Aircraft design is well known as a complicated compromising process, although the above theoretical analysis need not be considered as a dictating factor in the exact layout of an aircraft, its significance with special attention to Eq. (9) should be properly weighted in a well-rounded design or cargo/fuel disposition management for existing aircraft. Incidentally, the NLG should not be positioned too far forward from the c.g. of an aircraft to overprotect the NLG for abnormal landings, since too light a load on NLG will give an adverse effect to the steering capability and righting moment for the aircraft in risky drift landings. For aircraft, all the mass, the c.g. locale, the radius of gyration, and Co/Cp locales all are variables, obviously the sinking energy absorbed by the NLG is very sensitive to these variables whose volatility and sensitivity may have to be considered prudently to achieve an optimal overall design compromise in a probabilistic sense.

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Joined-Wing Model Vibrations Using PC-Based Modal Testing and Finite Element Analysis

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Introduction

IN recent years with the popularity of personal computers, experimental modal analysis has been greatly enhanced with the advances and development of PC-based fast Fourier transform (FFT) analyzers. When equipped with well designed and user-oriented modal analysis software, the analyzer-in-a-portable-PC provides a powerful and convenient method for studying practical structural vibration problems. In addition, in an educational environment, the portability feature of the modal system gives unique opportunities for presenting modal testing and mode animation in the university classroom.[1] Primary emphasis here, however, centers on the test and analysis comparison for a joined-wing vibration model. With a COMPAQ PORTABLE 386® personal computer, an impulse hammer and associated instrumentation, a joined-wing model is employed as a specimen in a modal testing experiment. The structural dynamic behavior of the joined-wing model is obtained and compared with MSC/NASTRAN analysis results. The aerodynamics of the joined-wing concept have been thoroughly overviewed by its inventor.[2]

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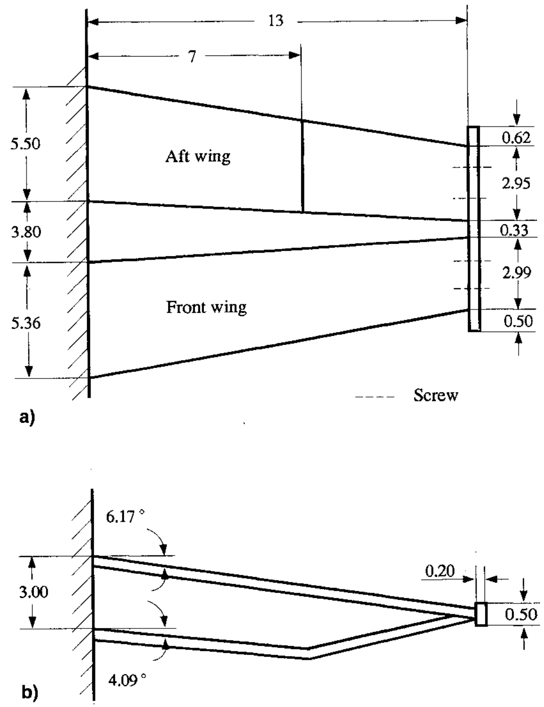

Fig. 1 Geometry of the joined-wing model (units in inches): a) planform view and b) front view.

A joined-wing airplane is defined as an airplane that incorporates tandem wings arranged to form diamond shapes in both plan and front views. The aerodynamics of the joined-wing have been studied by several individuals, but there is no literature dealing with its structural dynamics found to date. This work is an outgrowth of a variation of the typical joined-wing, but emphasis is on the structural dynamics, not the aerodynamics. The roots of each of the airfoils which make up the joined-wing of this work meet with the fuselage (as opposed to the typical joined-wing which has one wing attached to the fuselage and one attached to the tail of the aircraft). The aerodynamics of such an arrangement have been studied at Auburn University by Burkhalter et al.[3] including a wind-tunnel experimental model. The vibration model of this effort[4] has been based on their wind-tunnel model, but it was not intended to be an accurately scaled model due to the high cost of building such a model.

The geometry of the joined-wing model is shown in Figs. 1a and 1b. The model is for the left side of the aircraft. It consists of two wings in which the aft wing with anhedral from the bottom of the fuselage is swept forward and bent up near the middle of the span, to join the forward wing which is swept back with anhedral from the top of the fuselage. A joining beam connects the forward wing and the aft wing together by four screws at the tips. Both the forward and aft wings are fixed to an aluminum plate by bolts at the roots.

The plate is mounted on a large steel loading frame in the lab test arrangement.

The joined-wing is made of Alcoa 5086 aluminum plate which has a thickness of 0.1875 in., weight density of 0.096 lb/in.^{3}, modulus of elasticity of 10,300 kips/in.^{2}, and a Poisson's ratio of 0.33.

Experimental Test

The structural geometry for the joined-wing model is input into the Structural Testing, Analysis and Reporting Package (STAR)[5] by using 70 points. Figure 2 shows the structural mesh and coordinate system. Response is monitored by the Kistler accelerometer at point no. 15, at which all the response modes are effectively detected. The operational control of the test is done by the FFT "Analyze" program in the Waveform Analysis Package (WAVEPAK).[6] The frequency range of interest is from 0 to 800 Hz. Triggered stop mode is set in the force channel to capture the transient events of the hammer blows. In order to increase the signal-to-noise ratio and reduce leakage, the WAVEPAK force/exponential window option is selected. For each impact site, three data snapshots which correspond to three hammer blows are collected and then averaged in a nonoverlapping, straight-averaged format. Data is collected and analyzed for both the force and response channels. The time waveforms of the impulse force and transfer functions are chosen to be displayed on the computer screen, and in the meantime, cross-channel functions like phase and coherence are computed and may be displayed later using the "Analyze" program. The acquired measurements are first saved in the WAVEPAK data base for later analysis, and then transferred to the STAR package for modal parameter extraction.

Finite Element Analysis

A structural analysis of the joined-wing model is also performed using MSC/NASTRAN[7] in order to increase confidence in the test results. Three different finite element models are used to model the structure; they are as follows:

1) 9-CBAR model: the first model uses the CQUAD4 quadrilateral plate elements to model the front and aft wings. Rotational DOFs normal to the plate are constrained while all other DOFs are left unconstrained, except at the roots where all DOFs are fixed. The connecting beam at the model's tip is modeled by nine CBAR elements, all simple beam elements. The CBAR elements connect the grid points at the tips of the wings. Since the neutral axis of the connecting beam is offset from these grid points, offset vectors are defined on the CBAR statements. These vectors are treated as rigid links between the grid points and the end of the CBAR elements in the NASTRAN analysis.

2) CONM2 model: the second model also uses CQUAD4 elements to model the front and aft wings, but now only one CBAR element is used to connect the wings. The rest of the parts of the connecting beam are modeled by concentrated masses on the grid points at the tips of the wings. CONM2 elements, which are general mass elements, are used.

3) 5-CBAR model: for the third model, four more grid points are defined at the tips of the wings, and this changes four of the CQUAD4 elements which were used in the first and second models into four CQUAD8 elements. The coordinates of these four additional grid points are exactly the locations where the four screws are used to connect the two wings together in the physical model. The connecting beam is then modeled by five CBAR elements which connect the four additional grid points (screws). The purpose of using this model is to give a more realistic consideration of the actual connections of the wings and joining beam on the laboratory model.

The modified Givens' method is specified on the EIGR statement in NASTRAN in all three cases to find the first eight natural frequencies.

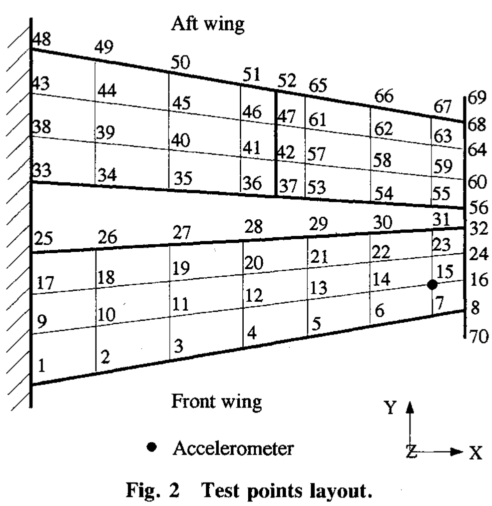

Fig. 2 Test points layout.

Results and Discussion

Eight resonant frequencies are found below 800 Hz after the modal parameters are extracted by the STAR program. The experimental frequency values are listed in Table 1 together with the first eight resonant frequency values found by the three NASTRAN models.

Figure 3 shows typical coherence, phase, and transfer functions of an impact site. It is clearly seen that there are eight resonant peaks on the transfer function plot. Corresponding to each of the peaks, there is a phase shift of 180 deg with the phase value being -90 deg, which is one of the phenomena of resonance. In practice, the coherence function, which is always less than or equal to one, is taken as an indication of how accurate the measurement is over a given range of frequencies. The figure shows that the coherence function values are not less than 0.95 in the vicinity of resonant frequencies, indicating the measurement is good.

It can be seen from Table 1 that for the first four modes the NASTRAN models give higher frequency values than do the test results. This is reasonable considering that the structure is treated as ideally fixed in the NASTRAN analysis, while it is highly improbable to achieve such a perfectly fixed condition in the lab. This means the joined-wing model mounted on the steel load frame has less stiffness than its NASTRAN model. The fact that no damping factor is considered in the NASTRAN analysis also contributes partially to this phenomenon. For the last four modes, the first NASTRAN model (using nine CBAR elements to model the joining beam) also gives higher frequencies than do the test results; this is also true for the third NASTRAN model (using five CBAR elements to model the joining beam), except for the fifth mode. But all the frequencies for these modes given by the second NASTRAN model (using CONM2 elements to model the joining beam) are lower than the test results. This is due to the different modeling of the joining beam. The most significant difference between the 9-CBAR model and the CONM2 model is that the CONM2 model alters the rigidity of the connection of the joining beam and the front and aft wings, and consequently lowers the stiffness of the whole structure and the frequencies of the last four modes. The 5-CBAR model is perhaps the best compromise between the 9-CBAR model and the CONM2 model in terms of modeling the rigidity of the connection of the joining beam and the wings. From Table 1, it can be seen that the frequencies of the lower order modes do not change very much among the three models compared to the higher order modes. This suggests that the joining beam has more influence on the higher order modes than it does on the lower order modes. Overall, the 5-CBAR NASTRAN model gives the best agreement with the test results, with only mode 4 differing by more than 10%.

Table 1 **Joined-wing model modal testing and finite element analysis results**

Mode no.	Modal testing frequencies, Hz	First NASTRAN model (9-CBAR) Frequency, Hz	First NASTRAN model (9-CBAR) Error, %	Second NASTRAN model (CONM2) Frequency, Hz	Second NASTRAN model (CONM2) Error, %	Third NASTRAN model (5-CBAR) Frequency, Hz	Third NASTRAN model (5-CBAR) Error, %
1	71.83	79.28	10.37	77.60	8.03	75.38	4.94
2	142.22	159.38	12.07	154.85	8.88	151.26	6.35
3	264.69	300.66	13.59	282.05	6.56	286.28	8.16
4	340.87	436.31	28.00	369.11	8.28	378.64	11.08
5	442.11	444.67	0.58	413.25	−6.53	429.60	−2.83
6	560.42	613.00	9.38	521.59	−6.93	598.99	6.88
7	613.03	672.23	9.66	604.65	−1.37	634.08	3.43
8	712.70	822.93	15.47	680.64	−4.50	727.01	2.01

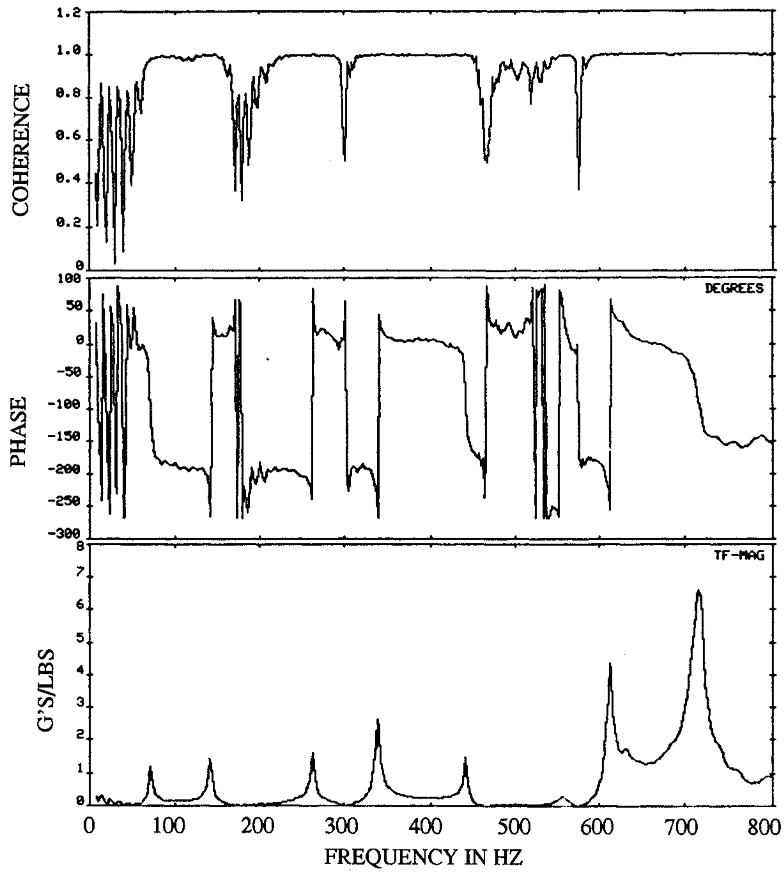

Fig. 3 Typical coherence, phase, and transfer functions of an impact site.

Comments and Conclusions

The COMPAQ PORTABLE 386® modal testing system is very convenient to use. It normally takes about 20 min to set up the instrument for a simple test. The various software are all menu driven and easy to use. The accelerometer and hammer system are very sensitive, so that the signal conditioning gains should be chosen properly, sometimes even for different impact sites of the same structure. A careful hitting technique is required in order to avoid double hitting and to achieve accurate measurements. This was especially true for this particular wing model.

Eight resonant frequencies are found below 800 Hz for the joined-wing model from the modal testing experiment. The first mode shape is simple bending, while the remaining mode shapes are combinations of bending and twisting. Finite element analysis results show good agreement with the test results for the first four modes in terms of the frequency values and mode shapes. Proper modeling of the joining beam is essential in this analysis and a five-bar NASTRAN model of the joining beam gives better results. The lower order natural frequencies appear to be mainly associated with the wing thickness, while the joining beam seems to have the major influence on the higher order natural frequencies and mode shapes. More detail is given in Refs. 4 and 8.

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Parameter Estimates of an Aeroelastic Aircraft as Affected by Model Simplifications

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Introduction

PARAMETER estimation from flight data as applied to aircraft in the linear flight regime is currently being used on a routine basis.[1] However, the rigid body models used successfully up to this time seem to be inadequate for newly introduced highly maneuverable aircraft with a high degree of structural flexibility. Zerweckh et al.[2] have suggested that research is required to include appropriate aeroelastic models in parameter estimation algorithms for flexible aircraft. Waszak and Schmidt[3] suggested a simplified integrated modeling approach to account for aeroelastic effects in aircraft dynamics, and its use for highly elastic aircraft was demonstrated in Ref. 3. Furthermore, several model reduction methods have been considered in Ref. 3 and the frequency responses of the resulting models (full order, rigid, residualized, and truncated) are compared to show how mismatch among them increases as the flexibility of the aircraft is increased.

A full order model of an aeroelastic aircraft has too many parameters to yield satisfactory estimates by using any of the known parameter estimation methods.[4] In view of this, a preliminary study has been initiated in this Note to investigate how estimation model may be simplified to reduce the number of unknown parameters, and how are the resulting parameter estimates affected by such approximate models. Special attention has been paid to the extreme case of using rigid body model in the estimation algorithm, and an analytical method is proposed to predict approximations to parameter estimates expected from the use of rigid body models.

Methodology

Only the longitudinal axis nonlinear equations of motion of a flexible aircraft given in Ref. 3 are considered, and linearized about a straight and level cruise flight. Assuming variations in velocity to be negligible (u = constant), the equations of motion of Ref. 3 may be approximated for the short period mode as

$$\dot{\alpha} - q = \rho u S/2m \left[C_{z_\alpha}\alpha + C_{z_q} qc/2u + C_{z_\delta}\delta + \sum_{i=1}^{n} (C_{z_{ni}} n_i + C_{z_{\dot{n}i}} \dot{n}_i c/2u) \right] \tag{1a}$$

$$\dot{q} = \rho u^2 Sc/2I_y \left[C_{m_\alpha}\alpha + C_{m_q} qc/2u + C_{m_\delta}\delta + \sum_{i=1}^{n} (C_{m_{ni}} n_i + C_{m_{\dot{n}i}} \dot{n}_i c/2u) \right] \tag{1b}$$

where vehicle angle of attack α, pitch rate q, and control input δ represent small perturbations from the chosen reference flight conditions. n_i and $\dot{n}_i$ are the generalized elastic deflections and their time derivatives. C_{z_α}, C_{m_δ} . . . are the stability and control derivatives as defined in Ref. 3. Air density ρ, total inertial velocity u, wing area S, wing chord c, aircraft mass m, and moment of inertia about Y axis I_y are the other quantities used in the above equations.

The following equation satisfied by the generalized coordinates n_i is taken from Ref. 3, except that a term $2\xi_i\omega_i\dot{n}_i$ representing the structural damping is also included into it

$$\ddot{n}_i + 2\xi_i\omega_i\dot{n}_i + \omega_i^2 n_i = \frac{\rho u^2 Sc}{2M_i} \left[C_\alpha^{ni}\alpha + C_q^{ni} qc/2u + C_\delta^{ni}\delta + \sum_{j=1}^{n} (C_{nj}^{ni} n_j + C_{\dot{n}j}^{ni} \dot{n}_j c/2u) \right] \tag{2}$$

where ω_i, ξ_i, and M_i are the in-vacuo frequency, modal damping, and modal generalized mass, respectively. The total force coefficients have the usual meaning as given in Ref. 3.

Rigid Body Modeling

The simplest possible approach to parameter estimation from flight data of an aeroelastic aircraft is to use a rigid body estimation model. Since in actual flight data, the effects of all the aeroelastic modes will necessarily be present, it is expected that the aeroelastic effects will get absorbed into the estimated parameters using rigid body model in estimation algorithm. For convenience, we shall refer to such parameter estimates by the name "equivalent parameters."

The basic question posed is, when and how useful are these estimated equivalent parameters. Can we analytically predict the expected values of equivalent parameters. For this purpose, it is assumed that the contributions of the generalized elastic deflections (n_i) are instantaneous. Steady-state expression for $(n_i)_{ss}$ is obtained from Eq. (2) by dropping the time derivative terms.

$$(n_i)_{ss} = \rho u^2 Sc/2M_i\omega_i^2 \left[C_\alpha^{ni}\alpha + C_q^{ni} qc/2u + C_\delta^{ni}\delta + \left(\sum_{j=1}^{n} C_{nj}^{ni} n_j + C_{\dot{n}j}^{ni} \dot{n}_j c/2u \right) \right] \tag{3}$$

Next, Eq. (3) is substituted into Eq. (1). Collecting the coefficients of various flight variables and control input yield approximate analytical expressions for the equivalent parameters. These represent approximations to the equivalent de-

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