# Engineering Notes

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## Divergence Speed Degradation of Forward-Swept Wings with Damaged Composite Skin

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### Introduction

WITH flight speeds in the high subsonic Mach number regime beginning to be attainable, aerodynamic designers found that sweeping a wing either forward or aft delayed the rapid increase of transonic drag to higher Mach numbers However the aeroelastic characteristics of a flexible wing forced structural designers to consider only swept-back wings Diederick and Budiensky[1] demonstrated the drastic drop in divergence speed with forward sweep and wind tunnel tests verified their theoretical results Consequently modern high performance aircraft have aft-swept wings to preclude the unrealistic wing weights necessary for adequate stiffening of forward swept wings However, there appear to be certain aerodynamic advantages of forward swept wings over aft swept winds as noted by Krone [2]

Renewed interest in forward swept wing technology is due to Krone,[3] who used a technique called "aeroelastic tailoring" to demonstrate that forward swept wings without divergence and weight penalties are possible through the use of selective laminated advanced composites Aeroelastic tailoring is essentially the use of composite materials for the manufacture of aircraft wings resulting in a favorable bend ing twisting coupling behavior which allows one to "tailor" the wing deformation to reduce the divergence tendency of wings An illuminating general discussion of the use of aeroelastic tailoring for the design of forward swept wings is given by Hertz et al [4] However the divergence speed of these tailored wings can be very sensitive to variations in stiffness properties of the composite skin The changes in stiffness could result from battle damage or propagation of initial manufacturing defects

The designer of aircraft wings using this aeroelastic tailoring scheme must be cognizant of the danger of damage and should consider possible damage conditions at the beginning of a design. Since the extent of damage as well as its location cannot be predicted in advance, it is often necessary to investigate a large number of damage cases Such in vestigations can be prohibitively expensive unless the ef ficiency of a divergence analysis method can be improved significantly

Investigation into the analytic prediction of damage effects on the structures has been completed by several groups [5 7] The investigation presented herein is an extension of a study of damage effects on structures conducted at the Flight Dynamics Laboratory[8] The objective of this paper is to present an efficient prediction procedure by which the effects of damage on the divergence speed of a composite forward swept wing can be determined at relatively low cost This is a continuation of the vulnerability analysis presented in Refs 7 and 8 in which survivability underscores the importance of damage tolerance of aircraft structures

The wing selected for damage investigation is similar to the one previously used in a weight optimization with aeroelastic constraints by Rudisill and Bhatia[9]; but with the metal skin replaced by a graphite epoxy composite material Ad ditionally, the wing is swept forward through 30 deg representing typical forward swept wing configurations envisioned at the present time The structure is represented by a finite element model, and incompressible aerodynamic strip theory[10] is used to generate the aerodynamic loading existing at the divergence condition A typical damage region is selected and is represented by complete loss of various layers of the upper composite skin to simulate the loss of coupled deformation patterns due to initial manufacturing flaws

### Estimation of Divergence Speed Degradation of Damage Wings

The equilibrium equation that expresses the static neutral stability of an elastic wing structure flying at the divergence velocity is written in matrix form as

$$[K]\{w\} = q_{\mathrm{DIV}}[A]\{w\} \tag{1}$$

where $[K]$ is the structural stiffness matrix, $[A]$ is the aerodynamic stiffness matrix, $q_{\mathrm{DIV}}$ is the divergence dynamic pressure and $\{w\}$ is the mode of deformation occurring at the divergence speed The aerodynamic matrix $[A]$ includes elements which represent aerodynamic forces beyond those necessary for flight of the wing as a rigid structure i e only the aerodynamic stiffness forces dependent on wing defor mation are included The aerodynamic stiffness matrix is computed using aerodynamic strip theory.[10] Equation (1) represents a balance of displacements due to aerodynamic loading and elastic restoring forces when dynamic motion can be neglected

The dynamic pressure at the divergence condition is the least eigenvalue of the eigen system represented by Eq (1) Because only the smallest eigenvalue of Eq (1) is required, a matrix iteration scheme called inverse power method is used to determine the eigenvalue $q_{\mathrm{DIV}}$ and the associated eigen vector $\{w\}$ One should note that the aerodynamic stiffness matrix is independent of the cases of damage considered herein; that is all the damage cases investigated will be represented as stiffness variation to the composite skin initiated by manufacturing flaws or other types of imperfections rather than ballistic failures, where indeed the aerodynamic load would vary with damage

The transponse of Eq (1) yields:

$$\{w\}^T[[K]^T - q_{\mathrm{DIV}}[A]^T] = \{0\}^T \tag{2}$$

where it is recognized that $[K]$ is a symmetric matrix and $[A]$ also is symmetric if simple strip aerodynamics are used in its

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representation. However, if an aerodynamic theory such as doublet lattice[11] is used, then $[A]$ would not necessarily be symmetric In the present investigation, a simple strip aerodynamic theory was selected so that Eq (2) becomes

$$\{w\}^T\Big[[K]-q_{\rm DIV}[A]\Big]=\{0\}^T \tag{3}$$

The degradation of the divergence dynamic pressure $q_{\rm DIV}$ with respect to a damage parameter $\alpha_i$ can be obtained by differenting Eq (1) with respect to the damage parameter The parameter $\alpha_i$ represents the damage to the $i$th composite skin element and may be a complete or partial loss of the stiffness of that particular element Differentiating Eq (1) we obtain:

$$\left[\frac{\partial[K]}{\partial\alpha_i}-\frac{\partial q_{\rm DIV}}{\partial\alpha_i}[A]-q_{\rm DIV}\frac{\partial[A]}{\partial\alpha_i}\right]\{w\}+\Big[[K]-q_{\rm DIV}[A]\Big]\frac{\partial\{w\}}{\partial\alpha_i}=\{0\} \tag{4}$$

Premultiplying Eq (4) by $\{w\}^T$ and using Eq (3) to eliminate the last term of the resultant equation yields

$$\{w\}^T\left[\frac{\partial[K]}{\partial\alpha_i}-\frac{\partial q_{\rm DIV}}{\partial\alpha_i}[A]-q_{\rm DIV}\frac{\partial[A]}{\partial\alpha_i}\right]\{w\}=0 \tag{5}$$

When the selected damage does not cause a change of the air flow about the wing, as is the case investigated here, the last term in Eq (5) vanishes Now the variation of the divergence dynamic pressure can be determined from Eq (5) as

$$\frac{\partial q_{\rm DIV}}{\partial\alpha_i}=\frac{\{w\}^T\dfrac{\partial[K]}{\partial\alpha_i}\{w\}}{\{w\}^T[A]\{w\}}=q_{\rm DIV}\frac{\{w\}^T\dfrac{\partial[K]}{\partial\alpha_i}\{w\}}{\{w\}^T[K]\{w\}} \tag{6}$$

where Eq (1) has been used once again to modify the denominator in Eq (6) Equation (6), simply stated, is an equation that requires the divergence dynamic pressure change to be proportional to the variation in stiffness of the composite skin with damage The change of the structural stiffness coefficient in the numerator of Eq (6) is computed for each damage case to be considered and the estimated degradation of divergence speed for that particular damage case determined from Eq (6) Thus, a full divergence analysis of the forward swept wing must be conducted initially, but thereafter damage effects can be determined quite efficiently from Eq (6) at relatively low computational cost. The divergence velocity can be calculated at a given flight altitude as:

$$V_D=\sqrt{2q_{\rm DIV}/\rho_\infty} \tag{7}$$

where $\rho_\infty$ is the density of air at that given altitude

## Damaged Forward-Swept Wing Selected

The wing selected for a damage investigation is shown in Fig 1 This wing, which has an 180 in semispan, is swept forward 30 deg and has a constant chord of 50 in (i e , untapered) The wing structure is a builtup wing box similar to the basic structure used by Rudisill and Bhatia,[9] but the upper and lower skins are constructed from a graphite epoxy composite material with the fiber orientation of each layer selected so that aeroelastic response is "tailored" to increase the divergence speed The composite skins are attached to a basic metal substructure composed of spars, webs and ribs as shown in Fig 2 The builtup wing is represented by finite elements as shown in Fig 2, which are 12 composite skin elements in spanwise direction (both upper and lower), 7 ribs and 2 spars simulated by shear panels, upper and lower rods, and posts placed at the intersection of the shear panels and ribs The composite skin is constructed in a manner such that the layers are symmetric about the wing midplane The various layers in the skin are aligned in a normal layup fashion; that is, the designated (1/0, 2/90, ±45 deg) composite Here the alignment is in reference from a chord line which is perpendicular to the swept axis and consists of five layers approximately 0 01 in. each The two outermost layers have their fiber direction 90 deg from a chord line the center layer has its fiber direction aligned with a chord line, and the remaining layers are at 45 and 135 deg from the chord line. The various structural properties are constant along the span with the modulus properties of the graphite epoxy layers given in Fig 3

The aerodynamic forces are obtained using strip theory with the aerodynamic planform modeled by the 12 aerodynamic strips of equal width as shown in Fig 1. The width of an aerodynamic strip was selected to represent the aerodynamic pressure over one half of each structural finite element The aerodynamic force acting on each strip is computed from a two dimensional aerodynamic theory and is

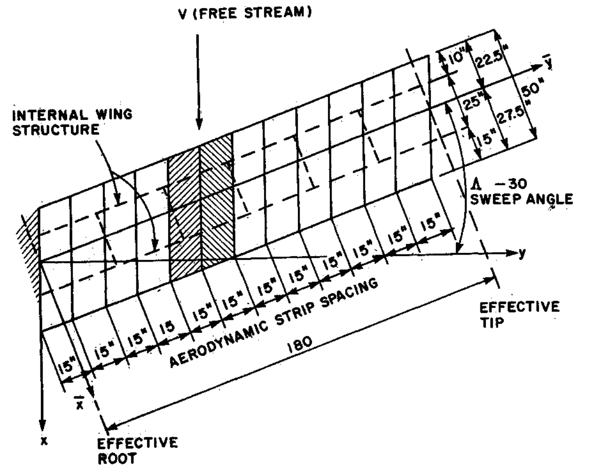


Fig 1 Swept forward wing planform.

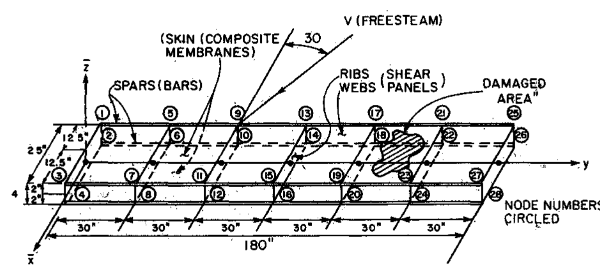


Fig 2 Wing structural representation

| MATERIAL CONSTANTS | |
|---|---|
| RIBS, WEBS, SPARS (ALUMINUM) | E 10 5 x $10^6$ psi<br>V . 3 |
| COMPOSITE SKINS (GRAPHITE EPOXY) | $E_1$ 21 58 x $10^6$ psi<br>$E_2$ 3 39 x $10^6$ psi<br>$E_{12}$ 1 36 x $10^6$ psi<br>$G_{12}$ 83 x $10^6$ psi |

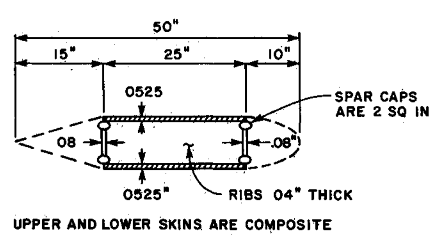


Fig 3 Typical wing section

Table 1 Description of damage cases (upper skin in bay with node points 17, 19, 21, and 23)

| Case | Description of damage | (Decrease of divergence velocity) ΔV(in /s) |
|---|---|---|
| 0 | Undamaged | 0 ($V_{DIV}$ = 4891 in /s) |
| 1 | One layer with fiber 0 deg | 8 |
| 2 | One layer with fiber 90 deg | 8 |
| 3 | One layer with fiber +45 deg | 76 |
| 4 | One layer with fiber −45 deg | 78 |
| 5 | Two layers with fiber 0 90 deg | 16 |
| 6 | Two layers with fiber 90 90 deg | 16 |
| 7 | Two layers with fiber +45 +90 deg | 96 |
| 8 | Two layers with fiber −45 +90 deg | 98 |
| 9 | Two layers with fiber −45 0 deg | 96 |
| 10 | Two layers with fiber 0 +45 deg | 98 |
| 11 | Two layers with fiber +45 −45 deg | 239 |
| 12 | Three layers with fiber ±45, 0 deg | 287 |
| 13 | Four layers 0 90 ±45 deg | 349 |
| 14 | Four layers 2/90 ±45 deg | 349 |
| 15 | Four layers 2/90 0 −45 deg | 146 |
| 16 | Four layers 2/90, 0 45 deg | 143 |
| 17 | Complete loss of five layers | 430 |

directly related to the angle of inclination between the streamwise chord line and the velocity vector of the wing

The structural stiffness $[K]$ and aerodynamic stiffness $[A]$ matrices were computed for the selected wing shown in Figs 1 and 2 The divergence dynamic pressure $q_{DIV}$ and accompanying divergence shape can then be calculated from Eq (1) using an inverse power eigenvalue and eigenvector extraction technique For the selected wing the undamaged $V_{DIV}$ was calculated to be 4891 in/s In the following section particular damage cases are specified and the incremental change of $V_{DIV}$ is calculated for the selected damage case using Eq (7)

## Typical Damage to Composite Skin and Results

The location of the damage area was selected to be the upper skin panel located in the next to last bay region, denoted by the cross region shown in Fig 2 The location was predetermined to be one critical region for the largest variation of flutter speed as determined by a previous study (see Ref 8) by the authors The damage cases considered in this study consisted of complete damage of single and multiple layers of the composite skin located in the next last bay area The various damage cases considered here are shown in Table 1, along with the decrease of divergence speed as predicted from Eqs. (6) and (7) The decrease of divergence velocity for the damage cases shown in Table 1 indicate that the damage to layers with fibers in ±45 deg directions are most critical This suggests that a vulnerability analysis must include damage to the layers of composite material with this fiber direction, hopefully giving some guidance toward design schemes addressing protection of these critical layers

It should be noted that the method for determining the sensitivity to structural damage of the composite skin is based upon a linear approximation [Eq (6)], which yields a valid approximation only if small amounts of damage are postulated. To access the order of the linear approximation, a revised divergence analysis was conducted for damage Case 17 representing the complete loss of the five layers of the upper skin in the next to last bay The reanalysis of damage Case 17 yields a divergence velocity change of 434 in/s as compared to 430 in/s obtained from Eq 6 This suggests that even damage Case 17 can be considered small damage It is further suggested that the seemingly modest amount of variation in the divergence speed of a damaged tailored surface is due primarily to the large stiffness of the undamaged metallic substructure so that damage to the composite skin represents a small variation to the total wing stiffness

The results of this study were obtained for only one preselected damage location which may not have been the most critical one for the divergence instability; however, the numerical technique presented will allow a rapid assessment of a number of damage locations without a complete divergence analysis Thus, the structural designer can investigate not only damage location, but also the extent of damage at the initiation of a structural design to preclude the divergence instability The damage tolerance of aircraft structures may be assessed through a vulnerability analysis to provide the survivability of the flight vehicle

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