Flap Span Effects on Boundary-Layer Separation

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Nomenclature

b	=	flap half span
H_{tr_s}	=	transformed form factor
M	=	Mach number
p	=	pressure
Re	=	Reynolds number
T	=	temperature
x'	=	distance from model leading edge
X	=	dimensionless distance, $(x_{HL} - x)/x$
y	=	distance from model centerline
δ	=	boundary-layer thickness
γ	=	ratio of specific heats
θ_F	=	flap deflection angle

Subscripts

1	=	beginning of interaction, two dimensional evaluated at $y = 0$
13	=	departure from two dimensional evaluated at $y = 0$
3	=	three dimensional evaluated at $y > 0$
HL	=	hinge line
i	=	incipient
s	=	separation or suction

Introduction

BOUNDARY-layer separation due to a compression corner, i.e., a deflected flap, or an external shock impingement has been studied both theoretically and experimentally for a number of years. The impetus of the studies has been the need to obtain predictive techniques for aerodynamic properties of control surfaces, inlets, etc. Two-dimensional boundary-layer flows have normally been stressed. Departure from two-dimensional flow due to flap span effects has been studied experimentally in a few cases, e.g. Refs. 1–4, but only in the spanwise plane of symmetry of the compression corner. This Note describes results of an experimental program to determine the spanwise distribution of the beginning of the separation interaction due to a deflected flap of varying span-length.
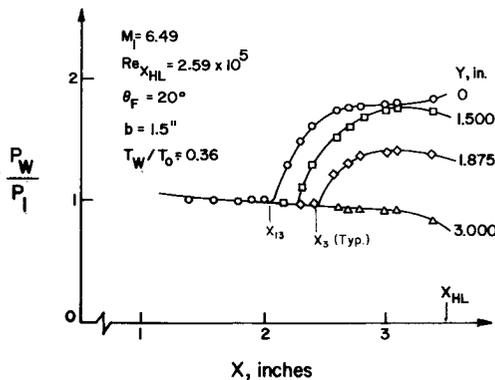

Fig. 1 **Typical streamwise pressure distributions for various flap span lengths.**

Test Model and Facilities

The surface pressure test model was a symmetrical wedge of 12° half angle followed by a flap whose angle could be varied from 0° to 30° with respect to the upper surface of the wedge to form the compression corner. The span and chord lengths of the wedge were 8 in. and 3.6 in., respectively, whereas the flap chord length was 1.5 in. The flap span could be varied from 1 to 8 in.

The tests were performed at the Aerospace Research Labs., Wright-Patterson Air Force Base, Ohio in the 20-in. Hypersonic Wind Tunnel at a nominal freestream Mach number of 12.3 and a stagnation temperature of 2000°R. The facility is of the open jet, nonreturn type. The following local flow conditions were obtained on the wedge by pitching the model: a) $M_1 = 5.4$, $Re_{x_{HL}} = 2.22 \times 10^5$, $T_w/T_0 = 0.38$; b) $M_1 = 6.5$, $Re_{x_{HL}} = 2.59 \times 10^5$, $T_w/T_0 = 0.36$; c) $M_1 = 7.9$, $Re_{x_{HL}} = 3.36 \times 10^4$, $T_w/T_0 = 0.43$. Further model instrumentation and facility description may be found in Refs. 5 and 6.

Results and Discussion

Initial tests, Ref. 6, established that the flow was laminar and that a flap chord length of 1.5 in. was sufficient to yield a full separation, i.e., the extent of separation was not governed by the flap chord length.

Representative streamwise pressure distributions at various spanwise stations are given in Fig. 1 for a flap half-span, b, of 1.5 in. It is seen that the extent of separation decreases in the spanwise direction although an almost constant plateau pressure is maintained in front of the flap, i.e., $y \leq b$. The constancy of the plateau pressure implies that the angle of separation is almost constant. A summary of the extent of separation for one Mach and Reynolds number combination is shown in Fig. 2 for the four flap span lengths investigated. For the conditions of the test, a 2-in. flap half-span results in a full separation on the model centerline akin to that which would be expected for an infinite span, i.e., an entirely two-dimensional flow. Departures from two-dimensionality appear for the 2-in. flap in the spanwise direction and in both the span and chordwise direction for the smaller span flaps.

It is clear that the effects of flap span length cannot be discussed in terms of a flap aspect ratio, or other similar geometric parameters, but must be related to a characteristic dimension of the flow. The boundary-layer thickness, evaluated at the hinge line, was chosen as a correlation parameter. The decrease in the extent of separation on the model centerline due to decreasing flap span length was correlated in terms of the ratio b/δ_{HL} and it was determined that to good approximation for the range of parameters investigated, no departures from two-dimensional flow may be expected on the centerline for a flap half-span larger than about nine boundary-layer thicknesses. Correlation similar to the above is
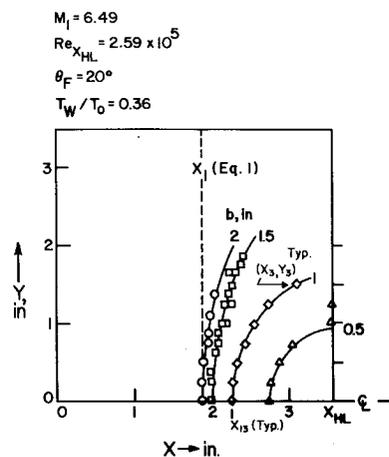

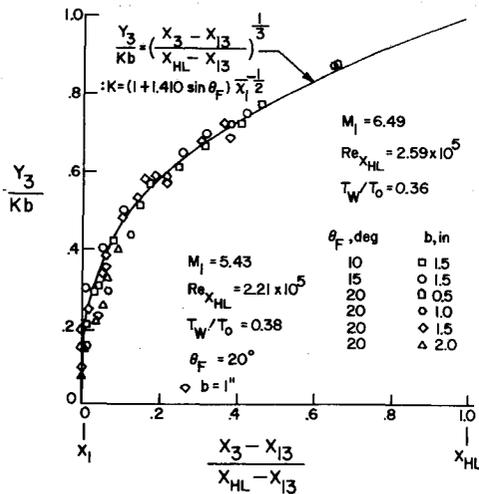Fig. 2 **Spanwise distributions of the beginning of the interaction.**

Fig. 3 Spanwise extent of separation correlation.

obtained if the boundary-layer thickness at the beginning of the interaction is used with the factor 9 changing to 10. Restating the results

$$X_{13} = X_1 = K_o M_1 \Delta\theta_F: \quad b/9\delta_{HL} \geq 1 \quad (1)$$

where $\Delta\theta_F = \theta_F - \theta_{Fi}$ and $K_o = 0.262 H_{tr_s}$ (Ref. 6)

$$X_{13} = (b/9\delta_{HL})X_1: \quad b/9\delta_{HL} < 1 \quad (2)$$

Through analysis of the experimental data and recalling the shock shape prediction of the modified blast wave theory for blunt plates the following equation was obtained for the spanwise extent of separation

$$y_3/Kb = (x_3 - x_{13}/x_{HL} - x_{13})^{1/3} =$$
$$X_{13}^{-1/3}(x_3/x_{13} - 1)^{1/3} \quad (3)$$

where $K = (1 + 1.4096 \sin\theta_F)/\bar{\chi}_1^{1/2}$. It should be noted that the second term of the numerator is numerically identical to $\gamma^{1/3}C_D^{1/3}$ of the blast wave theory where $C_D = 2 \sin^3\theta_F$. However, direct attainment of this functional relationship is not apparent.

Comparison of the experimental data with Eq. (3) in Fig. 3 results in excellent correlation of the experimental data over the Mach and Reynolds number range investigated.

A flap span of insufficient length, Eqs. (2) and (3), introduces departures from two-dimensionality in that the separation extent is not constant in y. These departures are related to the spanwise flow of low momentum air from the centerline, $y = 0$, in the separated region. The driving mechanism for this mass transfer is the pressure differential between the relatively high pressure in the separated region inboard of the flap, $y \leq b$, and the low pressure for $y > b$. The approximately constant separation angle for $y \leq b$ lends support to the statement that the outflow is mass transfer of low momentum air.

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Vibration Characteristics of Flexible Beams about Nonlinear Equilibrium States

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Introduction

EXTREMELY flexible cantilever beam configurations have found numerous applications recently as energy dissipating devices, communications antenna, and deployable booms for space applications. In a typical loading environment such flexible members can experience large displacements away from the initially straight state. As a result of this change in geometry and the corresponding internally developed stress distribution it is expected that significant changes in the vibration characteristics of the beam will occur.

It is the purpose of this Note to present the results of an investigation on the vibration characteristics of a cantilever beam in a deformed equilibrium state after it has undergone large displacements. In order that this be accomplished the equations for infinitesimal vibrations about the equilibrium state are derived by perturbation methods, from the nonlinear equilibrium equations, and solved by numerical integration. The prestress terms, which appear as variable coefficients in these vibration equations, are obtained from the solution to the nonlinear equilibrium equations.

Problem Formulation

It is first required to derive a set of equations to describe the equilibrium state at any point along the beam. By considering a small segment of the beam as shown in Fig. 1, the following set of six nonlinear differential equations are obtained after utilizing the Kirchhoff hypothesis and assuming inextensional deformations.

$$d\bar{M}/ds = \bar{Q}, \quad d\bar{\theta}/ds = \bar{M}/EI \quad (1a,b)$$

$$d\bar{T}/ds = -\bar{Q}\bar{M}/EI - p\sin\bar{\theta} + m(\ddot{\bar{w}}\sin\bar{\theta} + \ddot{\bar{u}}\cos\bar{\theta}) \quad (1c)$$

$$d\bar{Q}/ds = \bar{T}\bar{M}/EI + p\cos\bar{\theta} - m(\ddot{\bar{w}}\cos\bar{\theta} - \ddot{\bar{u}}\sin\bar{\theta}) \quad (1d)$$

$$d\bar{u}/ds = \cos\bar{\theta} - 1, \quad d\bar{w}/ds = \sin\bar{\theta} \quad (1e,f)$$

Here p is a "dead" distributed lateral loading, m is the mass per unit length, and dots over the symbols represent differ-