OPERATIONAL LOADS REGRESSION EQUATION DEVELOPMENT FOR ADVANCED FIGHTER AIRCRAFT

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Abstract

Operational loads regression equations used in a flight parameter-based fatigue monitoring system are essential to determine actual operational environment for a fighter type aircraft. In particular, an advanced fighter aircraft controlled by a digital fly-by-wire control system requires the loads regression equations to adjust maneuvering motion changes by control law modifications in the future.

This paper presents guidelines for the development of loads regression equations based on experience from the Japanese F-2 support fighter aircraft. To define the guidelines, it required accuracy for the regression equations to maintain flight safety with respect to inspection intervals for the airframe structure. To satisfy the required accuracy acceptance criteria of the regression analysis was evaluated based on typical damage tolerance calculation results. In addition, a technique to develop bilaterally symmetrical equations for symmetrical components is discussed to improve accuracy of loads prediction especially for fighter type aircraft.

Finally, showing of an operational load monitoring results, effectiveness of the flight parameter-based load regression is highlighted, and a future requirement for an advanced fighter aircraft is suggested.

1 Introduction

Present military aircraft requires fatigue monitoring of its airframe structure by Aircraft Structural Integrity Program (ASIP) [1]. Military aircraft of today incorporates an on-board flight usage monitoring system that is capable of recording flight parameters in service [2]. In a flight parameter-based fatigue monitoring system, operational loads in major structure components are calculated by the loads regression equations.

Loads regression equations must be developed for each aircraft model with very little specific guidelines and/or criteria for the development. Therefore, when a new aircraft is developed, it is necessary to discuss them individually.

The F-2 Support Fighter (Fig. 1) is a multi-role, single-engine fighter aircraft produced for the Japan Air Self Defense Force (JASDF). Based on the design of the F-16 C/D Fighting Falcon, the F-2 is customized to the unique requirements of the Japan Defense Agency. It is the first operational mass production fighter equipped with a digital fly-by-wire control system in Japan. September 2000 the F-2 started in-service operations.

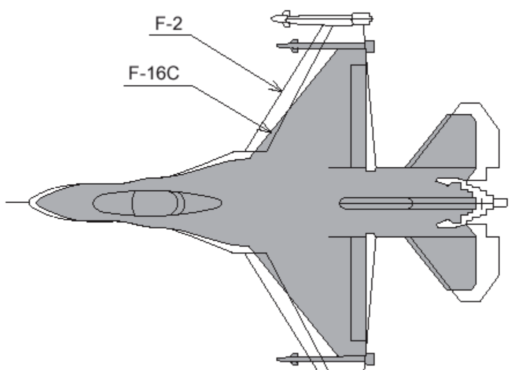


Fig. 1 F-2 Support Fighter
Shadowed area indicates F-16C.

The F-2 airframe structure is designed in accordance with the requirements of ASIP and its individual aircraft tracking program has adopted a flight parameter-based fatigue monitoring system. During development of the fatigue monitoring system for the F-2, guidelines and criteria for the development of the operational loads regression equations were discussed.

2 Operational Loads Regression Equations

The flight parameter-based fatigue monitoring concept of the F-2 support fighter is shown in Fig. 2.

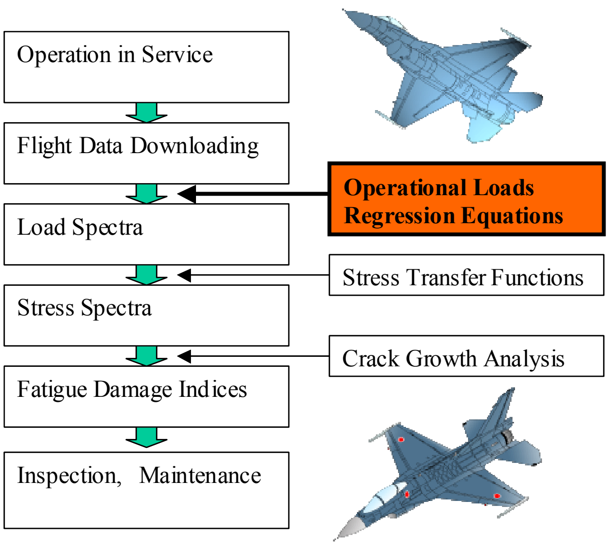


Fig. 2 Flight Parameter-based Fatigue Monitoring Concept

All F-2 are instrumented with a flight data recorder to collect flight parameters such as velocity, acceleration, altitude, deflection of control surfaces, which represent operational loads and environment. The flight parameters recorded are downloaded, and then are processed in the fatigue monitoring system on the ground. The relationship between the flight parameters and the loads are formulated by the operational loads regression equations in the system (Fig. 3). These loads in turn are related to stresses at tracking locations via transfer functions. Crack growth calculations are done to determine fatigue damage indices that are used for inspection schedule determination.

F-2 monitoring system has twenty-two loads regression equations to calculate operational loads in major load carrying components of the entire aircraft structure.

Basic form of the operational loads regression equation is defined as a equation (1). Operational loads are defined as a polynomial expression with flight parameters P_n and partial regression coefficients C_n.

$$Loads = C_0 + C_1 (P_1) \ldots + C_n (P_n) \qquad (1)$$

The flight parameters and partial regression coefficients are developed by multivariate analysis with a database that consists of actual flight loads and flight parameters accumulated through loads flight-testing. The actual flight loads are obtained from calibrated output of strain gauges attached to the flight test aircraft.

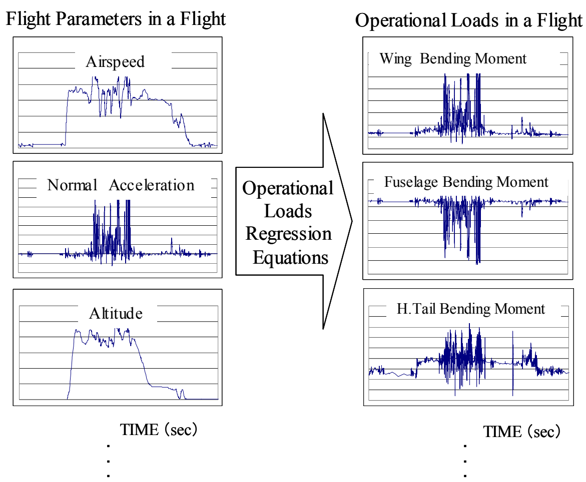


Fig.3 Operational Loads Regression Equation Role in Flight Parameter-Based Monitoring System

3 Flight Test Data for Regression Database

The operational loads regression equations should cover entire flight conditions expected in regular service. Therefore, the flight test data for the regression database should include:

- overall flight envelope in regular service, (i.e. wide airspeed range and wide altitude range);
- not only critical loads conditions but also off-critical load conditions such as ascent, decent, cruise and mild maneuvers;
- all parameters in regular service;
- all maneuver types such as symmetrical, asymmetrical and high angle of attack.

The F-2 loads regression analysis was done with approximately 40,000 data sets of flight data accumulated through loads flight-testing.

4 Flight Parameter Selections

As mentioned, the loads regression equations consist of flight parameters. All flight parameters recorded in the flight data recorder can be applied to the regression analysis, not all should be selected as candidates for specific loads. In other words, the candidate flight parameters for the operational loads regression equation should be selected in advance.

First, theoretical uncorrelated flight parameters should be removed from being a candidate even if they have strong correlation to the loads. For example, wing bending moment flight parameters in yaw direction such as angle of sideslip, yaw rate, and rudder deflection are theoretically uncorrelated. But, show a strong correlation when the regression database is insufficient or partial. Therefore, they should be removed before regression analysis.

Uncorrelated parameters should be removed as candidates. For example, when simple correlation coefficient is less than 0.2.

For parameters with multiple-collinearity, e.g. Nz (normal load factor) and NzW (Nz times gross weight), either parameter, which has better correlation to the loads, should be selected.

In addition to above, F-2 loads regression equations limited the number up to ten candidate flight parameters for each regression equation. This was determined by the preliminary analysis result, which showed correlation of the loads regression analysis would be saturated with up to ten parameters.

Flight parameters used for the F-2 operational loads regression equations are shown in Table 1.

Table 1 Flight Parameters for the F-2 Operational Loads Regression Analysis

Parameters	Meanings	Unit
ALT	Altitude	m
MACH	Mach Number	
QBAR	Dynamic Pressure	Mpa
VEAS	Equivalent Air Speed	m/sec^2
ALPHA (α)	Angle of Attack	rad
BETA (β)	Angle of Sideslip	rad
P	Roll Rate	rad/sec
Q	Pitch Rate	rad/sec
R	Yaw Rate	rad/sec
PDOT	Roll Acceleration	rad/sec^2
QDOT	Pitch Acceleration	rad/sec^2
RDOT	Yaw Acceleration	rad/sec^2
NZWT	NZ times Gross Weight	N
NZ	Normal Load Factor	
δLF	Leading Edge Flap Deflection	rad
δTFL	Left Flapperon Deflection	rad
δTFR	Right Flapperon Deflection	rad
δHTL	Left Horizontal Tail Deflection	rad
δHTR	Right Horizontal Tail Deflectior	rad
δRD	Rudder Deflection	rad
WT	Gross Weight	kg
FQ	Fuel Quantity	kg
ESW	External Store Weight	kg
δHA	Differential H. Tail Deflection	rad
THR EG	Engine Thrust	N
δRD*QBAR	δRD times QBAR	

5 Required Accuracy for the Operational Loads Regression Equations

Currently, the inspection interval of an aircraft using the ASIP is determined based on the conventional deterministic crack growth analysis results. The relations between crack growth analysis life and inspection interval is shown in Fig. 4.

The inspection interval is defined as T/2. Where T is crack growth analysis life from inspectable crack size to critical crack length. The one-half is for a fatigue scatter margin. The accuracy of the operational loads regression equation influences the crack growth life through the loads spectra applied to the analysis.

In this approach, if the crack growth analysis results are un-conservative with the loads error could be limited by 50% of the life, the inspection can be scheduled with at least 25% residual life to the critical crack length. For the worst possible scenario, there is still 50% of the analysis life for the other scatter such as stress estimation error, material, and process variations. Among them, the stress estimation error could be minimized from the airframe fatigue test and the analysis update. Moreover, the material and process variations could be compensated partly with the initial flaw size assumption. Therefore, we determined the required accuracy for the operational loads regression equations should be limited by ± 50% of the analysis lives.

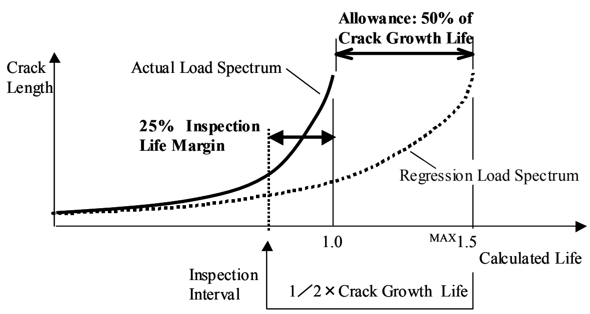


Fig.4 Crack Growth Life and Inspection Interval

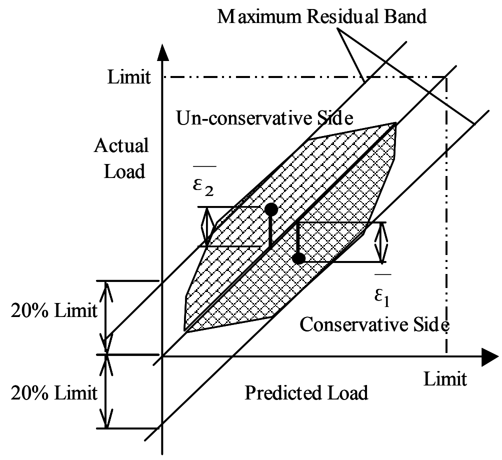
6 Acceptance Criteria of Loads Regression Analysis

6.1 Multiple Correlation Coefficient

For regression analysis, one of the indicators of the evaluation is multiple correlation coefficient "R". Although R should ideally be more than 0.9 for strong correlation as a goal, based on our experience of operational loads regression analysis results, we concluded that it is difficult to require the strong correlation as general criteria. In particular, it is difficult for control surfaces such as horizontal tails and leading edge flaps because their centers of aerodynamics loads move widely depend on flight conditions. Therefore, we determined R should 0.7 or more representing rather strong correlation criteria as a minimum requirement.

6.2 Maximum Residual

Another indicator for regression evaluation is residual between predicted and actual loads. An influence of the residual should be considered in association with the crack growth analysis. The maximum residual is defined here as the residual at 3 times the standard deviation at a given predicted loads level for the regression analysis. The maximum residual should be within the residual strength requirement of damage tolerance design because the maximum spectrum loads should not exceed the loads at the residual strength requirement. Therefore, the maximum residual between predicted and actual loads was determined less than 20% of the design limit loads.



- Multiple Correlation Coefficient : R ≧ 0.7
- Maximum Residual : ε_{max} < 20% Limit Load
- Mean Residual Deviation : $\left|\overline{\varepsilon_1} - \overline{\varepsilon_2}\right|$ ≦ 3% Limit Load

Where,

ε_{max} : Maximum Residual at 3σ

$\overline{\varepsilon_1}$: Mean Residual of Conservative Side

$\overline{\varepsilon_2}$: Mean Residual of Un-Conservative Side

Fig. 5 Allowable Criteria on Correlation Chart

6.3 Mean Residual Deviation

The mean residual deviation, $\Delta\varepsilon$ is defined here as absolute differential between mean residual of the conservative side, $\overline{\varepsilon_1}$ and one of the un-conservative side, $\overline{\varepsilon_2}$ on a correlation chart (See Fig. 5).

An influence of mean residual deviation was discussed based on typical damage tolerance analysis results for the F-2 airframe structure. Twenty cases of typical calculation results are shown in Fig. 6. All cases used given loads spectra for both actual and predictions, and had multiple correlation coefficients that were more than 0.7. The x-axis and y-axis show the mean residual deviation and crack growth life ratio respectively. The result shows the mean residual deviation should not exceed 3% of the design limit loads to keep the life ratio within ±50%, which is defined as the required accuracy in section 5.

In conclusion, based on typical damage tolerance analysis results, the guidelines for acceptance criteria of loads regression analysis were defined as follows (see Fig. 5):

- Multiple correlation coefficient, R should be 0.7 or more;
- Maximum residual, ε_{max} should be less than 20 % of the design limit loads;
- Mean residual deviation, $\Delta\varepsilon$ should not exceed 3 % of the design limit loads.

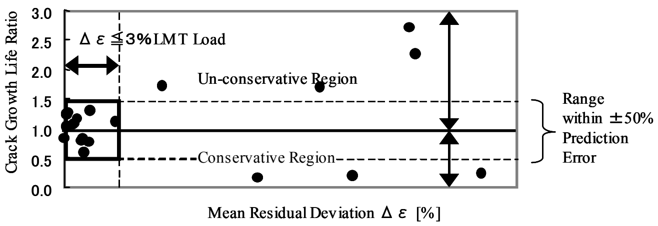


Fig. 6 Mean Residual Deviation vs. Crack Growth Life

7 Separate Equation Guidelines

As mentioned earlier, the basic form of the loads regression equation is a polynomial expression with flight parameters. The relationship between loads and flight parameters is not always linear over the entire flight conditions due to non-linear aerodynamics and adaptive control laws. In particular, an advanced fighter with wide flight envelope and high maneuverability requires separate equations on the transition conditions such as:

- Mach regimes: subsonic, transonic or supersonic;
- Normal loads factor: positive or negative G;
- Deflection angles of control surfaces;
- External store loadings, etc.

As a typical example, the correlation charts of the flaperon hinge moment for the F-2 are shown in Fig. 7. Left side of Fig. 7 shows a regression analysis result with one equation. We can easily see the results should not be accepted as shown on the correlation chart. Also, the values of R and ε_{max} were not satisfied with the allowable criteria presented in section 6. Therefore, an examination for separate equation was done. Right side of Fig. 7 shows the regression analysis results with eight separate equations divided by Mach regimes and deflection angles of the flaperon. The result showed strong correlation and the values of R, $\Delta\varepsilon$ and ε_{max} were satisfied with allowable criteria.

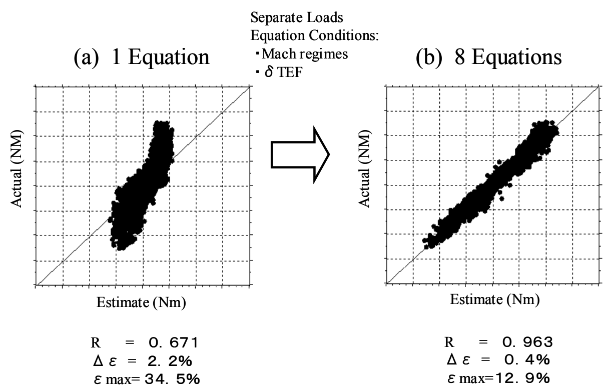


Fig.7 Regression analysis results for flaperon hinge moment using (a) one regression equation and (b) eight separate regression equations

8 Bilaterally Symmetrical Regression Equations

Generally, the loads regression equations are developed individually for each component. Each component includes symmetrical components such as wings and horizontal tails that are required to monitor left and right components individually. In particular, a fighter type aircraft requires individual component tracking for the symmetrical components due to high ratio of its asymmetrical rolling and yawing maneuvers. Therefore, it is important to consider bilaterally symmetrical conditions for symmetrical components. If the load regression equations for the symmetrical components were just developed based on the database of individual components, the load equations for the left and right components would consist of different flight parameters and their partial regression coefficients. This is because the load flight test data does not have equivalent flight conditions for left or right maneuvering direction of asymmetrical maneuvers.

Fig. 8 shows an example of operational loads calculation results using regression equations. The individual regression equation indicated in Fig. 8 shows different hinge moment values of Left Hand (L/H) flaperon and Right Hand (R/H) flaperon in a symmetrical maneuver period. The difference should not be neglected because the loads value for symmetrical condition usually becomes the basic value for load amplitude. Thus, the load amplitude error makes large calculation errors on crack growth life in the fatigue monitoring system because the crack growth rate of airframe metallic structure is generally proportional to the 3rd or 4th power of the load or stress amplitude.

Therefore, bilaterally symmetrical regression equations, which mean the equations have common flight parameters and common partial regression coefficients with only positive and negative sign difference for asymmetrical flight parameters such as β (aircraft angle of yaw), P (roll rate), and PDOT (roll acceleration) should be required.

To develop the bilaterally symmetrical regression equations, an integral regression database for symmetrical components can be used. The data of L/H component converted to the integral regression database for the R/H component is as follows: (See Fig. 9 or Table 1 for the flight parameter definitions)

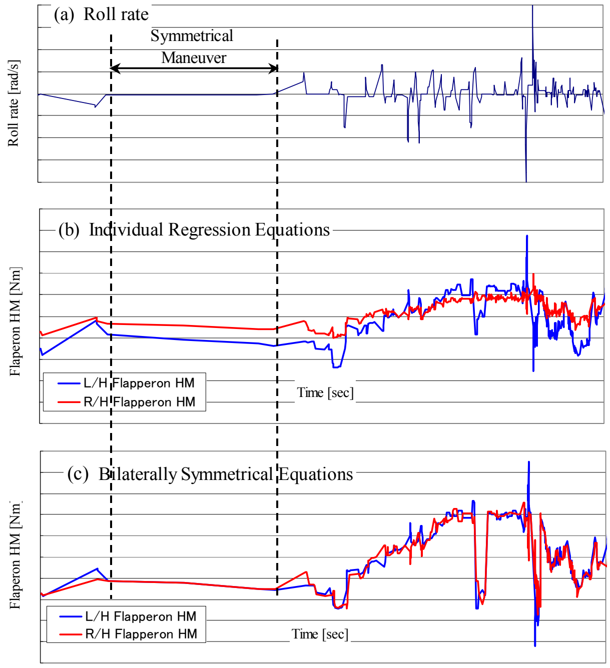


Fig. 8 Operational loads calculation results for flaperon hinge moment using (b) individual regression equations and (c) bilaterally symmetrical equations

- Flight parameters to reverse the sign are β, P, R, PDOT, RDOT, δ RD, and δ HA;
- Flight parameters to convert the values are δ TFR and δ TFL, δ HTR and δ HTL respectively.

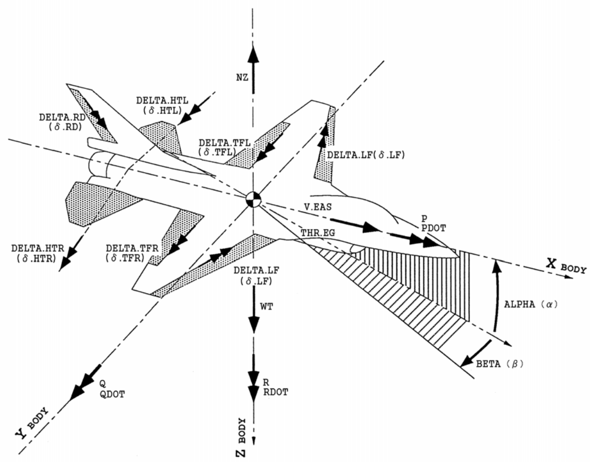


Fig. 9 Typical Flight Parameter definitions

First, with the integrated regression database, the load regression equations for the

R/H components will be developed. Then those for the L/H component will be developed just by reversing the sign and convert surface deflection parameters as described above.

Table 2 shows the regression equation development results before and after symmetrical consideration for the flaperons. Before symmetrical consideration, Flight parameters and their partial coefficients were not common for the L/H and R/H flaperons. After symmetrical consideration, they should be in common.

Table 2 Regression Equation Development Results Before and After Symmetrical Consideration (See Table 1 for abbreviations)

Considering Bilaterally Symmetrical Conditions	Before		After	
Regression Loads / Flight Parameters	Flaperon Hinge Moment		Flaperon Hinge Moment	
	Left	Right	Left	Right
ALT			C_{21}	C_{21}
MACH	C_1		C_{22}	C_{22}
QBAR		C_6	C_{23}	C_{23}
VEAS	C_2	C_7		
ALPHA (α)		C_8		
BETA (β)		C_9		
P		C_{10}	$-C_{24}$	C_{24}
Q		C_{11}	C_{25}	C_{25}
R		C_{12}		
RDOT		C_{13}		
δLF			C_{26}	C_{26}
δTFL	C_3		C_{27}	
δTFR	C_4	C_{14}		C_{27}
WT		C_{15}		
FQ			C_{28}	C_{28}
THR EG	C_5			

9 Loads Regression Equation Development Results

The results of loads regression equation development for the F-2 support fighter were shown in Table 3. The checked flight parameters in the table were selected for each loads regression equation. Each equation was separated by the conditions listed in bottom of the table. All equations were satisfied with the acceptance criteria, and all symmetrical components could be bilaterally symmetrical equation form.

10 Discussions

10.1 Loads Regression Equation for an Advanced Fighter Aircraft

As mentioned earlier, advanced fighter controlled by digital flight-by-wire control system has a possibility of flight control law modifications in the future. The loads of control surface and the loads influenced by the control surface could be changed greatly by the control law modifications.

The monitoring results for the flaperon loads and G spectrum of the F-2 are shown in Fig. 10. These spectra represent an influence of the flight control law changes. Although the G spectrum had little influence, the flaperon loads spectrum had significant influence. The difference of the flaperon loads spectra was caused with the deflection schedule changes by the flight control law and could be simulated with the loads regression equation. It showed an effectiveness of the flight parameter-based loads regression equations and necessity to include deflection of control surfaces in the flight parameter-based fatigue monitoring system.

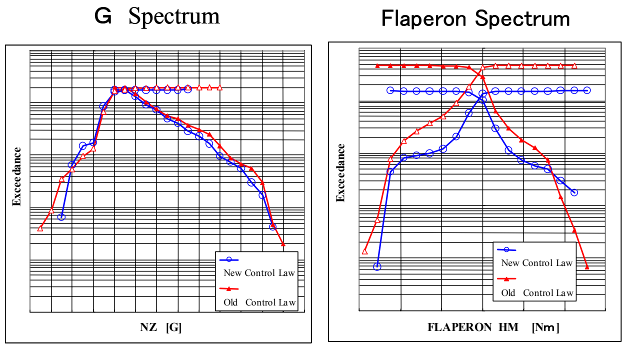


Fig. 10 Operational Loads Monitoring Results with Flight Control Law Changes

10.2 Necessity of Loads Spectrum with Time History for an Advanced Fighter Aircraft

Based on an experience of the operational loads monitoring for the F-2, we recognized a new maneuver behavior where the aircraft often sustained high G or even to allowable limit maneuver in several tens of seconds (See Fig.

11). Digital fly-by-wire flight control system allows this new maneuver while maintaining the allowable limit loads without overloading. Current fatigue monitoring system just counts loads or stress spectrum cycles without time duration information. It is another big challenge to confirm an influence of high loads sustaining to fatigue behavior. At the same time, it is necessary for the flight parameter-based monitoring system to add a capability to count sustaining time with each maneuver so that actual operational environment with time duration can be followed and evaluated for influence in the future.

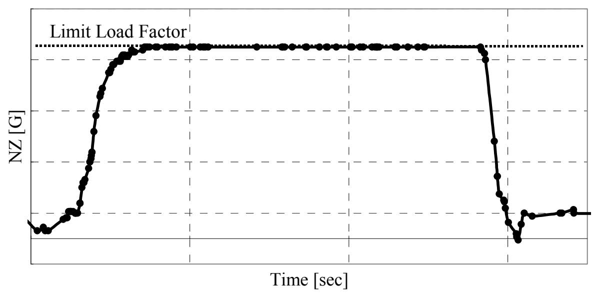


Fig. 11 High G Sustaining Maneuver

11 Conclusions

Guidelines for the development of the operational loads regression equation such as: flight-test data for regression database, selection of flight parameters, allowable criteria for regression analysis, separate equation, and bilaterally symmetrical equation development have been presented with the results of JASDF F-2 operational loads regression equation development.

In addition, showing an operational load monitoring result, effectiveness of the flight parameter-based load regression was highlighted and a future requirement for advanced fighter aircraft was also suggested.

12 Acknowledgements

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[1] MIL-HDBK-1530B Department of Defense Handbook Aircraft Structural Integrity Program, General Guidelines For, 3 July 2002

[2] L. Molent and B. Aktepe, Review of fatigue monitoring of agile military aircraft, *Fatigue Fract Engng mater struct 23*, pp 767-785, 2000.

Table 3 Loads Regression Equation Development Results for F-2 Support Fighter
(See Table 1 for abbreviations)

Regression Loads / Flight Parameters	Wing Shear		Wing Bending Moment		Wing Torque		Leading Edge Flap Hinge Moment		Flaperon Hinge Moment		Horizontal Tail Shear		Horizontal Tail Bending Moment		Horizontal Tail Torque	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
ALT			✓	✓					✓	✓						
MACH	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
QBAR					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ALPHA (α)											✓	✓	✓	✓	✓	✓
BETA (β)															✓	✓
P			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓
Q	✓	✓	✓	✓	✓	✓			✓	✓						
R																
PDOT			✓	✓	✓	✓					✓	✓	✓	✓	✓	✓
QDOT																
RDOT																
NZWT	✓	✓	✓	✓												
NZ	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
δLF	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓						
δTFL	✓		✓		✓				✓						✓	
δTFR		✓		✓		✓				✓						✓
δHTL											✓		✓		✓	
δHTR												✓		✓		✓
δRD																
WT	✓	✓	✓	✓			✓	✓								
FQ			✓	✓					✓	✓						
ESW	✓	✓			✓	✓										
δHA																
δRD*QBAR																
Conditions for Separate Loads Regression	NZ, ESW		NZ, ESW		MACH, δTFL,δTFR		MACH		MACH, δTFL,δTFR		MACH		MACH		MACH, δTFL,δTFR	

✓ : Symmetrical Parameter Coefficient with Positive Sign
✓ : Symmetrical Parameter Coefficient with Negative Sign
✓ : Symmetrical Parameter Coefficient with Positive and Negative Sign

Regression Loads / Flight Parameters	Vertical Tail Shear	Vertical Tail Bending Moment	Vertical Tail Torque	Rudder Hinge Moment	Center Fuselage Bending Moment	After Fuselage Bending Moment
ALT						
MACH			✓	✓	✓	✓
QBAR			✓	✓		✓
ALPHA (α)						✓
BETA (β)	✓	✓	✓	✓		
P		✓	✓	✓		
Q						
R	✓		✓	✓		
PDOT	✓		✓			
QDOT						
RDOT	✓	✓	✓			
NZWT						
NZ					✓	✓
δLF						
δTFL						
δTFR						
δHTL						✓
δHTR						✓
δRD	✓	✓	✓	✓		
WT						
FQ						
ESW						
δHA	✓	✓	✓	✓		
δRD*QBAR				✓		
Conditions for Separate Loads Regression	MACH	MACH	MACH, δRD	MACH, δRD	None	None