Engineering Notes

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Iterative Algorithm for Correlation of Strain Gauge Data with Aerodynamic Load

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I. Introduction

THE conventional method for converting flight-strain gauge data to aerodynamic loading is to draw a cut on the structure at some station, make a free-body diagram, and require the internal loads of all structural elements at the cut to balance the external aerodynamic load distributed over the free body. To account for every structural element along the cut, a large number of strain gauges must be installed. Load calibration of the strain gauges can be done in a static test with known applied loads. Examples of strain gauge calibration and predicted flight loads from measurements can be found in Refs. 1 and 2. A significant disadvantage with this approach arises if the wing is inadequately strain gauged or if the distribution of the aerodynamic loads is poorly understood.

The proposed approach presents a linear combination technique, which assumes the aerodynamic load on the structure can be represented by using a set of polynomial shape functions over the wing surface, including lift, drag, and side forces, as well as inertial force, even thermal load, because the measured strain gauge data reflect the influence of all forces. The linear combination technique is an attempt to simulate these forces by distinguishing each individual contribution to the measured strain gauge data, so that the shape functions used in the linear combination should include all possible forces. A finite element model of the wing structure is used to calibrate the shape functions in terms of unit strain at given gauge locations. From measured gauge data, weight factors for the shape functions are computed, thereby determining the pressure distribution on the structure.

The selection of these shape functions is crucial to the success of this method. The so-called iteration scheme provides a systematic approach of improving the combination of shape functions under the idea of minimizing residual strain, which is the difference between the computed strain (due to the computed pressure) and the measured strain. It will be shown in the following that iteration of this scheme can improve the accuracy of the computed pressure distribution.

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II. Formulation

The basis of the proposed strain gauge pressure distribution correlation algorithm is the linearity of elastic structural behavior. This assumes a unique correspondence between deformation and applied forces. Thus, if $F(\xi)$ represents the force required to produce a deformation state ξ, then for an additional deformation η, with α and β as multipliers, respectively,

$$F(\alpha\xi + \beta\eta) = \alpha F(\xi) + \beta F(\eta) \tag{1}$$

In the case of aerodynamic loading of a wing structure, if the shape of the pressure distribution is known, then only one calibrated gauge is needed to determine the magnitude of the loading. While the shape of the pressure distribution is generally unknown in practice, it may be possible to represent it as a linear combination of known shape functions:

$$F(x_i) = \sum_{j=1}^{N} a_j f_j(x_i) \tag{2}$$

where $F(x_i)$ is the real pressure distribution at (x_i) on the wing; $f_j(x_i)$ is a known shape function to simulate lift, drag, and inertial loads. For example, the shape functions for lift force are Lagrange polynomials, defined over a two-dimensional triangular domain, as in Zienkiewicz's book.[3] The triangular domain corresponds to the Space Shuttle wing planform. The term a_j is an unknown weight factor for the jth shape function.

Assuming linearly elastic behavior, one can also write

$$U(x_i) = \sum_{j=1}^{N} a_j u_j(x_i) \qquad \epsilon(x_i) = \sum_{j=1}^{N} a_j \epsilon_j(x_i) \tag{3}$$

where U and ϵ represent the real deformation and real strain states, respectively; u_j and ϵ_j represent deformation and strain states due to a unit loading function f_j. Thus,

$$u_j = K^{-1} f_j \qquad \epsilon_j = BK^{-1} f_j \tag{4}$$

K is the stiffness matrix of the structure; B is the displacement-strain differential operator matrix. The strain value at each

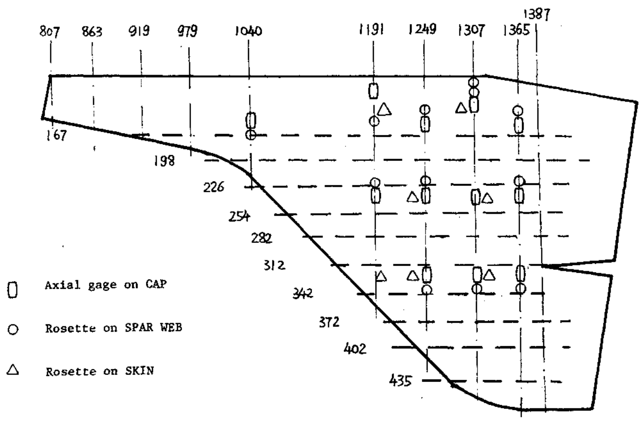

Fig. 1 Strain gauge instrumentation layout.

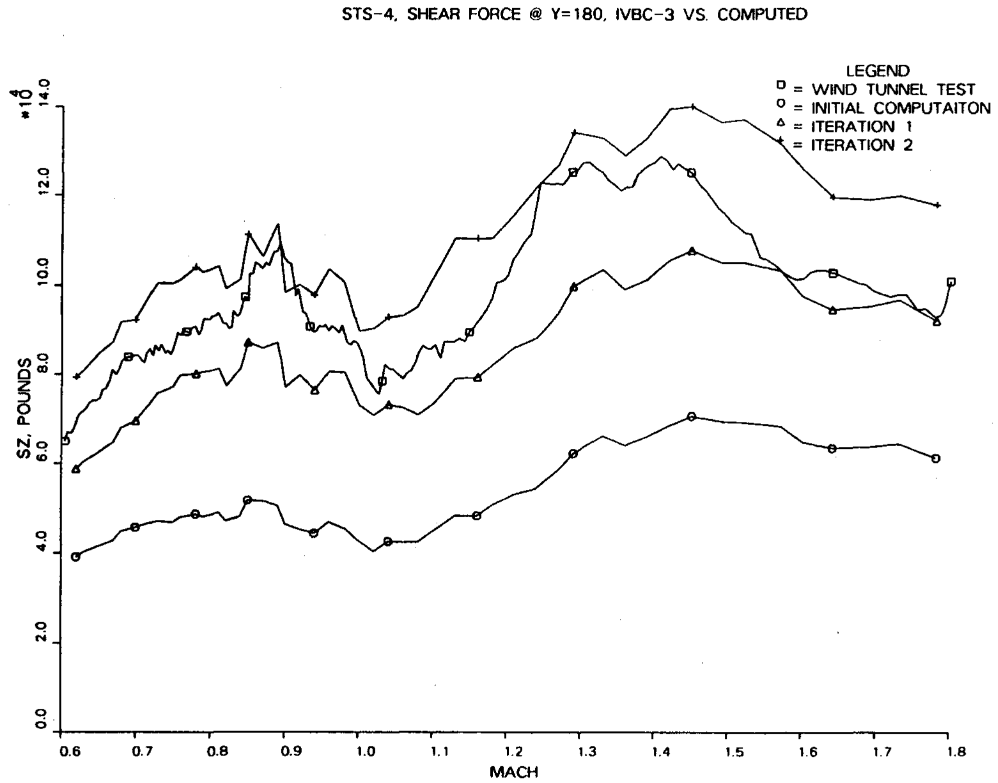

Fig. 2 Comparison of measured and computed shear force vs Mach number (STS-4, shear force at $y = 180$, IVBC-3).

gauge location due to each unit shape function can be computed by a finite element model, in effect a computer numerical calibration. Let C_{ij} represent the strain computed at the ith gauge location, due to a unit shape function f_j, then the weight factor a_j can be computed in terms of C_{ij} and the measured strain ϵ_{gauge}

$$\{a_j\} = [C_{ij}]^{-1}\{\epsilon_{\text{gauge}}\} \tag{5}$$

Substituting $\{a_j\}$ into Eq. (2), the actual pressure distribution can then be found. Equation (5) can be treated as overdetermined simultaneous equations (more equations than unknowns) and can be solved in the least-squares sense, i.e., $\min\|[C]\{a\} - \{\epsilon_{\text{gauge}}\}\|_2$. The purpose is to tolerate errors associated with real flight data.

The overdetermined system $[C]_{m\times n}\{a\}_{n\times 1} = \{\epsilon\}_{m\times 1}$, $m \geq n$, can be solved such as

$$[C]^T[C]\{a\} = [C]^T\{\epsilon_{\text{gauge}}\}, \qquad \{a\} = ([C]^T[C])^{-1}[C]^T\{\epsilon_{\text{gauge}}\} \tag{6}$$

III. Iterations

Applying the computed pressure distribution back to the finite element model of the structure, the residual strain can be found, that is, the difference between the computed strain at each gauge location and the measured strain from flight. The proposed iteration scheme takes the residual strain as input, assumes it corresponds to some supplementary pressure distribution made of another set of shape functions, which are higher order shape functions, and repeats the process to find out this supplementary pressure distribution to be added to the initial one. The mathematical basis of the iteration technique is under investigation.

Initial calculation (superscript I)

$$F^I = \sum_{j=1}^{N_1} a_j^I f_j^I; \qquad \{a^I\} = C^{-1}\{\epsilon_{\text{gauge}}\}$$
$$\{\epsilon_{\text{res}}^I\} = \{\epsilon_{\text{gauge}}\} - BK^{-1}\{F^I\} \tag{7}$$

First iteration (superscript II)

$$F^{II} = F^I + \sum_{j=1}^{N_2} a_j^{II} f_j^{II}; \qquad \{a^{II}\} = C^{-1}\{\epsilon_{\text{res}}^I\}$$
$$\{\epsilon_{\text{res}}^{II}\} = \{\epsilon_{\text{gauge}}\} - BK^{-1}\{F^{II}\} \tag{8}$$

Second iteration ....

IV. Example

The data fitting method presented here gives exact results when applied to a simple structure with accurate strain data. The purpose for development of the method is to obtain better correlation with flight-test data from a highly complex structural and aerodynamic configuration such as the Space Shuttle. An example based on Space Shuttle flight STS-4 (the fourth shuttle mission) is shown below. Three computed curves (initial and 2 iterations) of the foregoing algorithm are plotted against the one from wind-tunnel data base IVBC-3.[4] The load variables are shear force and bending moment, as functions of Mach number during Space Shuttle ascent. A strain gauge instrumentation layout on the Space Shuttle wing is shown in Fig. 1. Basically three types of strain gauges were installed: axial gauge on spar cap, rosette on spar web, and rosette on skin. Those gauge locations are considered as critical from a structural analysis point of view. Thermal and inertial effects are not significant for the orbiter wing structure during ascent.

Shuttle wing load was derived as follows: data from 48 strain gauges were obtained from the flight of STS-4. Lagrange polynomial shape functions for lift distribution on the triangular wing and for drag along the wing leading edge were defined as shown in the Table 1.

Shear force SZ and bending moment MX were computed at the station $y = 180$ in. as

$$SZ = \int_{\text{Sta}} F(x,y)\,\mathrm{d}x\mathrm{d}y, \qquad MX = \int_{\text{Sta}} F(x,y)\cdot(y - 180)\,\mathrm{d}x\mathrm{d}y \tag{9}$$

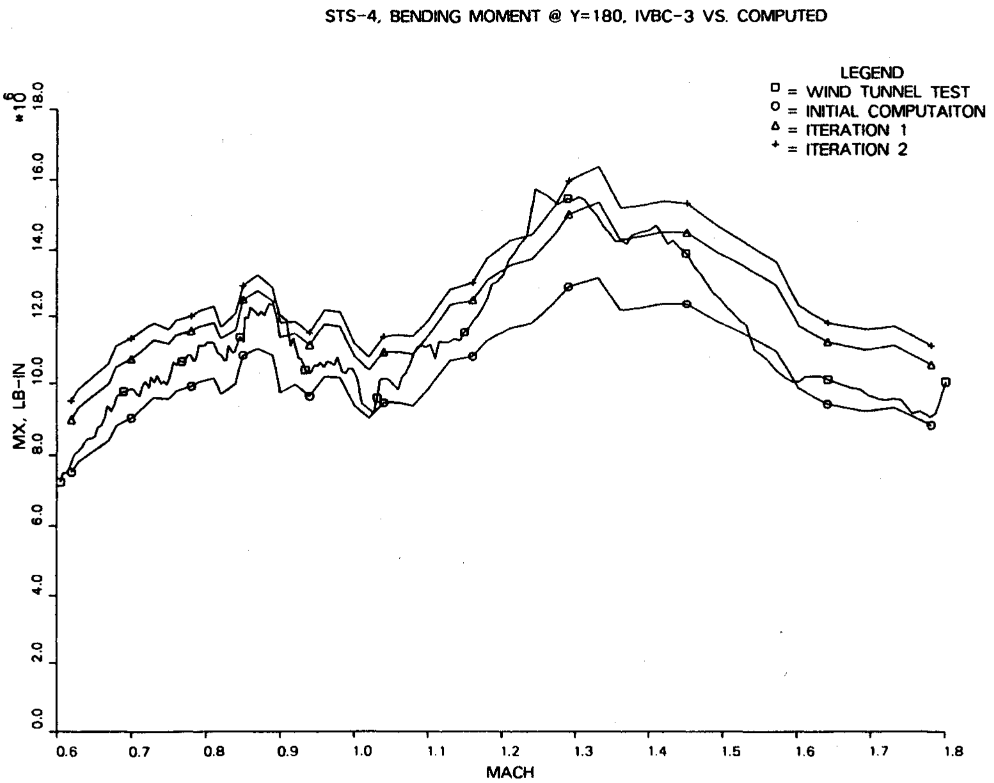

Fig. 3 Comparison of measured and computed bending moment vs Mach number (STS-4, bending moment at y = 180, IVBC-3).

Table 1

	Interpolation polynomial	
Iteration no.	Lift	Drag
0	2nd order	1st order
1	3rd order	2nd order
2	4th order	3rd order

The instrumentation layout (see Fig. 1) shows the coordinates; Sta is the area on wing from station y = 180 in. to tip. The variation in SZ and MX with Mach number are shown in Figs. 2 and 3, respectively.

Notice that the computed terms SZ and MX do not directly reflect the influence of drag force on the wing; however, the inclusion of drag terms in the assumed force distribution is necessary to account for drag effects on structural strain as recorded by the strain gauges. In addition to lift and drag distributions, an assumed twisting moment along the leading edge might be used to account for leading-edge suction effects. It was not used in this study.

V. Conclusion

By comparison with the wind-tunnel test-based IVBC-3 data, the proposed algorithm shows good correlation. In the transonic region, the proposed algorithm holds some inherent superiority to wind-tunnel test and computation fluid dynamics method due to the fact that the proposed algorithm is based on structural deformation. Because the general principles involved in deriving the algorithm are valid in most other engineering cases, its potential application should be adaptable to any aircraft loading problem.

References

[1]"B-1 Aircraft No. 2 Airload Survey Program Strain Gauge Calibration," Rockwell International Corp., Los Angeles, CA, Rept. No. AD-b027106L TFD-75-958, 1976.

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[3]Zienkiewicz, O. C., *The Finite Element Method in Engineering Science,* McGraw-Hill, London, 1971.

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Yaw Damping of Elliptic Bodies at High Angles of Attack

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Introduction

DEPARTURE and spin resistant vehicles are necessary for useful flight at high angles of attack. Forebody vortices in this flight regime can dominate the overall configuration stability and departure susceptibility. Rotary balance testing has been used to further our understanding of these flows[1] and to predict aircraft spin characteristics.[2] Experimental results for a series of bodies have been obtained[3,4] using a rotary balance. Bodies that were undamped in yaw at moderate angles of attack became damped as the angle of attack increased.

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