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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.

Received Oct. 17, 1988; revision received Nov. 14, 1988.

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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 ingredient both in the BFF of the oblique-wing aircraft and in the divergence of its forward-wing segment.

This common feature with the FSW aircraft suggests that the search for the divergence of FSW segment is still of high practical interest and not of an academic one.

Related to the comment about the use in our paper of the (corrected) strip-theory aerodynamics (STA), we are to mention that in spite of its local shortcomings, due to its intrinsic virtues it was, it is, and certainly it will be used further in aeroelastic research works. The research worker is not only attracted by its simplicity, ease of use, and possibility of getting trends while conducting parametric studies, but also by its capacity to predict in a reliable manner the aeroelastic instability characteristics of high- and moderate-aspect ratio wings. It was used by brilliant aeroelasticians and engineers, and the obtained results have been discussed and assessed by comparing them with the ones deduced within more accurate aerodynamic lifting surface theories (see, e.g., Refs. 12–18 and the papers quoted in Ref. 1 dealing with FSW, where in their large majority STA was used).

Since the commenter himself was one of the beneficiaries and users in earlier[19,20] and more recent papers[21,22] (and even in FSW aeroelasticity) of strip-theory aerodynamics, it is sure that he is fully aware also of its great virtues rendering it an aerodynamic tool of considerable value not only in the "classroom" but also in research, analysis, etc.

I fully agree with the comment related to the shortcomings experienced by the elementary beam theory in predicting accurately the stess distribution near the root of swept wings. However, suprisingly, the commenter has not remarked that the beam theory used in our paper is not the standard, but a refined one. In fact, just from this point of view there is an element of commonalty between our paper[1] and the one by Lange and Bisplinghoff[23] quoted by the commenter. This common element consists of the incorporation of warping inhibition effect at the wing root, which allows one to get a better description of the state of stress near the wing root by removing the free warping concept (intrinsic to the classical beam theory).

As was shown most recently,[24,25] the behavior of thin-walled composite beams is deeply modified by the warping restraint effect. In addition, it may have strong implications on the divergence behavior of swept-forward composite wings. Its incorporation within the anisotropic heterogeneous structural beam model and the analysis thereupon of the divergence instability reveal[1,26] the very complex and substantial role played by this effect even for high-aspect ratio wings.

It is hoped that this discussion will allow the commenter a better understanding not only of the goals and content of our paper, but also of the state-of-the-art of FSW aircraft aeroelasticity problem in general.

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