FBR 7898

AFFDL-TM-78-1-FBE

AIR FORCE FLIGHT DYNAMICS LABORATORY
DIRECTOR OF SCIENCE & TECHNOLOGY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OHIO

INDIVIDUAL AIRCRAFT TRACKING METHODS FOR FIGHTER AIRCRAFT UTILIZING COUNTING ACCELEROMETER DATA

Terry D. Gray

January 1978

RETURN TO: AEROSPACE STRUCTURES
INFORMATION AND ANALYSIS CENTER
AFFDL/FBR
WPAFB, OHIO 45433

Approved for public release; distribution unlimited

Reproduced From
Best Available Copy

20000111 075

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Approved for public release; distribution unlimited.

This technical report has been reviewed and is approved for publication.

TERRY D. GRAY

TERRY D. GRAY
Project Engineer

R.M. Bader

ROBERT M. BADER, Chief
Structural Integrity Br

Frank D. Adams

FRANK D. ADAMS, Tech Mgr
Fatigue, Fracture & Reliability Gp

RETURN TO: AEROSPACE STRUCTURES
INFORMATION AND ANALYSIS CENTER
AFFDL/FBR
WPAFB, OHIO 45433

Copies of this report should not be returned unless return is required by security considerations, contractual obligations or notice on a specific document.

FOREWORD

This document was prepared by Terry D. Gray of the Structural Integrity Branch, Structural Mechanics Division, Air Force Flight Dynamics Laboratory. The work was conducted in-house under Project 2401, "Structural Integrity for Military Aerospace Vehicles," Work Unit 24010109, "Life Analysis Methods." The research was conducted from November 1977 through January 1978.

ABSTRACT

This paper examines two individual aircraft tracking methods for tracking crack growth in fighter aircraft utilizing counting accelerometer data. Individual aircraft tracking programs were developed for the F-4 and A-7D aircraft in conjunction with damage tolerance assessment programs conducted for these aircraft. Both the F-4 and A-7D tracking methods were based on existing counting accelerometer data acquisition systems. The F-4 tracking method utilizes an equivalent S-N curve system to calculate a damage index at a monitoring location. The A-7D tracking method utilizes regression analysis to calculate equivalent baseline hours expended at a monitoring location. Both methods then relate damage at the monitoring location to damage at other critical structural locations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION

Maintaining the strength, rigidity, damage tolerance, and durability of USAF aircraft structures is dependent on the capability of the appropriate Air Force Commands to perform specific inspection, maintenance, and possibly modification or replacement tasks at specific intervals throughout the service life (i.e., at specified depot or base level maintenance times and special inspection periods). Experience has shown that the actual usage of military airplanes may differ significantly from the usage assumed during design. Likewise, individual aircraft within a force may experience a widely varied pattern of usage severity as compared to the average aircraft. Continual adjustments to initially determined safe crack growth intervals must be made for individual aircraft to ensure safety and to allow for modification and repair on a timely and economical basis.

Force management is the responsibility of the Air Force and is accomplished in accordance with the Force Management Tasks of MIL-STD-1530A [1] using a data package provided by the contractor for each new aircraft system. This data package consists of the necessary data acquisition and reduction techniques and analysis methods to acquire, evaluate, and utilize operational usage data to provide a continual update of in-service structural integrity.

A basic element of the force management data package is the Individual Aircraft Tracking (IAT) program. The objective of the IAT program is to predict potential flaw growth in critical areas of each airframe based on individual aircraft usage data. A tracking analysis method is developed to establish and adjust inspection and repair intervals for each critical structural location of the airframe. This analysis provides the capability to predict crack growth rates, time to reach crack size limits, and crack length as a function of total flight time and usage data. A data acquisition system is developed which is as simple as possible and is the minimum required to monitor those parameters necessary to support the tracking analysis method. The IAT program provides data to derive individual maintenance (inspection and repair) times for each aircraft.

For existing Air Force aircraft, damage tolerance assessment (DTA) programs have been and are currently being conducted. The objectives of these programs are to define operational limits and to provide any necessary modification or operational usage options. The operational limits include: (1) economic repair limits which specify the opportune time for repairs and modifications before such repairs and modifications become uneconomical; (2) inspection intervals which provide the opportune time for detecting damage by NDI techniques before the damage reaches critical proportions; and (3) fracture limits which specify the time at which aircraft failure potential is believed to exist if no inspection and/or repair is accomplished. These analytically predicted operational limits are based on the assumption that initial flaws exist in the airframe at the time of manufacture and that these flaws will grow under operational usage.

As companion efforts to the F-4 and A-7D DTA programs, IAT programs for monitoring crack growth were developed. The purpose of this report is to examine the F-4 and the A-7D IAT methods.

SECTION 2

BACKGROUND

The first IAT program for tracking crack growth in fighter aircraft was developed in conjunction with the F/RF-4C/D damage tolerance assessment [2]. This was followed by similar programs for the F-4E(S) [3] and the A-7D [4,5]. The IAT concepts used for the F/RF-4C/D were extended for the F-4E(S) and were generalized and documented in a later Air Force study[6]. The F/RF-4C/D and F-4E(S) tracking concepts and those used for the A-7D provide the basis for this report. In the remainder of the report, the term F-4 shall be used when referring to F/RF-4C/D and F-4E(S) aircraft.

Both the F-4 and the A-7D have similar backgrounds in terms of previous recorded usage data. At the time of their respective DTA's, both aircraft forces were recording load factor exceedance data via counting accelerometers installed in each aircraft. Before the crack growth tracking programs were developed, this data was input to fatigue damage tracking programs.

The F-4 counting accelerometers are set to record n_z counts at 3,4,5, and 6 g's. Extrapolation techniques were used to determine n_z counts at 7 and 8 g's. Over 3.5 million hours of this counting accelerometer data were available for the F-4. In addition, over 40,000 hours of VGH data (airspeed, load factor, altitude) were available for developing baseline operational stress spectra.

The A-7D counting accelerometers are set to record n_z counts at 5,6,7, and 8 g's. Over 400,000 hours of A-7D counting accelerometer data were available. During the A-7D DTA, 1250 hours of multi-channel data (airspeed, load factor, altitude, gross weight, wing strain, horizontal tail strain, and vertical tail strain) were recorded to assist in developing baseline operational stress spectra.

SECTION 3

TRACKING ANALYSIS METHODOLOGY

Since the F-4 and A-7D forces were already fitted with counting accelerometers and there was a large amount of recorded n_z data available for both, the decision was made to develop the F-4 and A-7D IAT programs around the existing data acquisition systems and, therefore, to utilize n_z data recorded for each aircraft to predict potential crack growth. This, of course, had a large influence on the tracking analysis methods developed for the F-4 and the A-7D.

3.1 F-4 Tracking Analysis Method

The "damage index and equivalent S-N curve" system was developed for the F-4 to simplify the crack growth tracking process. Instead of a cycle-by-cycle crack growth analysis being conducted for each critical location of each individual aircraft, only one number (the damage index), is computed for each aircraft based on individual usage. Through the damage index, crack growth at one location (the monitoring location), is determined. The amount of crack growth at other critical locations is evaluated by damage index limits that relate to the monitoring location.

3.1.1 Damage Index and Equivalent S-N Curves

Equivalent S-N curves are used to convert individual aircraft counting accelerometer data to a damage index for each airplane. These are not the standard S-N curves for fatigue which present stress versus number of cycles to failure for constant amplitude loading. These equivalent S-N curves represent flight-by-flight crack growth at the monitoring location and were developed from crack growth curves for three usages: mild, baseline, and severe (see figure 1).

To construct the equivalent S-N curves, crack growth testing was used to determine the percentage of total crack growth caused by each stress level in the flight-by-flight load history. Then knowing the percent crack growth of each stress level and the number of cycles of each stress level in the operational limit and establishing the damage index as 1.0 at the operational limit, the allowable counts at each stress level were determined. See References 2,3, and 6 for a more detailed description of S-N data development. Thus the equivalent S-N curves show the number of cycles at each stress level allowable or necessary to obtain a damage index of 1.0 which means that the operational limit of the monitoring location has been reached.

Tracking data consisting of n_z counts, flight hours, and tail number are received from field operations on a periodic basis, normally monthly. Actual flight hours are not used directly in the structural life calculations but are used for other maintenance considerations such as avionics and engines. The n_z counts are examined and grouped into one of three usage categories according to severity, Then, using the known stress-n_z relationship for the monitoring location. the number of counts or cycles of each stress level are determined. Note that these stress level counts are those experienced by a particular airplane in a particular time increment. These stress level counts are then divided by the allowable counts at each stress level and summed in a Miner's type analysis to compute damage index for a particular airplane.

$$\text{Damage Index} = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{1}$$

The relationship among the operational limit of the monitoring location, damage index, and flight hours may be understood by the following example. Assume that the operational limit of the monitoring location is 3900 hours of baseline spectrum usage. Using the equivalent S-N tracking analysis, if a given airplane were flown to the baseline spectrum for 3900 hours, the damage index of that airplane would be equal to 1.0. A second airplane flown to a spectrum more severe than the baseline would attain the same damage in a lower number of actual flight hours. The second airplane's damage index would also be equal to 1.0; i.e., it would have accrued the equivalent of 3900 baseline hours, but in a lower number of actual flight hours.

3.1.2 Damage Index Limits

Conversion of operational limits into damage index limits is required in order to be compatible with the damage index and equivalent S-N system and to evaluate crack growth damage at critical locations other than the monitoring location. As an example, assume that the operational limit for a monitoring location, Location A, is 3900 hours of baseline usage. This location is assigned a damage index limit of 1.0 (see figure 2).

The damage index limits for all other critical locations are equal to their baseline operational limits divided by the baseline operational limit of the monitoring location. Location B, with an operational limit of 7800 hours, would have a damage index limit of 2.0. The assumption inherent in this analysis is that when a given number of equivalent baseline hours has been expended at the monitoring location, the same number of equivalent baseline hours has been expended at all other critical locations. In the example, an airplane damage index of 0.5 would mean that 50% of the operational limit of Location A had been expended and 25% of the limit of Location B had been expended according to the simple equation

$$\text{\% Operational Limit Expended} = \frac{\text{Damage Index}}{\text{Damage Index Limit}} \qquad (2)$$

Note the difference between damage index and damage index limit. Damage index is the measure of damage accrued on an individual airplane and is calculated from equivalent S-N data. Damage index increases for a given airplane according to its individual usage. Damage index limit is a constant value and is associated with the operational limit for a specific critical location on the aircraft.

The linear relationship between damage at the monitoring location and damage at another critical location is valid only if the stress spectra at the two locations are both based on the same set of flight parameters. If the stress spectrum at one location is based on n_z and the stress spectrum at a second location is based on rolling acceleration, the crack growth damage cannot be ratioed from one location to the other without some further knowledge of the relationship between n_z and rolling acceleration. For the F-4, the stress spectra for all critical locations are all based on n_z, airspeed, altitude, and gross weight; therefore, ratioing damage from the monitoring location to other critical locations based on damage index limits is valid.

3.1.3 Accuracy

The accuracy of the damage index and equivalent S-N tracking analysis method was evaluated for several usage variations in Reference 6. This tracking analysis method is normally used only to predict percent operational limit expended; however, using the following equation developed in Reference 6, crack growth life may be predicted for the purpose of evaluating tracking analysis accuracy.

$$\text{Variation Life} = \frac{\text{Baseline Life} \bullet \text{Baseline D.I. per 1000 hrs}}{\text{Variation D.I. per 1000 hrs}} \qquad (3)$$

Table I presents life calculated using the damage index and equivalent S-N system and life calculated using standard crack growth analysis for several usage variations. The usage variations include two mission mix variations of the three F-4 missions: air-to-ground (A-G), air-to-air (A-A), and nontactical (N-T). Also included are two load factor exceedance variations in which a severe n_z curve is used in place of the baseline curve for the air-to-ground and the air-to-air missions. The last variation is actual counting accelerometer data from F-4E(S) SN 711072. The relative severity of each of these variations may be seen by comparing the variation life to the baseline spectrum usage life of 10,000 hours. From the small difference in calculated lives, it is evident that the damage index and equivalent S-N tracking analysis method is very accurate. Of course, the accuracy shown in Table I would most likely decrease for a larger range of variations or when comparing to test data.

3.2 A-7D Tracking Analysis Method

The A-7D tracking analysis method utilizes regression analysis to relate n_z counts directly to crack growth at a monitoring location. Equivalent baseline hours are determined, leading directly to the calculation of a damage index which is applied to the other critical locations. As in the F-4 method, only one damage calculation per aircraft is made, thereby greatly simplifying the crack growth tracking process.

3.2.1 Regression Analysis

The first step in developing the A-7D tracking analysis method was to derive a regression equation for time to a crack size limit at the monitoring location as a function of n_z counts. The time to crack size limit is, in effect, the operational limit of the monitoring location. An equation of the form

$$t_{OL} = C_1 + C_2 N_{5g} + C_3 N_{6g} + C_4 N_{7g} + C_5 N_{8g} \tag{4}$$

was written for the operational limit as a function of the number of n_z counts at 5, 6, 7, and 8 g's (normalized to 1000 hours) which are being recorded by the counting accelerometer in each airplane. Then crack growth curves and operational limits for a number of mission mix and load factor exceedance variations were determined through crack growth analysis and testing. The variations used in these crack growth studies were chosen so as to encompass the usage variation expected over the entire force of aircraft. A multiple linear regression analysis was then done to obtain the values of the constants C_i in Equation 4.

3.2.2 Equivalent Baseline Flight Hours and Damage Index

The crack growth curves, crack length versus flight hours, from the usage variation studies were plotted as a function of non-dimensional time $t^* = t/t_{OL}$ and were found to all fall on top of one another. Therefore, the following relationship is true:

$$t_{AC}/t_{OLAC} = t_{BL}/t_{OLBL} \tag{5}$$

where t_{AC} = individual aircraft flight hours

t_{BL} = equivalent baseline flight hours

t_{OLAC} = operational limit for individual aircraft usage, calculated by Equation 4

t_{OLBL} = operational limit for baseline spectrum usage

Therefore, the number of equivalent baseline flight hours expended is

$$t_{BL} = \frac{t_{AC} \cdot t_{OLBL}}{t_{OLAC}} \tag{6}$$

Damage index for the A-7D was then defined as the number of equivalent baseline flight hours normalized to the A-7D service life of 4000 hours.

$$\text{D.I.} = \frac{t_{BL}}{4000} \tag{7}$$

The actual quantity being used to monitor crack growth damage is the number of equivalent baseline flight hours expended. A damage index for the A-7D was defined for two reasons: (1) as a convenient means of relating the number of equivalent baseline hours to service life, and (2) in order to be compatible with an ASIMIS computer program which uses damage index from the F-4 and the A-7D as inputs.

Tracking data consisting of n_z counts, flight hours, and tail number are received from field operations on a periodic basis, normally monthly. The n_z counts at each level are added to the previous counts to obtain a current composite usage for each airplane. The total current n_z counts are normalized to 1000 hours and substituted into Equation 4 to determine the operational limit of the monitoring location based on the current composite usage. This operational limit and the current total number of flight hours are substituted into Equation 6 to obtain the number of equivalent baseline flight hours expended at the monitoring location. Equation 7 is then used to determine damage index. Figure 3 is a schematic of this process.

3.2.3 Damage at Other Critical Structural Locations

As in the F-4 method, the assumption is made in the A-7D tracking analysis method that when a given number of equivalent baseline hours has been expended at the monitoring location, this same number of equivalent baseline hours has been expended at all other critical structural locations. Maintenance actions are taken when the number of equivalent baseline hours expended equals the baseline usage operational limit of a particular critical location. In terms of the damage index, maintenance actions are taken when the airplane damage index equals a damage index corresponding to the baseline usage operational limit of the particular location. This is, in effect, the same as converting operational limits into damage index limits and relating damage at each critical location to damage at the monitoring location using Equation 2, although the term "damage index limit" is not used in the A-7D method.

3.2.4 Accuracy

The accuracy of the A-7D tracking analysis method was evaluated in Reference 5 by using Equation 4 to predict crack growth life at the monitoring location for several usage variations and comparing the results to actual crack growth analysis and test. Table 2 presents a representative sample of the results of this comparison. Included in the usage variations are two mission mix variations of the air-to-ground mission, the air-to-air mission, and the general mission (GM). Also included are the average base n_z spectra from recorded data for two bases. The last variation is counting accelerometer data from A-7D SN 701003. The relative severity of each of these variations may be seen by comparing the variation life to the baseline spectrum usage life of 12,200 hours. The results shown in Table 2 are representative of the accuracy of the A-7D method with one exception; one of the average base n_z spectrum variations reported in Reference 5 but not shown here produced an unexplained 27% difference in life between tracking analysis and test. Since there was only a single test, it is difficult to pinpoint the problem as either test scatter or analysis capability. In general, the A-7D tracking analysis method is very accurate when compared to both crack growth analysis and test.

SECTION 4

CONCLUSIONS

Two IAT methods for tracking crack growth in fighter aircraft utilizing counting accelerometer data have been examined. The IAT programs for the F-4 and A-7D aircraft were developed in conjunction with damage tolerance assessment programs for the existing F-4 and A-7D forces. The F-4 and the A-7D tracking analysis methods were developed from similar backgrounds in terms of previous recorded usage data. Both aircraft forces had large amounts of counting accelerometer data available when IAT development was begun. This fact had considerable influence on the tracking concepts developed.

Both the F-4 and the A-7D tracking methods compute crack growth damage at one location, the monitoring location, and then relate this damage to damage at all other critical locations. The assumption common to both methods is that when a given number of equivalent baseline hours has been expended at the monitoring location, this same number of equivalent baseline hours has been expended at all critical locations. The F-4 tracking analysis method calculates a damage index for each airplane. From damage index, equivalent baseline hours expended may be determined. The A-7D tracking analysis method calculates equivalent baseline hours expended for each airplane. From equivalent baseline hours expended, a damage index is determined. The F-4 method is an incremental approach in which damage index increases with each new increment of tracking data. The A-7D method bases equivalent baseline hours expended and damage index on the current total composite usage. Both methods are quite accurate for predicting the potential for crack growth based on individual aircraft counting accelerometer data.

Although these IAT methods were developed for the F-4 and A-7D aircraft and their existing counting accelerometer data acquisition systems, the concepts involved could be considered for other fighter aircraft forces. However, when selecting an IAT method, several variables must be considered: aircraft type and mission; number of aircraft in the force; usage severity and variability; and operational limits of critical locations. These variables must be evaluated and tradeoffs made between accuracy and cost before an optimum IAT method can be chosen.

REFERENCES

1. "Aircraft Structural Integrity Program, Airplane Requirements," MIL-STD-1530A, December 1975, Air Force Aeronautical Systems Division.

2. "Final Report, F/RF-4C/D Damage Tolerance and Life Assessment Study," Report No. MDCA2883, Vol. I, June 1974, McDonnell Aircraft Company.

3. "Model F-4E Slatted Airplane Fatigue and Damage Tolerance Assessment," Report No MDC A3390, Vol. I, July 1975, McDonnell Aircraft Company.

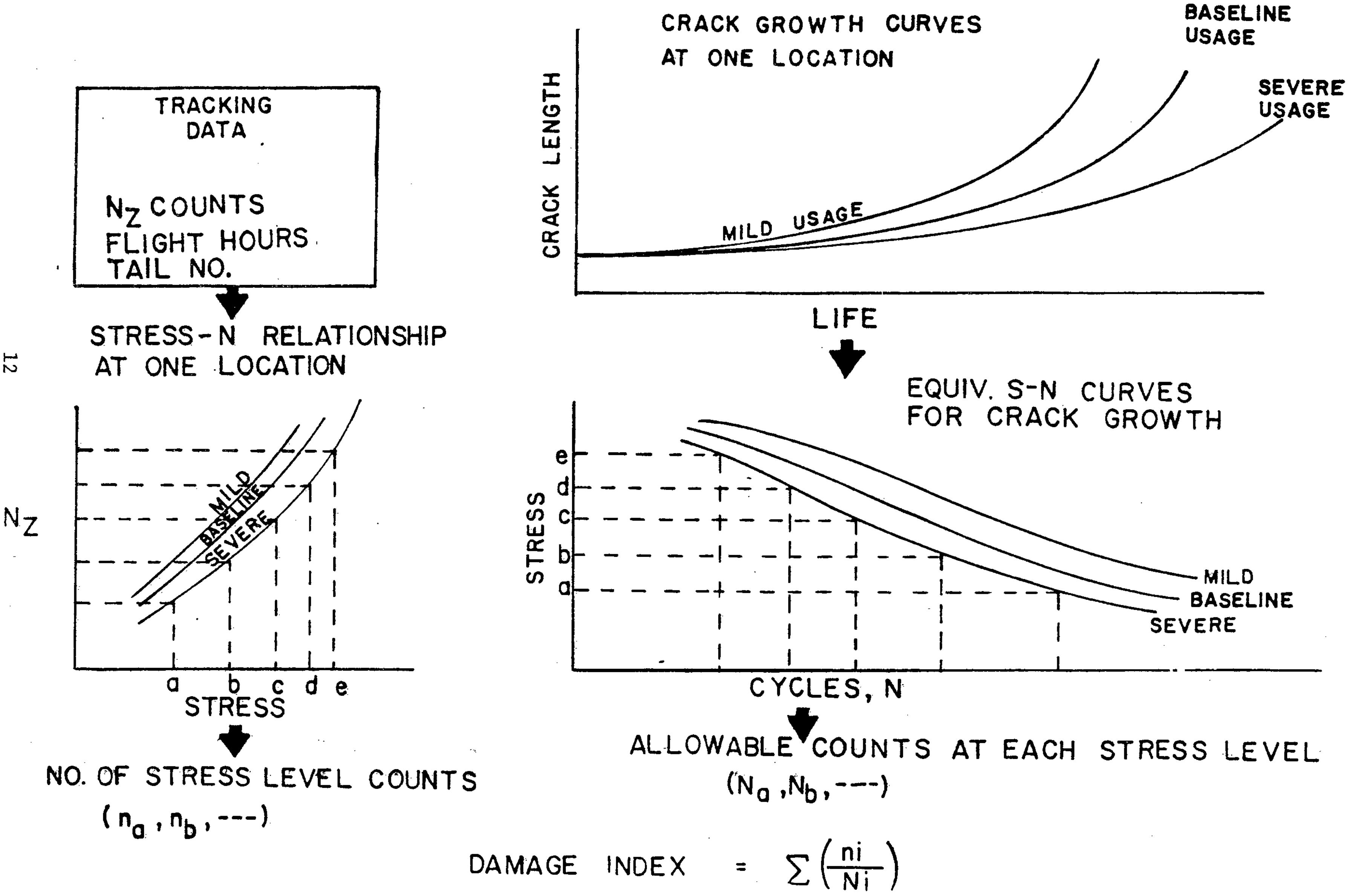
4. Dumesnil, C.E., Gratke, S.D., Wilson, R.P., Martin, C.P., White, D.J., and Hooks, O.L., "A-7D ASIP Part I, Damage Tolerance and Fatigue Assessment Program," Report No. 2 - 53440/7R-5928, Vol. I, January 1977, Vought Corporation.

5. Lauridia, R.R., "A-7D ASIP Part II, Flight Recorder Program," Report No. 2-53470/7R-5929, January 1977, Vought Corporation.

6. Parker, G.S., "Generalized Procedures for Tracking Crack Growth in Fighter Aircraft," AFFDL-TR-76-133, January 1977, Air Force Flight Dynamics Laboratory.

F-4 TRACKING ANALYSIS METHOD

DAMAGE INDEX AND EQUIVALENT S-N CURVE SYSTEM



$$\text{DAMAGE INDEX} = \sum\left(\frac{ni}{Ni}\right)$$

FIGURE 2
DAMAGE INDEX LIMITS

- OPERATIONAL LIMITS ARE CONVERTED INTO DAMAGE INDEX (D.I.) LIMITS TO BE COMPATIBLE WITH THE D.I. & EQUIVALENT S-N SYSTEM
- OPERATIONAL LIMIT FOR BASELINE SPECTRUM CRACK GROWTH AT MONITORING LOCATION IS GIVEN A D.I. LIMIT = 1.0
- AMOUNT OF CRACK GROWTH AT OTHER CRITICAL LOCATIONS IS EVALUATED BY D.I. LIMITS THAT RELATE TO MONITORING LOCATION

	LOCATION A (MONITORED)	LOCATION B
OPERATIONAL LIMIT	3900 hr	7800 hr
DAMAGE INDEX LIMIT	1.0	2.0
ASSUME AIRPLANE DAMAGE INDEX = 0.5		
PERCENT OF OPERATIONAL LIMIT EXPENDED	50 %	25 %

TABLE I

ACCURACY OF F-4 TRACKING ANALYSIS METHOD FOR SEVERAL USAGE VARIATIONS

VARIATION	LIFE[a] CALCULATED USING CRACK GROWTH ANALYSIS (FLIGHT HOURS)	LIFE[a] CALCULATED USING D.I. & EQUIVALENT S-N (FLIGHT HOURS)	PERCENT DIFFERENCE
75%A-G, 25%N-T	11,800	11,800	0.0
35%A-A, 65%A-G	7,700	7,960	+3.4
SEVERE A-G N_z	7,400	7,330	−0.9
SEVERE A-A N_z	8,600	8,880	+3.4
ACTUAL A/C DATA F-4E(S) SN 711072	7,700	7,520	−2.3

[a] CRACK GROWTH LIFE FROM .010" TO FAILURE AT MONITORING LOCATION, BASELINE LIFE = 10,000 HOURS

FIGURE 3
A-7D TRACKING ANALYSIS METHOD DETERMINATION OF CURRENT D. I.

TRACKING DATA

CURRENT TOTAL N_Z COUNTS AT 5,6,7,& 8g's

CURRENT TOTAL FLIGHT HOURS, t_{AC}

TAIL NUMBER

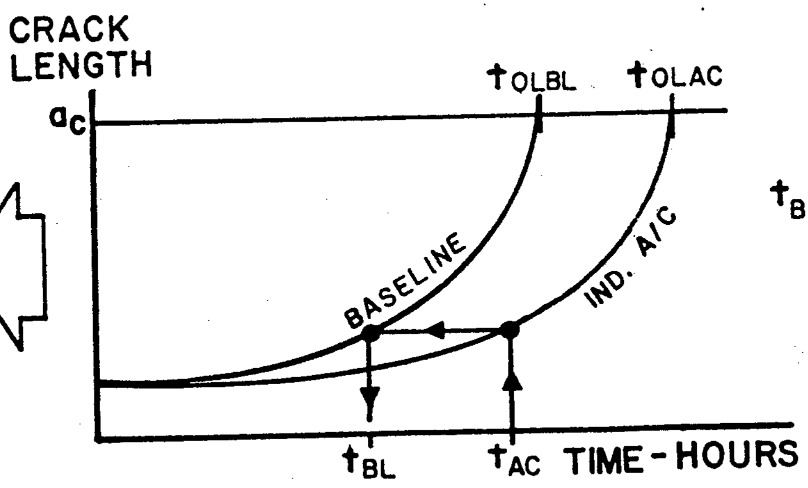
NORMALIZE N_Z COUNTS TO 1,000 HRS-
$N_{5g}, N_{6g}, N_{7g}, N_{8g}$

SOLVE REGRESSION EQUATION FOR OPERATIONAL LIMIT FOR INDIVIDUAL AIRCRAFT USAGE

$$t_{OLAC} = C_1 + C_2 N_{5g} + C_3 N_{6g} + C_4 N_{7g} + C_5 N_{8g}$$

DETERMINE EQUIVALENT BASELINE HOURS FLOWN

$$t_{BL} = \frac{t_{AC} \cdot t_{OLBL}}{t_{OLAC}}$$



COMPUTE DAMAGE INDEX

$$D.I. = \frac{t_{BL}}{4,000}$$

TABLE 2

ACCURACY OF A-7D TRACKING ANALYSIS METHOD FOR SEVERAL USAGE VARIATIONS

VARIATION	CRACK GROWTH ANALYSIS/TEST LIFE[a] (FLIGHT HOURS)	LIFE[a] CALCULATED USING REGRESSION EQUATION (FLIGHT HOURS)	PERCENT DIFFERENCE
30% A-G, 40% A-A, 30% GM	18,690[b]	18,560	-0.7
70% A-G, 30% GM	11,300[b]	11,340	+0.4
AVERAGE BASE N_Z SPECTRUM-BASE #1	14,259[c]	14,783	+3.7
AVERAGE BASE N_Z SPECTRUM-BASE #2	9,884[c]	9,766	-1.2
ACTUAL A/C DATA A-7D SN 701003	12,713[c]	12,590	-1.0

[a] CRACK GROWTH LIFE FROM 0.05" TO 1.21" AT MONITORING LOCATION, BASELINE LIFE = 12,200 HOURS

[b] ANALYSIS LIFE

[c] TEST LIFE

RETURN TO: AEROSPACE STRUCTURES
INFORMATION AND ANALYSIS CENTER
AFFDL/FBR
WPAFB, OHIO 45433