Engineering Notes

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Aerodynamic Lag Functions, Divergence, and the British Flutter Method

William P. Rodden* and E. Dean Bellinger†
The MacNeal-Schwendler Corporation, Los Angeles, Calif.

IN Ref. 1, a transient formulation of the flutter and divergence problems was presented using aerodynamic strip theory and an exponential approximation to the Wagner function (or its compressible counterpart) which led to a definition of aerodynamic lag functions. A different approximation was used earlier by Richardson,[2] and various other approximations have been suggested recently.[3-6] The need for approximations to aerodynamic transfer functions may be essential for control system *design*, e.g., for load alleviation or flutter suppression, but the need for such approximations for aeroelastic stability *analysis* is not obvious. Recently, Woodcock has remarked[7]: "However, it is hoped that the reader will have been emphatically convinced, as the writer is, that the rational approximation (such as the *N*-point Padé approximation) is the simplest, most foolproof, and most convenient for use in aeroelastic investigations." Earlier, Woodcock had remarked[8]: "Thus the traditional UK method of flutter investigation with lined-up frequency parameter is completely adequate for determining such stability; for it determines any roots with zero real part correctly and so by a survey of the speed range finds whether any root becomes unstable. There is also some evidence that it determines complex roots with a fair degree of accuracy even when the real part is negative and relatively large (compared with the imaginary part)." The present authors prefer Woodcock's earlier view of the matter.

The purpose of this Note is to present some calculated results for a two-dimensional airfoil to compare the transient method (*p* method in the notation of Hassig[9]) and the British flutter method[10-12] (*p-k* method in the notation of Hassig, *PK* method in NASTRAN®,‡ and UK method in Woodcock's writings) in the prediction of both flutter and divergence instabilities. The transient method includes the transient aerodynamic representation *explicitly*, whereas the British flutter method only includes the transient aerodynamics *implicitly*. It will be seen that either format for the aerodynamic forces results in the same prediction of instabilities: the flutter occurs when the torsion root becomes unstable, the divergence occurs when one of the aerodynamic lag roots becomes unstable.

Two examples of a two-dimensional airfoil mounted on bending and torsion springs are considered. The examples are the same except for the center of gravity location: in the first example it is at 37% chord, and in the second example it is at 45% chord. Both examples have the aerodynamic center at 25% chord ($\xi = 0.25$ in Ref. 1), and the elastic axis is at 40% chord. This choice of parameters results in example 1 having a divergence speed (V_d) below the flutter speed (V_f), and in example 2 having $V_d > V_f$. The remaining parameters for the analysis at sea level include a chord of 6.0 ft, a radius of gyration of 1.5 ft about the elastic axis, a mass ratio $\mu = 20.0$, uncoupled bending and torsion frequencies of 10.0 and 25.0 rad/s, respectively, and equal structural damping coefficients $g = 0.03$ in both modes. The lift curve slope is the theoretical incompressible value of 2π and the downwash is matched at the ¾-chord location ($r = 1.0$ in Ref. 1). The transient aerodynamic approximation constants are those of W.P. Jones[14,1]: $\alpha_1 = 0.165$, $\alpha_2 = 0.335$, $\beta_1 = 0.041$, and $\beta_2 = 0.320$.

The results for example 1 with the forward center of gravity (37%) are shown in Fig. 1. The curves in the figure are obtained from the transient method. Two sets of plotted points are also shown and were obtained from the *PK* method in MSC/NASTRAN: one using the exact Theodorsen function, and the other using the Jones approximation to the Theodorsen function.[15] As in Ref. 1, the transient method shows flutter occurs when the torsion root becomes unstable whereas divergence occurs when an aerodynamic lag root becomes unstable. In the *PK* method, the same behavior is seen although the results are not continuous. A discontinuity occurs at some velocity (slightly different in the two representations of the Theodorsen function) at which the *PK* algorithm converges to an aerodynamic lag root (with zero frequency) rather than the bending root. The present *PK* algorithm in NASTRAN then skips over the bending root in the reduced frequency "lining-up" process and next obtains the torsion root.

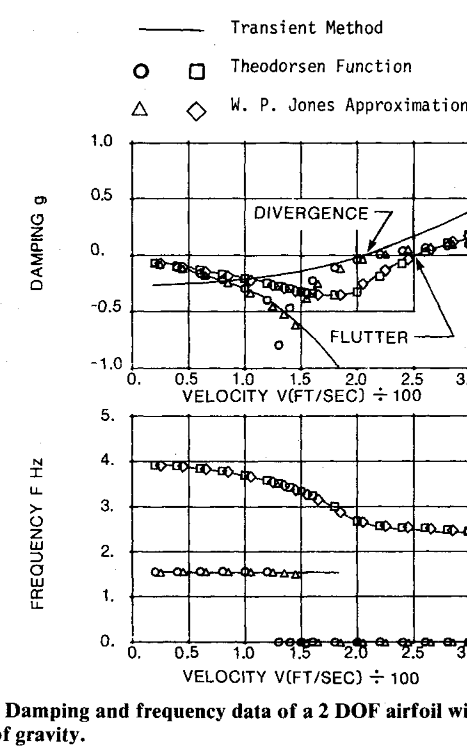

Fig. 1 Damping and frequency data of a 2 DOF airfoil with forward center of gravity.

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*Consultant. Associate Fellow AIAA.

†Senior Engineer.

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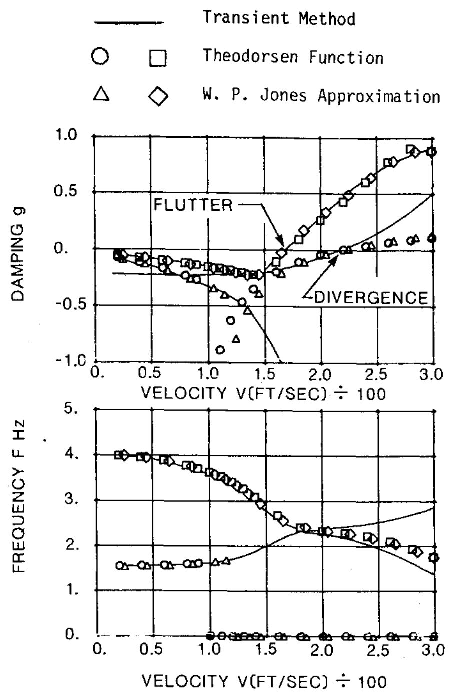

Fig. 2 **Damping and frequency data of a 2 DOF airfoil with aft center of gravity.**

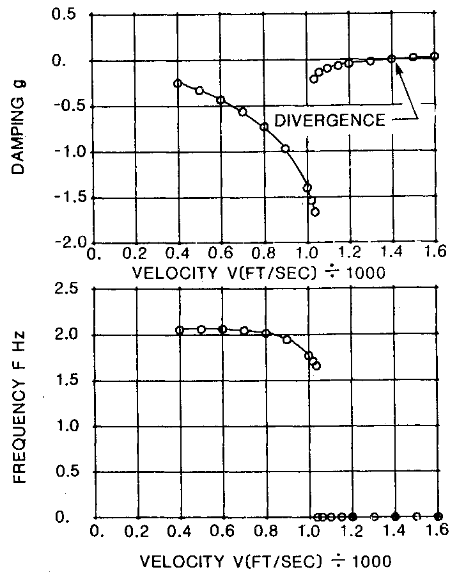

Fig. 3 **First mode damping and frequency data for the jet transport wing of Ref. 12.**

In state-space, with 2 degrees of freedom (DOF) and the two-term Jones approximation, the order of the transient method eigenvalue problem is six.§ In the *PK* method, the 2 DOF only lead to a fourth order eigenvalue problem, but the aerodynamic degrees of freedom, 2 in the case of the Jones approximation and an *infinite* number in the case of the exact Theodorsen function, are present implicitly and appear in the solution at speeds near the divergence speed. In the *PK* method, above the speed at which the aerodynamic lag root appears, the variations in damping are similar (the frequencies are zero in both cases) between the two representations of the Theodorsen function, and the divergence speed is identical in the two *PK* solutions and the transient method.

The results for example 2 with the aft center of gravity (45%) are shown in Fig. 2. The behavior is seen to be similar to Fig. 1 with the flutter instability now occurring below the divergence speed (which is independent of the center of gravity location); the flutter and divergence speeds agree with Fig. 9-5 (A)(r) and Eq. (8-7), respectively, of Ref. 13.

As a matter of "errata", Fig. 3 presents the jet transport wing example of Ref. 12 (and Refs. 13 and 1) with the bending and aerodynamic lag roots presented slightly differently: the damping coefficients are shown according to the different definitions in NASTRAN for oscillatory and real roots. This presentation makes the discontinuity obvious. The transition from the bending to the aerodynamic lag root was not recognized when Figs. 17 and 19 of Ref. 12 were prepared because the real part of the first eigenvalue was shown in Fig. 19 for comparison to the aerodynamic lag root from the transient method.

From the examples presented here, it is seen that the British flutter method adequately predicts all of the instabilities of aeroelastic systems without any need for approximations to aerodynamic transfer functions. The addition of an active control system[12,16] does not change this characteristic of the method. The problem of *design* for aeroservoelastic stability is another matter (see e.g., Refs. 17 and 18), but it might be suggested that limited approximations to the aerodynamic transfer functions (say, one-term Padé approximants for each vibration mode) may provide the basis for a design whose stability characteristics then can be accurately verified by analysis using the British flutter method.

§Richardson's description[2] (p. 13) of this situation is: "An illuminating feature of these results is that the series approximation for the aerodynamic terms is closely related in principle to the series approximation of the aeroplane structure. The continuous structure has an infinite number of degrees of freedom which is restricted by a finite number of modes, just as the infinite series for the aerodynamic forces is restricted by a finite number of terms." Woodcock[7] differs from Richardson's view of the aerodynamic approximation: "A disadvantage is an increase, perhaps large according to the order of the approximation, in the order of the eigenvalue problem and hence the introduction of a number of spurious eigenvalues." The transient formulation certainly increases the order of the eigenvalue problem, but the aerodynamic lag roots can hardly be regarded as spurious, not only for the reason given by Richardson, but also because one of them led to the divergence speed here and in Ref. 1.

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Stress Measurements in a Ribbon Parachute Canopy

Thomas A. Konicke*
U.S. Air Force, Edwards Air Force Base, Calif.
and
William L. Garrard†
University of Minnesota, Minneapolis, Minn.

Nomenclature

F	= drag force
n	$= (\sigma_{max}/\sigma_{ss})(F_{ss}/F_{max})$
R	= nominal radius
S	= distance from apex measured along gore centerline
S^*	= nondimensional distance, S/R
t^*	= ratio of time of maximum stress to time of maximum drag
σ	= stress

Subscripts

max	= maximum
ss	= steady state

Introduction

THE objective of this study was to experimentally determine the distribution of circumferential stress in a ribbon parachute canopy during inflation and at steady state. Stress measurements have been previously reported for block-[1,2] and bias-constructed,[3,4] flat, solid parachutes and for ringslot parachutes[2,5]; but not for ribbon parachutes. Stresses were measured on a circular, flat, block-constructed ribbon parachute model of 20% geometric porosity. Omega sensors[6] were mounted along the centerline of one of the gores in order to measure the distribution of circumferential stresses in the horizontal ribbons. Omega sensors were also mounted in different gores on the same ribbon in order to obtain the variation in stress from gore to gore. Additional Omega sensors were mounted across the slots to measure the force in the vertical tapes.

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*Second Lieutenant. Member AIAA.

†Associate Professor, Department of Aerospace Engineering and Mechanics. Associate Fellow AIAA.

Parachute Design and Test Procedure

The parachute model used had a nominal diameter of 4.64 ft (1.43 m) and was constructed with 24 gores. The parachute was cut from 1.1 oz/yd^2 (37.4 g/m^2) rip stop nylon cloth which had an effective porosity of 4%. A hot knife was used to cut slots in the cloth in order to simulate the ribbons in a full-scale parachute. A total of 27 horizontal ribbons was simulated. Each gore contained four vertical tapes. Radial tapes were fabricated from the same material as the canopy and no pocket bands were used. The parachute was very flexible and exhibited a stable trim angle of attack of 0 deg.

Omega sensors were mounted on the outside of the parachute canopy. Six sensors were mounted at an S^* of 0.63 at the centerlines of every fourth gore in order to measure variations in circumferential stress from gore to gore. Ten additional sensors were mounted at S^* values of 0.19, 0.26, 0.33, 0.41, 0.48, 0.56, 0.70, 0.78, 0.85, and 0.93 at the centerline of gore 1 to obtain the circumferential stresses in the horizontal ribbons. Sensors were mounted between horizontal ribbons at S^* values of 0.44 and 0.77 to measure the force in the vertical tapes.

Wind tunnel tests were conducted in the same manner as in Ref. 4. It is important to note that the Omega sensors were calibrated after attachment to the parachute.

Results

A typical time history of three stresses and overall force for a test at 4.16 psf is given in Fig. 1. The power spectral density of the steady-state stress was measured at various values of dynamic pressure and, as shown in Ref. 7, there was no value of frequency other than zero at which the stress exhibited significant peaks. A hot wire anemometer showed large fluctuations in velocity outside the canopy near the Omega sensors. The power spectral density of the velocity fluctuations was relatively flat and had about the same bandwidth as the stress fluctuations. Thus it appears that the stress fluctuations resulted from turbulence rather than from some type of aeroelastic instability.

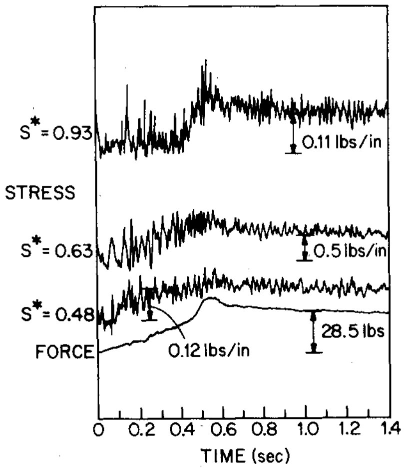

Fig. 1 Typical time history of stress and drag force.