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APPLICATION OF VIBRATION-AND-FLUTTER INTEGRATION ANALYSIS SYSTEM FOR A TRAINER

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Abstract

In this paper, a Vibration-and-Flutter integration analysis system is presented, which is an analytical system integrating the vibration evaluation and the vibration tests and the flutter evaluation. In the system, the corrected frequencies and mode shapes are obtained from both evaluation of the finite element method and measured data of the ground vibration tests. The corrected flutter results are obtained from the evaluation based on the corrected frequencies and mode shapes . Above tesks are finished in testing ground.

The Vibration-and-Flutter integration analysis system had been applied successfully in the flutter analysis of a Trainer. As shown by the results, it not only made the aircraft flutter analytical results more accurate and reliable, but also shortened the working period, thus enhance working efficiency.

Introduction

A Vibration-and-Flutter Integration Analysis System (VFIAS) is currently under development at the Nanchang Aircraft Manufacturing Company. The objective was to provide a flutter analysis method of integration of vibration tests and flutter evaluation for development of the K-8 jet Trainer and the N5A agriculture aircraft.

In 1990, the VFIAS was applied in a Trainer. As shown by the results, it not only made the aircraft flutter analysis results more accurate and realiable, but also shortened the working period, thus enhance working efficiency.

Integration of vibration tests and flutter analysis has been developed since 1980, gradually become a method of the aircraft flutter analysis. Development in the field has been done by Boeing Company U.S.A, Prodera Company FRANCE,and Aircraft Structure Strength Research Institute CHINA.(1,2, 3,4)

The concept of the VFIAS had been developed by us is shown as Figure 1. Multiple random input and the identification of multiinput and multioutput (MIMO) model parameters have been used in the ground vibration tests (GVT). The measured data are used to improve the dynamic analysis results of the finite element method (FEM).It is important to accumulate a wealth of experience of the flutter analysis for the VFIAS development.

A corrected results of structural dynamic analysis are often based on both subjective evaluation of the FEM and measured natural frequencies and normal mode shapes of the GVT of the complete real aircraft. Application of the VFIAS will improve frequencies and mode shapes of the FEM of the predicted by the measured data of the GVT.

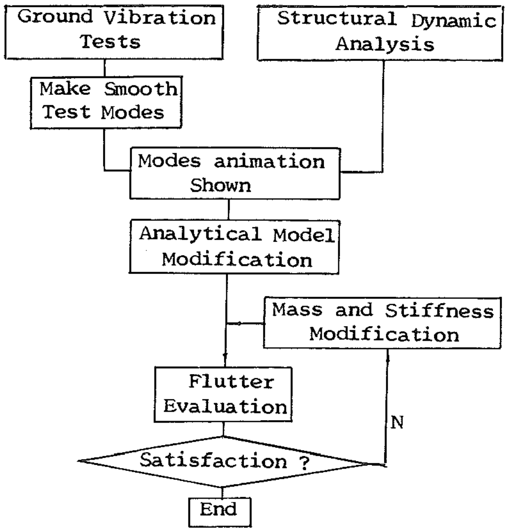

Figure 1. Integration Analysis System Concept

In the same time, flutter evaluation based on satisfied dynamic analysis results are performed. It can be seen that, the VFIAS will integrate two separated tasks, which are structural dynamic analysis and flutter analysis.

The VFIAS has been set up the micro computer AST P/386, and can be applied to join the GVT system together. The VFIAS has a good beforetreatment and aftertreatment, and has the more mobile managerial system of the documents. The analysis results of the VFIAS, such as vibration mode shapes and flutter speed-damping, will be shown on the screen by the picture and the graph, which have a better visualization. The system program are consisted of a lot of the separated modules. Each module can independently do evaluation and treatment of mathematics or mechanics.The data information are shared by every module through the data base. It were the independent modules that realized the set-up of the great program system on the micro computer.

The system program are written in FORTRAN and MASM language

Ground Vibration Tests

With the realization of the measurement technique of multiple exciting frequency response fun-

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\+ Eegineer, Department of Structural Dynamic Testing ction, and the development of the dynamic analysis equipment, the identification method of multiinput and multioutput (MIMO) model parameters is gradually maturing and making step from theoretical research towards practical application.MIMO identification technique has been an effective method of the aircraft GVT. At the same time, the method of sine dwell model tests are still an effective one. Where,both methods are combined to finish aircraft GVT in the VFIAS.

The exciting modes are selective when an aircraft GVT are performed with the system. They are periodic random with controllable bandwidth, burst random, pulse,chirp,step sine sweep and fixed-time domain signal excitation.

The system can perform the test with 8 exciting points (the gain and phase controlled), and the measurement with 256 response points. It can also generate aircraft frequency response function matrix by the application of multiple whole coherence or uncoherence frequency response function estimate technique and the aircraft model parameters by applying the method of the MIMO parameter identification at frequency and time domain.

There are several frequency domain identification method, such as the cross multiple term formula method, the method of the multiple reference at frequency domain and the pure model identification method.The time domain identification methods include broad-sense frequency domain method, and improved IDT method, or the method in which the rate of undamping coefficient frequency to turn pure model force is got in improved Asher method and then the frequency-adjusting force is gradually adjusted in Deck method to get the pure model parameters in the aircraft pure vibration.

The system selects the working mode at which two micro computer run. The pre-model-module pattern is adopted for exciting and sampling. The various functions of analysis, calculation, identification and controlling can be formed with model modules, which may be combined by the operator for a special test.

Dynamic Analysis

The flutter analysis is on the basis of the structural dynamic analysis.In the aircraft design phase,the flutter speeds are obtained by a subjective evaluation of the FEM and the wind tunnel tests of the predicted. But the subjective evaluation and the wind tunnel tests were performed under some assumed conditions of the aircraft structures before a complete real aircraft was produced. It is clear that, in the aircraft development phase, it is necessary to perform the GVT of the complete real aircraft in order to obtain it's dynamic behaviour, which contain frequencies, mode shapes and damping. But up to present, it is impossible to satisfy completely the orthogonality condition based on the measured mode shapes. The satisfied results of the structural dynamic analysis are often based on the subjective evaluation of the FEM of the predicted and the measured data of the GVT of the complete real aircraft.

It is known from practice,the error of between the subjective evaluation of the FEM and the measured data of the GVT of the complete real aircraft of natural frequencies and mode shapes exist. It is generally agreed that the results of the GVT are more reliable then the subjective evaluation. But the measured mode shapes can't satisfy orthogonality condition. It is obvious that, the information obtained from the GVT often leads to the correction of major deficiencies in the modeling of the FEM.Both analytical mass and stiffness matrices are modified by using the vibration test data.

Dynamic analysis uses two basic theoretical relationships which apply to linear,undamped structures represented by the FEM.These are orthogonality of the normal mode shapes, and the eigenvalue equation as described in Eqs. (1) and (2):

$$H^T M H = I \tag{1}$$

$$(-\omega^2 M + K) H = 0 \tag{2}$$

Where

M	mass matrix
K	stiffness matrix
ω	eigenfrequency
H	mode shape matrix
I	unit matrix

The orthogonality relation for the generalized stiffness is given an

$$H^T K H = \mathrm{diag}(\omega^2) \tag{3}$$

In the VFIAS, these are two methods based on the measured data of the GVT to modify equation(2).

In the first method,it is assumed that the mass matrix is correct and introduced a constrained minimization procedure to adjust analytical stiffness and flexibility matrices. Now this method has been modified to include the treatment of weighted orthonormal conditions and number of mode shapes less then the number of the degrees of freedom of the structure. (5)

In the second method, it is assumed that both the analytical mass and stiffness matrices are modified simultaneously by using the measured data of the GVT. One simple approach is to first modify the analytical mass matrix to satisfy the orthogonality condition based on the measured mode shapes . Then stiffness matrix is modified to satisfy the eigenvalue equation (2) as a function of the measured mode shapes, natural frequencies, and the corrected mass matrix. (6,7)

In the VFIAS, the variation of mass and stiffness in equation(2) were investigated by applying different control circuit stiffness and control surface mass balances.

In the first step the additional mass, ΔM, and stiffness, ΔK, matrices are calculated. Adding the 'Delta' mass and stiffness matrices to the main structure one obtains

$$(-\bar{\omega}^2 (M+\Delta M) + (K+\Delta K))\bar{H} = 0 \tag{4}$$

where

$\bar{\omega}$	new eigenfrequencies
$\bar{H}$	new mode shape matrix

Assuming that the corrected mode shapes can be described by a linear combination of the original ones, one can be written

$$\bar{H} = HQ \tag{5}$$

Taking mode shapes into account, the matrix of the generalized coordinates Q is a (mxm) matrix After premultiplication by H^T , equation(4) may be written as

$$(-\bar{\omega}^2(1-H^T\Delta MH)+(\mathrm{diag}(\omega^2)+H^TKH))Q = 0 \qquad (6)$$

In the present case, the order of equations (1) and (4) is about 120, where as equation (6) has the order of about 20. Since the matrices M and K are sparse and the eigenvalue solution can be performed in core, the entire process, including the orthogonal transformations in equation (6), only requires about 5 minutes for CPU to complete.

Typical aircraft dynamic analysis

The typical aircraft with a wing, horizontal stabilizer and fuselage was modeled by elastic beam element are shown as Figure 2. The vertical stabilizer and rudder are lumped into the fuselage as point masses at the condition of the symmetrical vibration. The wing root and horizontal stabilizer root flexibilities are modeled by lumped springs. The aileron and elevator are modeled by rigid beams. Their root flexibilities are modeled by lumped circuit springs.

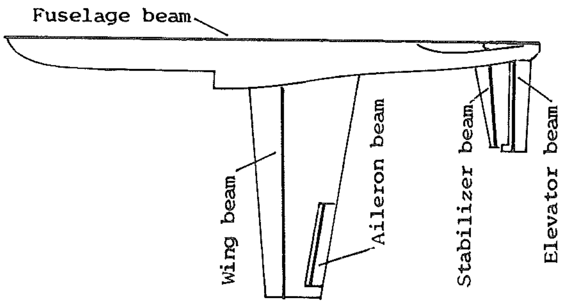


Figure 2. Complete Aircraft Structural Model

The symmetrical vibration frequencies of the typical aircraft are shown as Table 1. It will be seen from the table that, results of the finite element methods and the measured data are incompletely compatible.

Compared with the measured data, the maximal error of the initial analysis frequencies is 18.11%, the main frequencies average error is 6.16% . The orthogonality condition of the test mode shapes may be modified by the first modification method. But it can't modify the frequencies.

Using the second modification method, may first modify the analytical mass matrix to satisfy the orthogonality condition based on the measured mode shapes. Then the stiffness matrix is modified to satisfy the eigenvalue equation as a function of the measured mode shapes, natural frequencies, and the corrected mass matrix. Finally, compared with the measured data, the maximal error of the corrected analytical frequencies is 3.73%, and the main frequencies average error is 2.57%.

The symmetrical vibration mode shapes of the typical wing are shown as Figure 3. Because the results of the FEM are modified by the measured data in testing ground, the corrected dynamic analysis results will be obtained from this.

Flutter analysis

The flutter is self-excited aeroelastic phenomenon of the interaction between aerodynamic, elastic, and inertia forces. The flutter equation is written as

$$(-\omega^2 M+(1+ig)K)Q = \omega^2 FQ \qquad (7)$$

In equation(7), M, K and F are the generalized mass, stiffness and aerodynamic matrices, respectively. Where, the $Z=(1+ig)/\omega^2$ = Re+Im, Hence the flutter frequency becomes

$$\omega = \sqrt{1/Re}$$

and the damping

$$g = \omega^2 Im = Im/Re$$

and the flutter speed is defined by

$$V = \omega b/k$$

Where, the equations have been non-dimensionalized and b equals a reference length and k equals a reference value of reduced frequency, $k=\omega b/v$.

Currently, in the VFIAS only the k-method of flutter analysis is a looping procedure. The values of v, g, and are solved for various values of k, M is the Mach number and ρ is the air density. Plots of v versus g can be used to determine flutter speed (When g goes through zero to positive values).

Table 1. Typical Aircraft Dynamic Analysis Results

	Frequencies (HZ)					
Mode number	Test	Initial analysis	Percent error	Corrected analysis	Percent error	Mode shapes
1	10.56	10.55	-0.09	10.77	1.98	Elevator rotation
2	12.32	11.92	-3.24	11.93	-3.16	Wing 1st bending
3	23.53	25.39	7.90	22.84	-2.93	Stabilizer 1st bending
4	40.57	39.95	-1.53	39.87	-1.72	Aileron rotation
5	52.82	54.14	2.49	54.66	3.48	Wing 2nd bending
6	70.09	57.39	-18.11	71.39	1.85	Wing 1st torsion
7	75.00	77.43	3.24	73.66	-1.78	Stabilizer 1st torsion
8	84.79	95.99	12.61	81.80	-3.73	Stabilizer 2nd bending
		Average	6.16	Average	2.57	

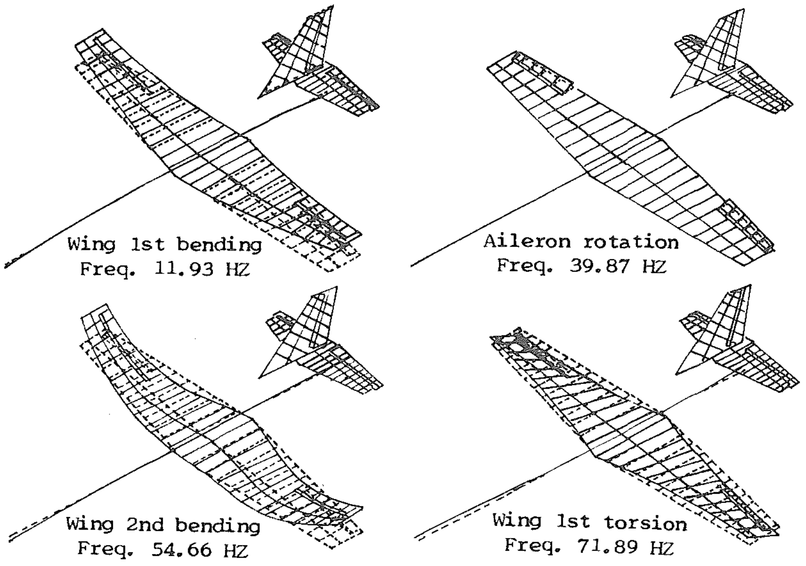


Figure 3. Typical Wing Symmetric Vibration Mode Shapes

The Doublet-Lattice Method is used for subsonic unsteady aerodynamic of the lifting surfaces and of the fuselage slender body. (8,9)

In the flutter analysis of the typical wing, the wing and aileron were subdivided into 80 and 20 micro lifting surface elements, respectively. Four wing's vibration mode shapes and one aileron rotation vibration mode shape were used to flutter analysis.The k-method flutter evaluation for M=0.1 at sea level is performed. The conventional v-g-ω graph of this wing was given as Figure 4.

In the flutter analysis of the typical horizontal stabilizer,the stabilizer and elevator were subdivided into 60 and 40 micor lifting surface elements, respectively. Four stabilizer vibration mode shapes and one elevator rotation vibration mode shape and one fuselage bending mode shape were applied to flutter analysis.At the same time, change of the elevator mass balance is considered in horizontal stabilizer flutter analysis. Where, the change of the elevator mass balance has an effect upon not only the elevator deflection vibration frequency,but also the stabilizer vibration frequencies.

The flutter analysis results of the typical horizontal stabilizer are presented in Table 2 and as Figure 5. In the meanwhile, the wind tunnel

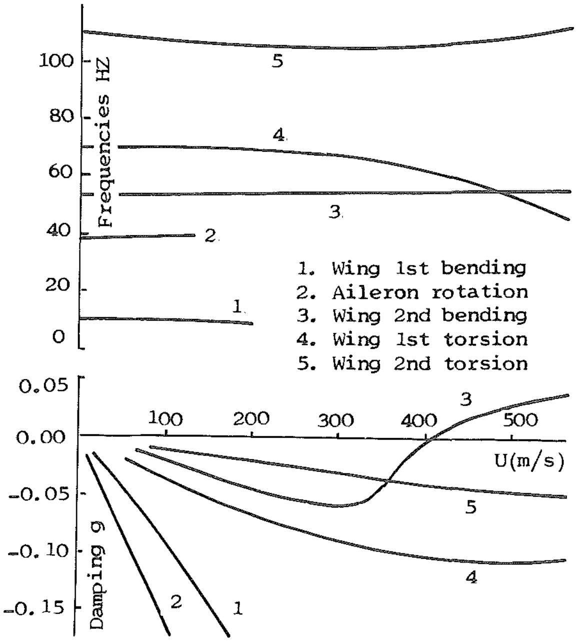
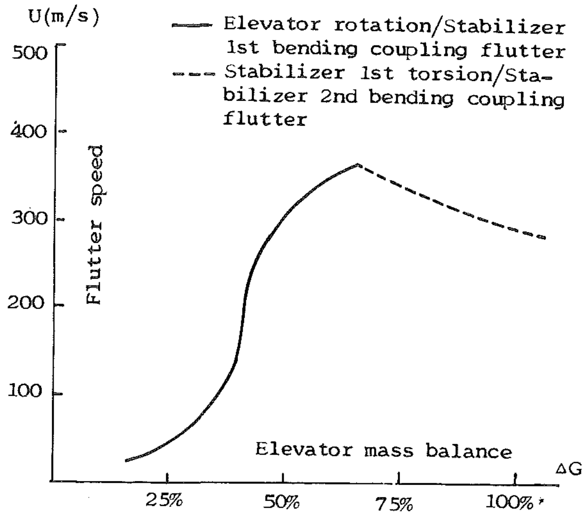


Figure 4. Typical Wing Flutter g-v-ω Graph



* ΔG=100% is initial design condition

Figure 5. Typical Horizontal Stabilizer Flutter Speeds Vary with the Elevator Mass Balances

test results and the evaluation results by MSC/NASTRAN V.66B are presented too in Table 2.

Table 2. Typical Horizontal Stabilizer Flutter Analysis

Model	Flutter speed (mps)	Flutter frequency (HZ)	Natural frequencies (HZ)
Wind tunnel tests	327	83.8	———
Initial analysis	297	78.0	20,69,88,104
GVT data analysis	299	79.0	23,75,86,108
MSC/NASTRAN V.66B	319	80.0	20,75,87,109
VFIAS	299	78.5	23,75,84,105

Conclusions

The VFIAS is to realize integration of dynamic evaluation, dynamic testing and flutter speed evaluation. The corrected frequencies and mode shapes are obtained from both evaluation of the FEM and measured data of the GVT. The corrected flutter speeds are obtained from the evaluation based on the corrected frequencies and mode shapes. Application of the VFIAS not only made the aircraft flutter analysis results more accurate and reliable, but also shortened the working period, thus raising working efficiency.

The VFIAS had been applied in the flutter analysis of a Trainer. The obtainable flutter speeds have the same value as the wind tunnel test results , and as the MSC/NASTRAN system evaluation results. The results presented here indicate that VFIAS will be a useful engineering tool for the aircraft development.

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