Technical Comments

Comment on "General Formulation of the Aeroelastic Divergence of Composite Swept-Forward Wing Structures"

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ONE can only wonder at the reasons for the incessant refinements to an academic formulation of an aeroelastic problem that does not exist in flight. Reference 1 and many of its references have addressed the problem of divergence of a *cantilevered* composite forward-swept wing (FSW), whereas a FSW airplane will flutter in flight rather than undergo a quasistatic divergence. A number of papers[2-6] have shown that the flutter speed of a FSW aircraft is lower than the divergence speed of its cantilevered wing. A limited study[7,8] of a simple two-dimensional wing/fuselage with only a rigid-body degree of freedom in plunge also showed that the instability is always oscillatory for a large range of fuselage to wing mass ratio. (An earlier attempt[9] to study the divergence characteristics of an unrestrained FSW configuration by a quasistatic stability analysis was unsuccessful, but indicated the necessity of a dynamic stability analysis.) A number of other papers[10-14] show that an oblique-wing aircraft does not diverge either, but has a flutter speed higher than the divergence speed of its cantilevered FSW component. Weisshaar[15] has compared the oblique wing and FSW situations:

> "An important conclusion of these (oblique wing) studies was that the inclusion of the freedom of the oblique aircraft to roll as a rigid body during aeroelastic oscillation enhances the stability of the system. In particular, the aeroelastic divergence mode of instability associated with cantilevered forward-swept wings disappears and is replaced by a low-frequency, oscillatory instability that occurs at a higher flight speed than does divergence. (This is unlike the freely flying FSW, which experiences body freedom flutter at an airspeed lower than its divergence speed.) The inclusion of pitch and plunge rigid body freedoms further modifies the low-frequency instability speed, but not to the extent seen with the inclusion of rigid body roll freedom."

The main purpose for this Comment, however, is to criticize the use of aerodynamic strip theory. The assumption of strip theory is, of course, a sine qua non for a "closed-form" solution. The assumption has no compensating errors in a static aeroelastic problem, in contrast to the flutter problem where it sometimes enjoys some compensation (An even number of mistakes), viz., a conservative aerodynamic stiffness may offset an unconservative aerodynamic damping, depending on the reduced frequency of flutter, although the results are unreliable, as discussed in Ref. 16. The assumption of static strip theory has its maximum error in the wing tip region since the loading should go to zero in a somewhat elliptical manner at subsonic speeds and to zero according to conical flow theory at supersonic speeds. (See Ref. 17 for an approximate subsonic load distribution, Ref. 18 for the total lift curve slope of a swept planform at low subsonic speeds, and Ref. 19 for supersonic load distributions.) A secondary aspect of strip theory is the constant fraction of the chord assumed for the line of aerodynamic centers, again in the interests of a closed-form solution. [No mention is made of the implicit assumption that the airfoil has no camber; with camber, of course, the aerodynamic center and center of pressure are quite different, and the loadings in Eqs. (1a) and (1b) are not "complete."] On a swept wing in subsonic flow, lifting surface theory (and experiment) shows the line of aerodynamic centers tends to become perpendicular to the side edges at the root and at the tip; this aft movement near the FSW tip will modify the coupling between bending and torsion, so critical to the problem under consideration. The concluding remark in Ref. 16 seems to bear repeating: "It is hoped that these comments have served to illuminate the relative values of strip theory (its historical and *qualitative* values in the classroom) and lifting surface theory (its *quantitative* value in design, analysis, research, and in flight)."

The errors in the structural deflection theory should be well known, but deserve a few remarks. The elementary beam theory has been useful for high-aspect ratio *unswept* wings. Its assumptions are not valid in the region of a cantilevered root (or a fuselage side) of a swept wing. In fact, the problem of the stress distribution near the root of a swept-back wing led to one of the early developments of the finite-element method by Lang and Bisplinghoff[20] for exactly this reason. Some consequences of the errors at the root are inaccurate estimates of outboard deflections, which, of course, provide the *physical mechanism* for divergence; these errors increase substantially with the amount of sweep.

Since Ref. 1 did not even employ a "modified" aerodynamic strip theory that accounted for finite-span effects on the loading and the aerodynamic center location, and used a structural deflection theory that does not represent the effects of sweep adequately, its results are probably grossly inaccurate (and not entitled to five significant figures in Table 1). The additional fact that the rigid-body degrees of freedom were neglected does not warrant the results being presented as a "general formulation" since the FSW aircraft will not diverge in flight, but it will flutter, whether that flutter be called body-freedom flutter,[3] rigid-body/wing-bending flutter,[2,4] dynamic divergence,[7,8] aircraft aeroelastic divergence,[5] or just plain flutter. Finally, we note that analytical solutions of aeroelastic differential equations have given way to solutions of the aeroelastic integral equations by structural and aerodynamic finite-element methods in the current state-of-the-art, e.g., Ref. 21.

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Reply by Author to W. P. Rodden

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DURING the past ten years, a tremendous deal of progress toward a better understanding of aeroelastic behavior of forward-swept wing (FSW) aircraft and development of new technologies for its aeroelastic enhancement has been accomplished.

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Part of the studies devoted to FSW aircraft has dealt with the analysis of the divergence (known from earlier studies to appear at very low speeds) and flutter of restrained FSW. Appropriate references could be found in Ref. 1 and in the survey papers quoted there.

Other studies[2–4] have considered the aeroelastic instability experienced by an FSW aircraft in free-flight conditions. They have revealed *that under certain circumstances,* the aircraft rigid body motion could modify the restrained wing counterpart aeroelastic behavior in the sense that the loss of aeroelastic stability of FSW aircraft could occur dynamically at an airspeed slightly lower to the static divergence of its cantilevered wing (considered earlier to be the most critical one). This dynamic instability is known as body-freedom flutter (BFF).

It is important to underline the fact (see Refs. 4–6) that both aforementioned aeroelastic instabilities are due to the destiffening (drop in frequency) of the primary wing-bending mode with increasing airspeed. Whereas, for a restrained wing the destiffened mode yields the wing divergence instability, for a wing mounted on an unrestrained vehicle the destiffening mode frequency can coalesce, in certain cases, with the short-period mode of the aircraft, resulting in a low-speed dynamic instability (BFF).

Moreover, as it was revealed most recently, both theoretically and experimentally, [7–9] "the effect of aeroelastic tailoring on BFF follows the trend of cantilever wing divergence tailoring."

This trend suggests that destiffening of the primary wing-bending mode constitutes in general the basic ingredient both in the dynamic aeroelastic instability of FSW aircraft and of cantilever wing divergence. This conclusion is not only of a theoretical, but also of an exceptional practical importance. It implies that the prevention of BFF could largely be relied on the control of the destiffened wing mode instead of the flight dynamic mode. This could be accomplished by using either aeroelastic tailoring concept or active control procedures.

This further suggests[9] that aeroelastic tailoring findings based on wing divergence can be used in the design process to insure the avoidance, within the operational envelope of the aircraft, of BFF, or as initial data for a wing-based active control procedure envisaging the unrestrained vehicle as a whole.[5]

This shows undoubtedly that studies of the divergence of a cantilevered composite FSW and its "incessant refinements" are not of an "academic," but of a highly practical importance, playing a great role just in the avoidance of BFF instability.

Of course, all these considerations concern the case when BFF instability is more critical than its wing divergence counterpart. However, as it was pointed out in Refs. 6 and 10 (to which point of view we are fully adhering):

> "Although body freedom flutter has been calculated to be more critical than divergence of a cantilever wing for selected aircraft configurations, the aeroelastician should not generalize these findings. It is conceivable that cantilever wing divergence may, for peculiar aircraft configurations, be the most critical aeroelastic instability. Therefore, divergence of a cantilever wing should not be disregarded in the development of any new and promising aeroelastic control procedure."

These few elements presented constitute, in our opinion, enough arguments for the "incessant refinements" to the divergence instability problem and of its implications in the aeroelastic enhancement of FSW aircraft in general.

As regards the aeroelastic behavior of oblique-wing (OW) aircraft (a problem raised by the commenter but not addressed in our study), we are to observe by following the results obtained in Ref. 11 that the aeroelastic dynamic instability within the bend/twist/roll oscillatory coupling of OW aircraft occurs at slightly higher airspeeds than the divergence speed of its FSW segment. The results in Ref. 11 also reveal that the bending destiffening mode of the forward-wing segment is the basic