatively short test-time span with a small operating crew. The span for the P3A program was 20 weeks, operating on a three-shifts-per-day basis with a three-man test crew per shift. The methods described can be readily adaptable to supersonic aircraft testing.

Introduction

TODAY'S airplanes are designed for longer service lives and more severe operating conditions than ever before, resulting in significant increases in the number and severity of the cyclic loadings that contribute to fatigue damage. As a result, there has been an increased emphasis directed toward the various problems of fatigue and fatigue evaluation. Because of the complexity of the nature of fatigue, purely analytical solutions are in themselves not adequate to provide results that can be used with any acceptable degree of confidence. To supplement analytical evaluations, the trend has been toward greater reliance on full-scale fatigue tests that employ test spectra closely simulating service conditions.

Recognizing the need for the experimental approach it is imperative that methods and procedures are devised that duplicate service conditions on a test specimen accurately and expeditiously. Some of these methods and procedures are discussed in this paper. Specific reference is made to the P3A wing and main landing gear fatigue test program conducted recently at the Lockheed-California Company under the auspices of the Bureau of Naval Weapons. The development of the program is described from the selection of the loading spectrum to the methods and procedures employed in applying the spectrum to the test specimen. Emphasis is placed on the realistic flight-by-flight simulation and the degree of automation and resulting testing efficiencies that were attained.

Test Purpose

A fatigue test program on a full-scale specimen is the only effective means that can be employed to account for the true mechanical environment of an airframe structure. Such a test allows for the proper interaction of all of the structural components. In addition, an experimental program provides a realistic basis for the determination of in-service inspection and repair procedures.

The specific purpose of the P3A program was to demonstrate the fatigue characteristics of the wing and main landing gears under a simulated flight-by-flight loading spectrum that represented the planned service life of the model. A 7500-hr life representing approximately ten years of service was specified.

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Description of Test Specimen

The specimen is shown, installed in the test setup, in Fig. 1. The test specimen consisted of a structurally complete P3A production wing including flaps, nacelles, and main landing gears. The engines were omitted; however, the loads normally introduced into the wing by the engines were applied through special loading fixtures attached to the nacelles.

The wing integral tanks were filled with Stoddard's solvent, which served as the test fuel for the tank qualification tests that were conducted as part of the program. The solvent was dyed with an oil soluble blue aniline dye to aid in crack detection. The tanks were not pressurized.

The wing was mounted to a foreshortened section of a production fuselage that was used during a previous static test program. The use of the fuselage as a test fixture to support the wing assured the proper simulation of stiffness characteristics in the wing center section area. The reworked fuselage was supported at each end by steel fixtures mounted to floor tie-down rails. Test loads to the wing and gear were reacted at these end fixtures and by jack loads applied through straps cemented tangentially to the fuselage at various ring locations.

Development of Loading Spectrum

When carrying out an investigation of the potential service life of an airplane, it is imperative that the loadings to be considered reflect the types of service in which that particular model may be utilized. In order to represent adequately the total service experience of the model, it is necessary to combine the range of missions performed by this model and to assign to each type of mission a proper percentage of the total flight time.

Five types of operation were considered to cover the range of probable utilizations of P3A aircraft in service. These are the following:

1) Pilot training flights: Service conditions characteristic of pilot indoctrination were represented by this type of mission and comprised approximately 25% of the test spectrum.

2) Squadron operational flights: Normal anti-submarine warfare (ASW) operation is characteristic of this mission. Fifty-five percent of the test spectrum was allotted to loadings representing this mission.

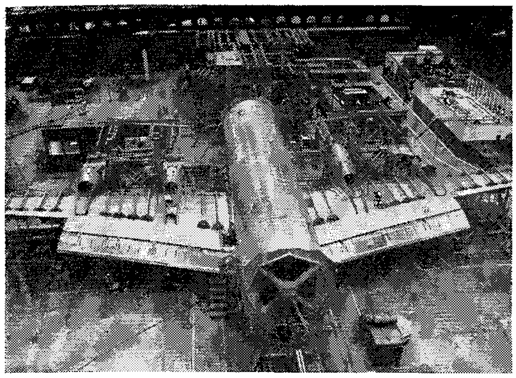

Fig. 1 General view, P3A fatigue test.

3) Long-range squadron operational flights: Ten percent of the test spectrum was allotted to this mission that supplies the critical loading conditions produced by high takeoff weights.

4) Practice mine laying flights: Five percent.

5) Demonstration mine laying flights: Five percent.

The gross weights, velocities, altitudes, and times applicable to each type of mission were employed in converting available spectra of external loadings to discrete sets of test loadings. The test spectrum, made up of loadings from the types of service operations listed previously, was applied to the test specimen on a flight-by-flight basis. In the past, it has been the practice to apply all of the loads of equal magnitudes to the specimen in blocks. Test programs employing this type of loading are relatively simple and economical to conduct. Because of long runs at constant load amplitudes, elaborate load control equipment is not required. Block-by-block loading is justified by linear cumulative damage theory, which does not restrict the order in which loads are applied to the specimen. However, recent investigations have shown that the order in which loads are applied does, in fact, affect fatigue damage. Therefore, to achieve a closer service simulation, a flight-by-flight loading schedule was specified for the P3A program. The desirability of a flight-by-flight simulation was borne out by a recent test program conducted at Lockheed and reported in Ref. 1, where data were obtained on notched material coupons. Test lives were obtained for a purely flight loading spectrum, purely ground loading spectrum, and for a ground-air-ground loading spectrum. Test lives were then obtained for various combinations of these loadings. It was shown that the test lives for the combined spectrum were much shorter than lives predicted (by linear cumulative fatigue damage theory) from individual loadings. These tests pointed out the importance of including in any

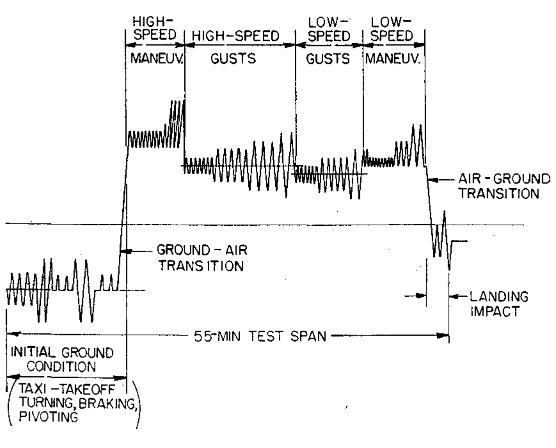

Fig. 2 Schematic representation of a typical test loading pattern, P3A wing gear fatigue test program.

fatigue evaluation the large transitions in loading that normally occur in service during each flight. The effects of these large transitions, specifically the ground-air-ground cycles, are automatically accounted for by a flight-by-flight loading sequence where the proper interaction between the spectrum loading severity and large transition loading severity is introduced.

The P3A specimen was subjected to a repeated load spectrum for 7500 hr of simulated flight represented by 2225 flights. A schematic of a typical flight pattern is shown in Fig. 2. Each flight was represented by ground conditions including a sequence of taxi, turning, braking, and pivoting loads followed by a transition to flight conditions that included the application of maneuver and gust loadings and finally a transition back-to-ground conditions during which a sequence of landing impact loadings were applied. A total of 24 loading conditions was represented in each flight. To account for the statistical growth in loading severity with the accumulation of flight hours, ten different flight patterns were employed. These flight patterns differed only in the number and size of the cyclic loadings within each condition. The ten flight patterns were applied in a scheduled sequence so as to simulate the loading history properly.

Test Loads

An essential feature to conducting a successful fatigue test program is the ability to apply loads to the specimen in such a way that they faithfully simulate the service loadings that were selected for the test spectrum. During the P3A program the specified loadings were duplicated on the specimen by applying test loads with hydraulic jacks through fixtures attached to the specimen at a discrete number of loading points. Wing loads were applied by the jacks through frames located at specific wing stations. The frames extended chordwise along the upper and lower wing surfaces and contacted the front and rear beams through felt-faced pads. The upper and lower frames were connected by rods passing through the leading and trailing edge structure of the wing. One pair of fore and aft jacks loaded four such frames whiffletreed together with up and/or down loads as required to produce the specified shears, moments, and torsions. These jacks were located at six loading stations along each wing half span. Additional test loads were applied to the specimen through fixtures attached to the flap, gear, and nacelle structure. Typical loading arrangements are shown in Figs. 3 and 4.

A computer program determined the magnitudes of the mean and maximum varying loads applied through each jack. The applied jack load produced an incremental shear, moment, and torsion effect along the wing span. The incremental effect of each jack combines to provide the over-all wing loading. These jack loads were the unknowns that had to be determined. It was possible to devise a number of equations relating individual jack loads to the desired shears, moments, and torsions at various stations along the wing. For the P3A program, 24 equations per wing half span were set up. The solution to these equations yield the required load for each jack. These equations were arranged in convenient matrix form:

$$[C]_{m,n}\,\{D\}_{n,1} = \{A\}_{m,1}$$

where $[C]$ is a matrix of coefficients (unity for the shear equations and distances for the moment and torsion equations); $\{D\}$ is a column matrix of the unknown jack loads; and $\{A\}$ is a column matrix of the specified shears, moments, and torsions.

This matrix equation was solved by the least squares method of solution of simultaneous equations which is a typical problem for a computer program. The solution yielded a set of individual jack loads that gave the "best possible" fit for the specified loading distribution. This procedure was employed for each of the 24 different loading conditions that comprised each flight. For all of the loading conditions, the dead weight of the test structure and loading fixtures were hydraulically counterbalanced.

Load Programing System

The load programing system for the fatigue tests was designed to provide accuracy and speed of testing. A hydraulic closed-loop electrohydraulic servo system consisting of servo valves, amplifiers, and load transducers, as shown in the schematic of Fig. 5, controlled load to each hydraulic jack (or group of jacks with identical loads).

Each "flight" of the simulated flight-by-flight loading was programed on multichannel magnetic tape. Ten different tapes were employed to simulate each of the ten different flight patterns. The program tapes were prepared by recording a preset series of sinusoidal and command pulse signals on each tape using a complex fatigue spectrum generator constructed especially for this type of program. This function generator provided the basic capability of producing the complex spectrum traces that were required to simulate service life adequately. On one channel of the tape, a.c. signals were recorded that provided the source for the required varying load. Simultaneously, command signals were recorded on a second channel of the tape. These signals activated stepping switches, which, in turn, selected the proper coefficient resistors to provide the desired d.c. voltage for each mean load and also to control the magnitude of the varying load.

Signals from the control tape programed the action of servo valves in metering cyclic flow of oil to the tension and compression ports of each jack. The feedback signal to the controller was supplied by a load cell mounted in series with each jack. The instantaneous summing of the command and load cell signals created the error signal which drove the servo valve.

The programing system was designed to provide safeguard against inadvertent overloading because of possible system malfunctions. The error signal that drove the system normally did not exceed 2% of the full-scale range of the load cell. However, the load programer was equipped with two error monitors to detect any occasional system errors that did exceed 2%. The first error monitor merely indicated that an error signal of over 4% was present so that corrective action could be taken. The second error monitor became effective whenever the error signal exceeded 10%. When this occurred, relays were de-energized to activate the normally closed solenoid valves resulting in a lockup of all of the loading jacks. The solenoid valves responded (i.e., closed) within 40 to 60 msec after the solenoid coil voltage was removed. The system was locked up (i.e., the hydraulic jacks maintained their load) rather than unloaded so as to prevent structural damage to the wing that could occur during a sudden reduction of load and to prevent the application of unscheduled load cycles.

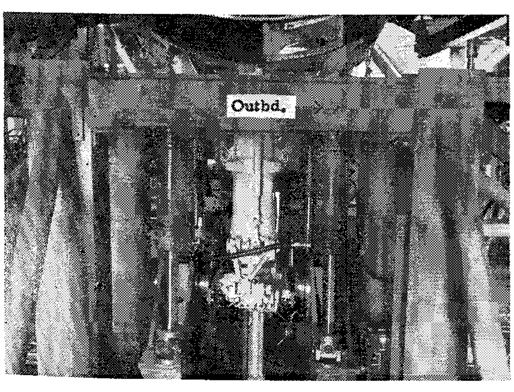

Fig. 3 Gear loading fixture.

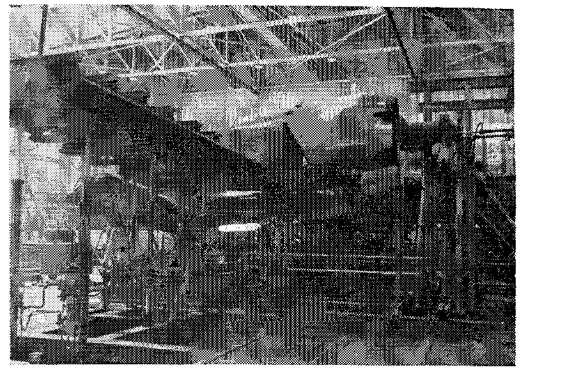

Fig. 4 Wing, flap, and nacelle loading fixtures.

It should be noted that the error detectors sensed error in instantaneous load amplitude over each complete loading cycle rather than error in peak load amplitude alone. To act as a back-up safety system, pressure relief valves in the hydraulic system were set to relieve at pressures slightly above the maximum pressures programed for each jack. There were 51 servo channels in all (as described previously) to control the force output of 105 hydraulic jacks.

The system was capable of instantaneously affecting frequency changes during each "flight." The applied loading frequency ranged from 2 to 19 cycles/min, depending on the particular magnitude or load being applied. These loading rates were a function of the equipment loading capacity only and were not related to service loading frequencies.

Extensive use of strain gages was employed during the program. Axial, shear, and rosette-type gages measured strains in potentially high stress areas of the wing, nacelle, and gear. These gages were selectively monitored at approximately 220 "flight" intervals during the program in order to detect possible changes in strain distribution under the programed loading.

Test Operation

The load control system for the P3A fatigue program performed two very important functions required of such a system. First, it provided a faithful duplication of service conditions to the specimen by the use of a flight-by-flight loading spectrum. Second, and equally as important, this system enabled the simulated life program to be completed in a relatively short time span with a small test crew. The P3A wing and gear tests, operating 24 hr/day five days per week, were conducted in 20 weeks (exclusive of shutdowns because of specimen damage and subsequent repair). The test crew for each 8-hr work shift included two engineers and one shop mechanic. In addition to the test crew, a program engineer

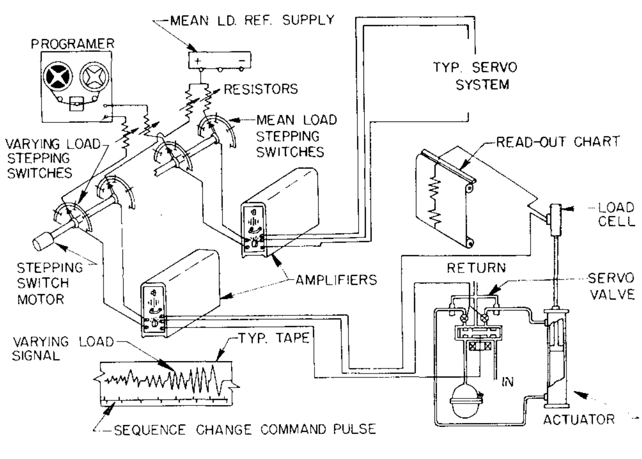

Fig. 5 Schematic of loading system.

was assigned to coordinate the various phases of the program, and other engineering and shop personnel were employed as required to perform any necessary equipment maintenance. On the average, a 13-man work crew was required to direct, conduct, and maintain the program over the 20-week test span. Each simulated "flight," representing a $3\frac{1}{3}$-hr mission, was applied to the specimen in approximately 55 min. Continuous test operation was possible through the use of dual tape consoles, each provided with a programed flight tape. The final landing sequence of one "flight" was immediately followed by the initial ground takeoff sequence of the next "flight" simply by switching over to the appropriate tape. A maximum of 130 simulated flights were applied each week.

There were no shutdowns scheduled during the week except for an extensive recalibration of the loading system which was carried out prior to "going on the air" each Monday. During any extensive shutdown periods, when the electrical and hydraulic systems were deactivated, the wing was supported in cradles, thereby preventing the introduction of large fictitious "air-ground" transitions.

Inspection Procedures

The test specimen was kept under general visual observation throughout the test program. In addition, detailed visual inspections of accessible areas were performed at 100 flight intervals. In areas where fatigue damage was suspected, specialized inspection methods were employed. These included x ray, dye and fluorescent penetrants, and ultrasonic pulse echo techniques. The blue-dyed test fuel used for the tank qualification tests proved to be an invaluable visual aid in the early detection of fatigue cracks in the wing tank areas. Fuel leaks would show in the area where cracks had extended through the skin. The dye would leave a stain on the skin surface that was readily discernible to the eye. Subsequent to the 7500-hr program, a final comprehensive inspection of the test article was performed employing all of the available inspection techniques.

These inspections have provided a valuable basis for fleet operation inspection and repair procedures. Information obtained from the test has been supplied as to the types and areas of damage that may be anticipated during service, thereby enabling suitable corrective action to be planned well in advance of their occurrence.

General Comments

A full-scale test program is the most effective way to insure a safe fatigue life in aircraft structures. Analytical analyses provide a sound basis for the design of a structure. They cannot, however, assure a safe service life for the structure.

Methods and procedures have been developed for the P3A wing and fatigue program that provided accurate means of simulating the fatigue effects of service conditions on the test specimen in a relatively short time span. The loads were applied to the specimen closely simulating the manner that they occur in service, namely, on a flight-by-flight basis.

It is felt that, in spite of the added complexities that will be introduced, tomorrow's supersonic aircraft can be tested equally as well, employing similar methods and procedures. No basically new test methods and procedures will be required to conduct these programs. However, current testing techniques will have to be re-evaluated in the light of the latest "state-of-the-art" experience, expanded, and further developed to handle the specific requirements that will be imposed during these tests. Additional tests parameters, such as elevated temperature levels and gradients, heating and cooling rates, fuel management, and cabin and tank pressurization, can be incorporated employing a programing system similar to the system described here to program loads. The full-scale fatigue test program is a vital step in the development of the airframe structure. How well such a program is planned and conducted will determine to a great extent the adequacy of the structure in service. Therefore, the challenge to the test engineer is to assure that as high a degree of simulation is obtained as is technically feasible.

Reference

[1] McCulloch, A. J. et al., "Investigation of the representation of aircraft service loadings in fatigue tests," Aeronautical Systems Division TR-61-435 (1961).