dure was used to calculate the adhesive strength of bonded double-lap joints. The results of these calculations show the effects of loading condition, bond size, and adhesive material behavior on bonded joint strength.

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References

[1]Hart-Smith, L. J., "Adhesive-Bonded Double-Lap Joints," NASA CR-112235, Jan. 1973.

[2]Hart-Smith, L. J., "Adhesive-Bonded Single-Lap Joints," NASA CR-112236, Jan. 1973.

[3]Hart-Smith, L. J., "Designing to Minimize Peel Stresses in Adhesive-Bonded Joints," Douglas Aircraft Company, Long Beach, CA, Paper 7389, Nov. 1983.

[4]Rice, J. R., "Mechanics of Crack Tip Deformation and Extension by Fatigue," *Fatigue Crack Propagation*, American Society for Testing and Materials, ASTM STP 415, 1967, pp. 247-311.

Readers' Forum

Brief discussion of previous investigations in the aerospace sciences and technical comments on papers published in the AIAA Journal *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Comment on "Direct Component Modal Synthesis Technique for System Dynamic Analysis"

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THE authors of Ref. 1 have presented an excellent method which has a number of advantages over conventional component modal synthesis techniques. By eliminating the usual displacement coordinates in favor of the joint or generalized, forces between substructures, the size of the governing matrix equations is substantially reduced. Indeed, the order of the matrix is equal to the number of compatibility, or constraint, connection, and joint, conditions between substructures. The authors' examples and conclusions further support the advantages of the method.

The present writer is particularly pleased to see the publication of this paper as he developed essentially the same method some years ago, and described it in a series of publications. In the present writer's approach, the Lagrange Multiplier method is used to incorporate the constraint or compatibility conditions between substructures and the forces of constraint or compability are simply the Lagrange Multipliers themselves.[2-9] This method has also been used to incorporate the effects of nonconservative forces including damping,[5] as well as nonlinearities.[6-8]

It has also been shown how the method may be used to add or subtract a substructure without a total reanalysis of the system.[9]

Now that the method has been rediscovered, it will hopefully be more widely used.

References

[1]Lee, E. K. L., and Tsuei, Y. G., "Direct Component Modal Synthesis Technique for System Dynamic Analysis," *AIAA Journal*, Vol. 27, No. 8, 1989, pp. 1083–1088.

[2]Dowell, E. H., "Free Vibrations of a Linear Structure with Arbitrary Support Conditions," *Journal of Applied Mechanics,* Vol. 38, No. 3, 1971, pp. 595-600.

[3]Dowell, E. H. "Free Vibrations of an Arbitrary Structure in Terms of Component Modes," *Journal of Applied Mechanics,* Vol. 39, No.3, 1972, pp. 727-732.

[4]Dowell, E. H., "On Some General Properties of Combined Dynamics Systems," *Journal of Applied Mechanics,* Vol. 46, No. 1, 1979, pp. 206-209.

[5]Dowell, E. H., "Bounds on Modal Damping by a Component Modes Method Using Lagrange Multipliers," *Journal of Applied Mechanics,* Vol. 47, No. 1, 1980, pp. 211-213.

[6]Dowell, E. H., "Component Mode Analysis of Nonlinear and Nonconservative Systems," *Journal of Applied Mechanics*, Vol. 47, No. 1, 1980, pp. 172-176.

[7]Dowell, E. H., "Component Mode Analysis of a Simple Nonlinear, Nonconservative System," *Journal of Sound Vibration*, Vol. 80, No. 2, 1982, pp. 233-346.

[8]Dowell, E. H., and Tongue, B., "Component Mode Analysis of Nonlinear Nonconservative Systems," *Journal of Applied Mechanics*, Vol. 50, No. 1, 1983, pp. 204-209.

[9]Dowell, E. H., "Theory and Application of Dynamic Decoupling in Structural Analysis: Another View," *Finite Elements in Analysis and Design*, Vol. 3, No. 2, 1987, pp. 119-125.

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Reply by the Author to Earl H. Dowell

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We appreciate the comments from Prof. E. H. Dowell. Dowell presented a method, as discussed in his references, which is a variation of a Rayleigh Ritz approach to determine the system eigen frequency. The Lagrange multiplier lambda vector in his method corresponds to the modal force vector in the modal force method. Contrary to Dowell's variational approach, we formulate the solution equation by physical coordinates. Futhermore, after the modal force vector has been obtained, the modal force method provides the mode shape of the entire system in physical coordinates directly without any inversion of matrix.

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As Dowell discussed, the size of the governing matrix equations is substantially reduced by eliminating the usual displacement coordinates in favor of the joint forces or modal force vector, between substructures. This is the key difference between the Receptance method and the modal force method.[1,2] The latter directly uses the physical coordinates at joints to generate the system equation. The emphasis is on the determinant of the modal force matrix ($\bar{H}$) for natural frequencies and on the modal force vector ($\bar{f}$) for mode shapes of the synthesized structure.

The Modal Force method has been extended and applied for the system modification,[2,3] rotor dynamics,[4] and system transient response analysis.[5]

We share the same feelings as Dr. Dowell and hope that the method will be more widely used for system dynamic analysis.

References

[1]Yee, E. K. L., and Tsuei, Y. G., "Direct Component Modal Synthesis Technique for System Dynamic Analysis," *AIAA Journal*, Vol. 27, August 1989, pp. 1083-1088.

[2]Tsuei, Y. G., Yee, E. K. L., and Lin, A. L. Y., "Physical Interpretation and Application of a Component Modal Synthesis Technique (Modal Force Method)," *Proceedings of the Eighth International Modal Analysis Conference Proceedings*, Orlando, Florida, Feb., 1990.

[3]Tsuei, Y. G., and Yee, E. K. L., "A Method for Modifying Dynamic Properties of Undamped Mechanical Systems," *American Society of Mechanical Engineering Dynamic Systems, Mearsurment, and Control*, Vol. 111, Sept. 1989, pp. 403-408.

[4]Tsuei, Y. G., Yee, E. K. L., and Wang, S. S., "A Component Modal Synthesis Technique for the Lateral Vibration Analysis of Aircraft Engine Systems," *Proceedings of the Seventh International Modal Analysis Conference*, Las Vegas, Nevada, Feb., 1989, pp. 377-383.

[5]Tsuei, Y. G., and Yee, E. K. L., "Component Synthesis Method for Linear and Nonlinear Transient Response," *AIAA Journal*, (to appear).

Comment on "Optical Boundary-Layer Transition Detection in a Transonic Wind Tunnel"

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DURING recent years, methods to nonintrusively measure details of the laminar-to-turbulent transition process have been developed mostly for high-Mach-number flows where, for example, hot-wire probes are not practical. A differential laser interferometer is applied in the experiment discussed in Ref. 1 to detect relative variations in density fluctuations in a laminar, transitional, and turbulent boundary layer over a wind-tunnel model at freestream Mach numbers ranging from $M = 0.7$ to $M = 0.8$. The purpose of this Comment is to clarify some details of the transition process in the flowfield of Ref. 1 and to point out a few inconsistencies in the experimental setup and the presented analysis of the transition mode in Ref. 1.

Figure 1 presents the predicted subcritical pressure distribution along the upper surface of an NACA 66-006 airfoil, which has a slightly negative angle of attack. The two-dimensional method of Ref. 2 that models wind-tunnel walls is used to analyze the potential flowfield for the test configuration as described in Ref. 1. The compressible laminar boundary-layer development and the linear stability characteristics of the boundary layer along the airfoil are analyzed for the appropriate conditions (chord-Reynolds number R_c = 1.96 million and $M = 0.70$) using the methods of Refs. 3 and 4, respectively. The onset of laminar separation is predicted to occur at 11.6 cm ($x/c \cong 0.77$, where the airfoil chord is $c = 15$ cm) from the leading edge. The well-defined transition pattern in the spanwise direction indicated by the sublimating chemical technique in Fig. 5 of Ref. 1 (the segment unaffected by the turbulent wedges) is indicative of transition due to shear-layer instability at laminar separation[5]. Transition occurs at $x/c = 0.80$ in the experiment. Also, the increased spreading angle of the turbulent wedge after $x/c \cong 0.66$ in Fig. 5 of Ref. 1 corresponds with the predicted onset of streamwise pressure increase at $x/c = 0.65$ in Fig. 1 of this Comment. Thus, the predicted flowfield along the upper surface of the airfoil appears to match the experimentally measured flowfield reasonably well.

The predicted logarithmic amplification growth ("n-factor") for several Tollmien-Schlichting (T-S) disturbance frequencies is presented in Fig. 1 for the given test conditions. The most amplified unstable frequencies in the attached boundary-layer ahead of the separation point are in the range of 15-40 kHz. The calculated wavelength for the 25-kHz disturbance is about 7δ (δ is the boundary-layer thickness, $\delta = 0.004c$ at $x/c = 0.65$). The combination of the favorable pressure gradient over the front portion of the airfoil, the relatively low chord-Reynolds number and the damping effect of flow compressibility[6] prevents the growth of these disturbances until the onset of pressure recovery at 9.8 cm ($x/c = 0.65$) from the leading edge. The n-factor for the T-S frequencies around 25 kHz grows rapidly in the adverse-pressure-gradient region but does not exceed 4. (If the Mach number is increased to $M = 0.8$, even lower amplitudes are obtained for the unstable T-S frequency range.) Natural transition due to catastrophic growth of unstable T-S waves has been correlated for wind-tunnel experiments to coincide with amplification factors of 7-11.[7]

Unfortunately, the range of most amplified unstable frequencies lies below the chosen bandwidth of the inter-

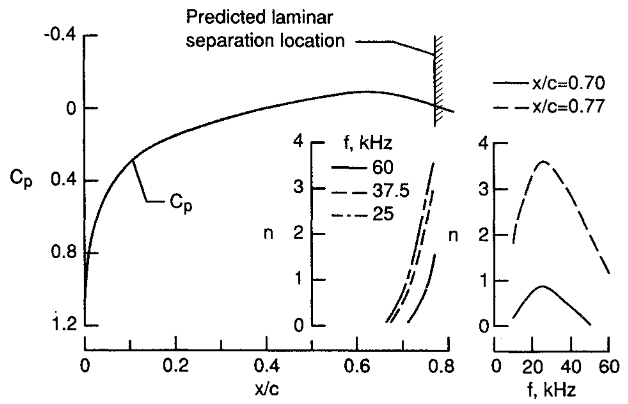

Fig. 1 Predicted surface-pressure distribution (C_p-Pressure coefficient) over NACA 66-006 airfoil in tunnel geometry of Ref. 1 and predicted amplification ratios for several unstable T-S disturbance spectrum (f-frequency); $M = 0.70$, $R_c = 1.96$ million.

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