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HAJIF-II, A PROGRAM SYSTEM FOR THE DYNAMIC ANALYSIS OF AERONAUTICAL STRUCTURES

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Abstract

HAJIF-II is a program system developed for the calculation of modal parameters of aircraft structures as well as flutter and gust response analyses with active control systems taken into consideration. 99 substructures each with 7000 degrees of freedom can be used in the calculation of modal parameters and 50 modes for the flutter and gust response analyses. Some new techniques, such as revised hypermatrix technique, improved algorithm of simultaneous iteration and new methods of modal synthesis etc., were developed to improve the efficiency of the system. Typical aircraft structures were analysed and good results were obtained.

1. Introduction

For modern high performance aircrafts, structure design and even structural and aerodynamic configurations are significantly effected by aeroelastic and dynamic design requirements. Therefore, aeroelastic and dynamic analyses with acceptable accuracy and high efficiency become more and more important for the design of such aircrafts. HAJIF-II is a program system developed by Chinese Aeronautical Establishment (CAE) for this purpose. It's able to carry out the calculation of modal parameters (natural frequencies and mode shapes) of aircraft structures as well as flutter and gust response analyses with active control systems taken into consideration. The system is programmed on a Siemens 7.760 computer belonged to CAE.

Calculation of modal parameters is based upon finite element displacement method. The structure can be analysed either as a whole or by the use of modal synthesis techniques. 99 substructures each with 7000 degrees of freedom can be used. In order to improve the efficiency of the system, some new techniques, such as revised hypermatrix technique, improved algorithm of simultaneous iteration and new methods of modal synthesis etc., were developed.

Flutter and gust response analyses are based on mode superposition method and 50 modes are allowed. Nonsteady aerodynamic forces are calculated by the use of subsonic doublet lattice method for multi-wing and 300 panels are permitted. Nonsteady aerodynamic forces in Laplace plane are approximated by a curve fitting procedure of sinusoidal results.

For the convenience of users, the data generation system promises the input of numerical data and topological statements flexibly. 31 computational flows are prescribed by the system and the users can organize their own computational flows as needed. The system is composed of about 26000 FORTRAN statements, more than 300 subroutines and 21 functional programs.

Typical aircraft structures were analysed and satisfactory results were obtained.

2. Stiffness and mass matrices

The aircraft structure analysed should be discreted into finite element model and following eigenvalue problem is formed

$$ku = \lambda mu \qquad (1)$$

where k, m and u are physical stiffness, mass matrices and displacement vector respectively, and λ is the square of natural frequency.

12 beam, rod and plate elements are contained in HAJIF-II for the simulation of lifting surfaces, fuselages, external stores and their connections.

Variable degree of freedom technique is adopted to omit all of the inactive degrees of freedom.

Single-point and multi-point constraints[1] were programmed in HAJIF-II. The function of single-point constraint is to prescribe the displacements of some of the degrees of freedom and they are used to realize different boundary conditions, symmetric or antisymmetric conditions as well as the treatment of zero-stiffness directions.

The function of multi-point constraints is to express the displacements of some of the degrees of freedom in terms of a linear combination of others, i.e.,

$$Ru = 0 \qquad (2)$$

where R is constraint matrix, so as to simulate the coordination of degrees of freedom. Rigid element is also handled by the concept of multipoint constraint.

Bandwidth optimization is performed by means of Cuthill-Meckee method[2]. Because of the use of multilevel substructures, some special arrangements were made.

For the management of stiffness and mass matrices, a revised hypermatrix technique was developed. In the conventional procedure of hypermatrix technique[3], the matrix is partitioned into a number of zero level submatrices and zero or nonzero submatrix is symbolized by zero or nonzero, and first level symbolic matrix is still too large to handle, it will be partitioned further. Obviously, there will be still a lot of zero elements in the nonzero submatrices, so that a procedure of detail treatment was proposed. For the stiffness matrix, the concept of active column[9] is adopted, i.e., for diagonal submatrices, sequence numbers of diagonal elements, and for nondiagonal submatices, sequence number of the last element of each column are used as indices, then the "height" of each column can be obtained. For the mass matrix, because it is kept unvaried during the iteration process, so the index is formed by the sequence number of the first element of the partitioning of each node point and diagonal partitioning is indicated by negative number.

This revised procedure minimizes the requirement of internal storage apparently as shown in Tab. 1.

Tab. 1

Examp.	DOF	Requirement of internal storage			
		Stiffness matrix		Mass matrix	
		Conven.	HAJIF-II	Conven.	HAJIF-II
1	870	107712	78557	21312	1549
2	210	11520	5596	9590	1930
3	138	6336	1458	5357	979

In assembling the stiffness and mass matrix, only non-zero partitionings are assembled with compacted storage method.

3. Real eigenvalue analysis

In determining the lower order eigenpairs of a sparse matrix, simultaneous iteration is a very effective process. Various kinds of algorithm were suggested by some authors, such as Rutishauer[4], Reinsch[5], McCormick[6], Bathe[7], and Nicolai[8] et al. Basing on theoretical analysis and a lot of numerical experiments a new algorithm were developed and convergence of this algorithm was proved by the use of the concept of E_k subspace.

The features of the algorithm are : (1) mass matrix will not be decomposed, (2) Gram-Schmidt orthogonal process is adopted and so, dimension of the problem will be reduced successively, (3) other improvements are made, therefore the rate of convergence is the same with other methods but its amount of computation of each iteration is the least.

The algorithm is shown as following,

$$\begin{aligned} kZ^{(j)} &= S^{(j-1)} \\ mZ^{(j)} &= Y^{(j)}R^{(j)} \\ B^{(j)} &= R^{(j)}R^{(j)T} \\ Q^{(j)T}B^{(j)}Q^{(j)} &= D^{(j)(-2)} \\ S^{(j)} &= Y^{(j)}Q^{(j)} \end{aligned} \qquad (3)$$

where

$$Y^{(j)T}m^{-1}Y^{(j)} = I,$$

$R^{(j)}$ is an upper triangular matrix, $D^{(j)}$ is diagonal, and supercript (j) denotes the times of iteration. The eigenproblem of project matrix is solved by either Q-R or Jacobi method.

Characteristics of Sturm sequence[9] is used to check if there are eigenroots missed and this process is conducted in conjunction with the determination of the amount of test vector.

Decomposition of matrix k or $k-\lambda m$ is realized by a wave frontal elimination method with buffer.

Comparison of effectiveness of the new algorithm with other current methods is shown in Tab. 2.

Tab. 2

	Example	1	2	3	4
	Order	500	100	200	500
	Half bandwidth	301	5	20	10
	Amount of test vector	13	30	33	38
cpu sec	Rutishauer	1106			
	Reinsch	1069			
	McCormick	992			
	Nicolai	973			
	Bathe	780	194	368	986
	HAJIF-II	753	93	234	558

4. Modal synthesis

Two main branches of modal synthesis -- free interface method and fixed interface method are all included in HAJIF-II. Besids, two new methods of synthesis called multilevel synthesis and successive synthesis were developed attempting to improve the efficiency of calculation.

Physical equation of motion of a substructure is

$$m\ddot{u} + ku = r \qquad (4)$$

where r is the reactive force on the interface. By the use of normal modes and "interface modes", eq. (4) is reduced to

$$\bar{m}\ddot{p} + \bar{k}p = r \qquad (5)$$

If generalized coordinates q of the synthesized structure are related to generalized coordinates of substructures p by the relationship

$$p = Tq \qquad (6)$$

then equation of motion of the synthesized structure is

$$M\ddot{q} + Kq = R \qquad (7)$$

where R is the reactive force vector. When the process of synthesis is finished, R=0, and the final expression is obtained.

In fixed interface method, normal modes of fixed interface,

$$\phi^n = \begin{bmatrix} \phi_i^n \\ 0 \end{bmatrix} \qquad (8)$$

and "constraint modes",

$$\phi^c = \begin{bmatrix} \phi_I^C \\ I \end{bmatrix} \quad (9)$$

are used[10], where I is an unit matrix and subscript I denotes the internal points.

For free interface method[11], normal modes of free interface and "attachment modes" are used. Effects of residual stiffness and inertia of the truncated higher modes should be considered, but numerial tests indicated that the effect of residual inertia is neglectable.

Futhermore, in HAJIF-II, free interface normal modes and attachment modes are transfered to "quasi-fixed interface normal modes" $\bar{\phi}^n$ and "quasi-constraint modes" $\bar{\phi}^c$ [12] respectively, i.e.,

$$\bar{\phi}^N = \begin{bmatrix} \bar{\phi}_I^N \\ 0 \end{bmatrix} \quad (10)$$

$$\bar{\phi}_I^N = \phi_I^{NF} - \bar{\phi}^C \phi_B^{NF} \quad (11)$$

$$\bar{\phi}^C = \begin{bmatrix} \phi_I^C \\ I \end{bmatrix} \quad (12)$$

$$\bar{\phi}_I^C = G_{IB} G_{BB}^{-1} \quad (13)$$

where ϕ^{NF} is free interface normal mode and subscript B denotes the interface point.

In order to determine ϕ^{NF} and G, the concept of "virtual structure" is used. Equation of motion of the virtual structure is

$$k^* u = \lambda^* m^* u \quad (14)$$

where

$$k^* = k + m$$
$$m^* = m$$
$$\lambda^* = \lambda + 1$$

and

$$G = \begin{bmatrix} G_{II} G_{IB} \\ G_{BI} G_{BB} \end{bmatrix} = (k^*)^{-1} - \phi^{NF} K_I^{-1} \phi^{NFT} \quad (15)$$

with

$$K_I^{-1} = \mathrm{diag}\,((\omega_1^*)^2,\ (\omega_2^*)^2,\ \cdots\cdots,\ (\omega^*_N)^2)$$
$$(\omega^*)^2 = \lambda^*$$

The concepts of multilevel synthesis and successive synthesis are sketched in Fig. 2. It can be seen that multilevel synthesis method is principlely similar to one level synthesis methods but for the successive synthesis method, only two substructures will be involved in each step of synthesis. The one will be synthesized in its reduced form of equation of motion and the other one in that of its physical equation of motion.

Special arrangement was made to handle the rigid substructures and it's only necessary to synthesis them in the first level if multilevel synthesis method is used.

The frequency truncation criteria is revised to fulfill the requirement of multilevel and successive syntheses. For fixed interface method,

$$\omega = \alpha^{P-p} \omega_{max} \quad (16)$$

and for free interface method,

$$\omega = [(\alpha^{P-p} \omega_{max})^2 + 1]^{\frac{1}{2}} \quad (17)$$

where P is the total levels of synthesis, p is the level to be synthesized, α is a coefficient, ω_{max} is the maximum circle frequency in consideration and ω is the frequency of truncation.

5. Flutter and gust response analyses

Most of the modern aircrafts have the ability of supersonic flight, but critical flutter conditions are usually encountered in low level near-sonic speed range. Therefore in HAJIF-II, subsonic doublet lattice method for multi-wing[13] was programmed first.

Interpolation of the mode shapes from structural node points to the characteristic points of aerodynamic panels is realized by the use of two-way spline curve method[14].

Rogar's curve fitting procedure[15] is adopted to obtain an approximate expression of nonsteady aerodynamic forces in Laplace plane.

V-g and p-k methods[16] are included in HAJIF-II for flutter analysis and active control system can be considered in p-k method. Complex eigenvalue problems are solved by L-R, Q-R or inverse power method with origin shift which can be selected by the users.

Gust response is analyzed in the frequency domain and continuous atmospheric turbulence model is used. Either Karman spectrum or any other spectrum assigned by the users is permitted. Also, active control system can be taken into account [15].

6. Program Organization

The program of HAJIF-II is organized by the management of two levels. The first level is monitor program which is composed of almost only call statements. The second level consists of a number of functional programs which are the highest level subroutines and can be called by the monitor program to conduct some specific mathematical or mechanical functions. Functional programs can't be called by each other and all the data used are only related to the date file management system, so the extension and modification of the system are very convenient.

A common array with variable length is settled in the monitor program and almost all of the arrays used in the functional programs will be generated statically, dynamically or static-dynamically from this common array.

The collection of data in HAJIF-II is called "dictionary" which contains 100 "books" (the amount of books can be extended). Each books is composed of 100 "volumes" which are designed for the collection of data for some repeated calculation. Each volume contains 100 "Chapters" and the data of a read/write statement are stored in one chapter. The chapter is the basic unit of data.

Advanced data file management system was developed and it's able to perform the read/write function automatically only if I/O table and chapter address are suggested.

7. User's interface

For the convenience of users, there are two manners of data input permitted in HAJIF-II. The one is the input of numerical data alone and the other one allows the input of numerical data and topological statements flexibly. Topological statements include: (1) simple descriptions of the node coordinates and element information of idealized components, (2) simplification of some reguler data, and (3) functions for data modification. Macro-instruction lanquage was designed and one set of which is used to operate the following 31 prescribed computation flows :

(1) Calculation of parameters
 M1. Analyze the structure as a whole,
 M2. One level synthesis for free interface,
 M3. One level synthesis for fixed interface,
 M4. Multilevel synthesis for free interface,
 M5. Multilevel synthesis for fixed interface,
 M6. Successive synthesis for free interface,
 M7. Successive synthesis for fixed interface,

(2) Flutter analysis
 F1. v-g method,
 F2. p-k method,

(3) Gust response analysis (G1),

(4) Combined analysis
 The combination of M1-M7 with F1, F2 and G1.

The other set enables the calling of 21 functional programs to organize the additional computational flows. Because of the complication of the modal synthesis, an integrated statement was designed.

The ability of error diagnosis was prepared and hundreds of informations can be output as the users need. Error diagnosis is emphasized to the check of original data.

8. Examples calculated

(1) Calculation of modal parameters and flutter analysis of a delta wing-fuselage-tailplane combination. The wing structure was simulated by bars and shear panels and the fuselage and tailplanes by spars. The finite element model has 315 nodes, 1011 degrees of freedom and typical comparison of calculated modal parameters with the results of ground resonance test is shown in Fig. 1. Good agreement is inspected and also for the comparison of calculated flutter results with wind tunnel tests results.

(2) Modal synthesis of a straight wing-fuselage-tailplane-external store combination. The structures were simulated by spars. The model has 46 nodes, 138 degrees of freedom and is divided into 4 substructures, as shown in Fig. 2. All of the modal synthesis techniques programmed in HAJIF-II were used and encouragement comparison of these methods are shown in Tab. 3.

Tab. 3.

mode	Natural frequencies c/s						
	1	2	3	4	5	6	7
1	2.5130	2.5130	2.5130	2.5146	2.5130	2.5130	2.5130
2	3.2683	3.2683	3.2683	3.2685	3.2684	3.2682	3.2683
3	4.0450	4.0450	4.0450	4.0605	4.0451	4.0450	4.0450
4	4.5917	4.5917	4.5917	4.5921	4.5917	4.5918	4.5917
5	4.9912	4.9912	4.9912	4.9913	4.9912	4.9912	4.9912
6	5.5063	5.5066	5.5063	5.5061	5.5063	5.5066	5.5063

Note: 1--complete model, 2-one level fixed interface, 3--one level free interface, 4--multilevel fixed interface, 5--multilevel free interface, 6--successive fixed interface, 7--successive free interface.

(3) Gust response analysis of B-47. Data presented in ref. 17 were used. Because of different methods of the calculation of nonsteady aerodynamic forces used in HAJIF-II and ref.17, so some discrepencies are observed in the comparison shown in Fig. 3.

9. Conclusion

Brief description of a program system for the dynamic analysis of aeronautical structures named HAJIF-II is presented. Some new techniques were developed and satisfactory results were obtained. The system will be extended further.

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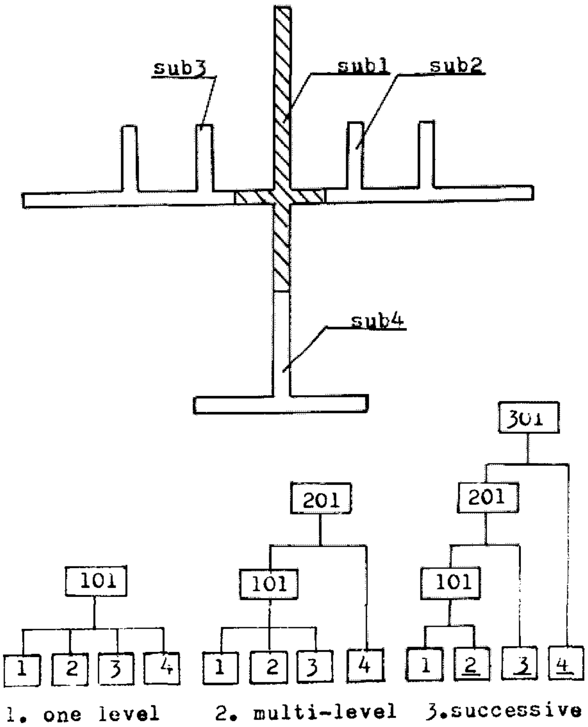
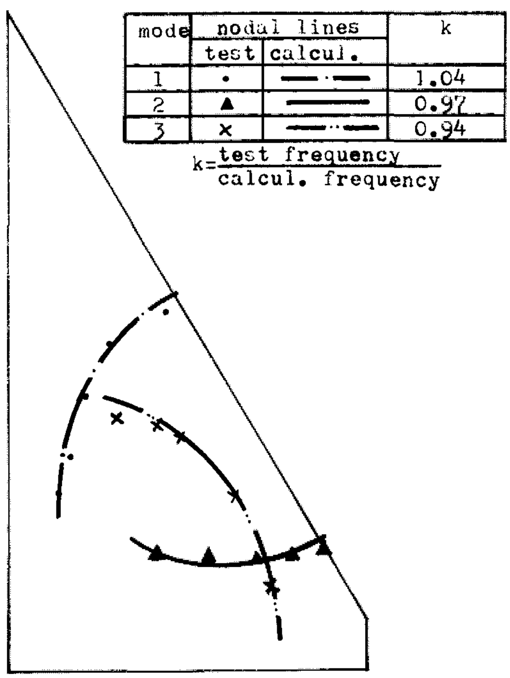


Fig. 2



mode	nodal lines		k
	test	calcul.	
1	•	—·—	1.04
2	▲	——	0.97
3	×	—··—	0.94

$k = \dfrac{\text{test frequency}}{\text{calcul. frequency}}$

Fig. 1

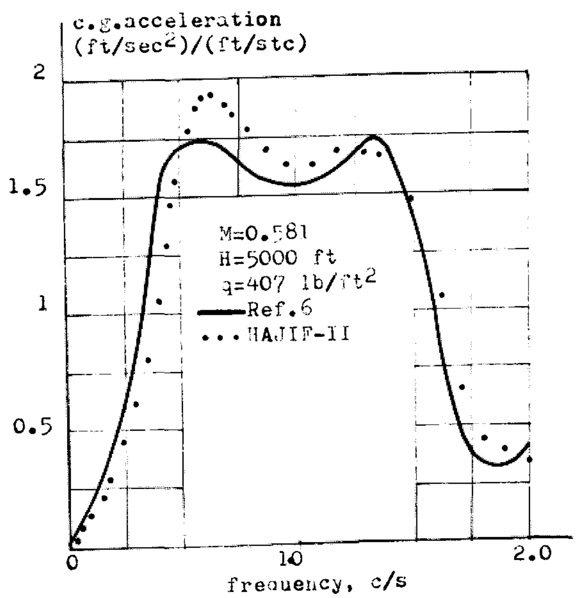


Fig. 3