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Shock Interaction Effect on a Flapped Delta Wing at $M = 8.2$

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THE effects of wave interactions on hypersonic vehicles have received considerable attention in recent years. Edney[1] has identified different types of interactions, and some examples of such interactions in practical situations have recently been reviewed by Korkegi.[2] Although the emphasis has been on local surface heating problems associated with wave-interaction fields, in some instances the modification of surface pressure distributions causes significant variations in vehicle aerodynamic characteristics. The loss in stability of flare-stabilized missiles caused by the interaction of bow and flare shocks[3] is an example. An analogous situation was observed in a recent investigation of trailing-edge flap effectiveness on delta wings at hypersonic speeds.[4] Balance measurements on a 76° swept delta wing with a 30° positively deflected full-span flap (conducted in the Imperial College Gun Tunnel fitted with a $M = 8.2$ contoured nozzle) yielded aerodynamic coefficients significantly below inviscid estimates. Flow visualization results suggested that the loss in aerodynamic loading was more than could reasonably be adduced to separation effects. From pressure measurements and oil flow studies, a considerable proportion of the flap appeared to be influenced by the reflected wave emanating from the intersection of the wing and flap shocks. This phenomenon has been discussed in the literature[5] and is well evident in the experimental flap pressure distributions on the two-dimensional model analyzed by Hill.[6]

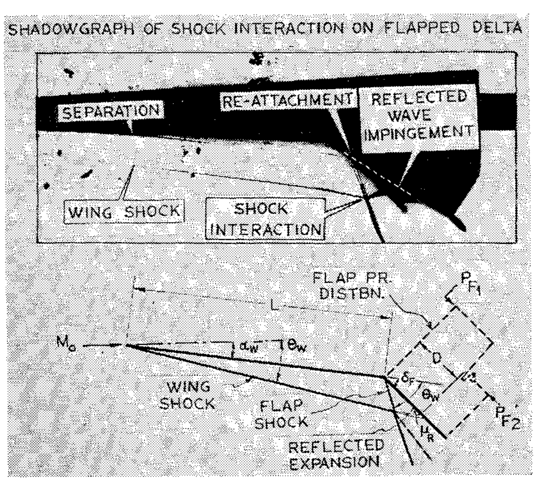

Fig. 1 Wing shock/flap shock interaction.

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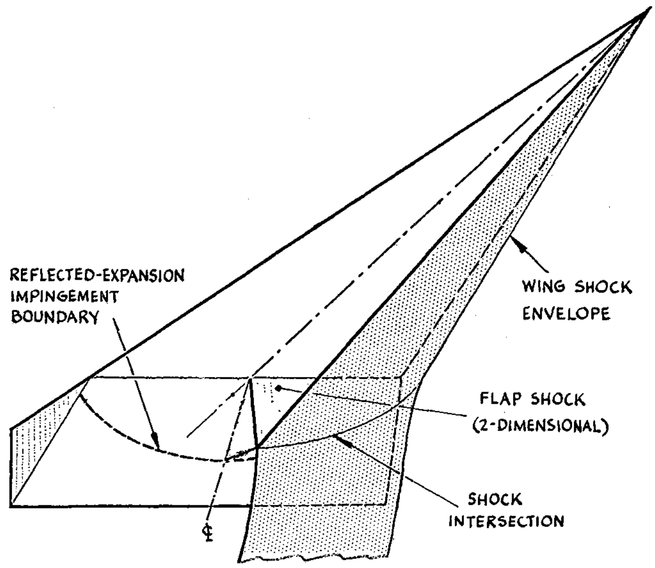

Fig. 2 Model of shock interaction on flapped delta wing.

In this Note, a simple method to estimate the reflected wave impingement effect on the aerodynamic characteristics of a flappaed delta wing, using a simple flow model, is presented. Experimental measurements[4] have been used to assess the proposed prediction method.

The shadowgraph presented in Fig. 1 serves to illustrate the phenomenon under consideration. As depicted in the sketch, the intersection of the wing and flap shocks in an inviscid hypersonic flow generates a merged shock, a slip layer and a reflected wave. At hypersonic Mach numbers and with the deflection angles of interest, the reflected wave is an expansion, and this is the case considered here. A fall in pressure occurs on the flap surface at the impingement position of the reflected expansion, the pressure asymptotically approaching the far downstream value assumed to correspond to a single shock deflection of the freestream through the combined angle $\alpha_w + \delta_F$ via further wave reflections. The solutions presented in Ref. 5 indicate that the approach to the final pressure is quite rapid downstream of the first impingement, as also found experimentally.[6]

The distance from the flap hinge line to the first reflected expansion is given by

$$\frac{D}{L} = \frac{\cot(\theta_F - \delta_F) + \cot\mu_R}{\cot(\theta_w - \alpha_w) - \cot\theta_F} \cdot \frac{\sin(\theta_F - \delta_F)}{\sin\theta_F} \tag{1}$$

(see Fig. 1).

The three-dimensional shock interaction on a flapped delta in inviscid hypersonic flow is depicted in Fig. 2. The wing shock envelope is calculated from delta wing solutions, viz., Babaev[7] for attached leading-edge shock and Squire[8] for both attached and detached shocks. With an unswept hinge-line, the flap shock may be reasonably assumed to be locally two-dimensional up to the interaction. With attached wing shock, the local Mach number upstream of the flap shock is obtained from oblique shock theory, whereas in the case of detached shock, conical shock solution may be used as a reasonable approximation. Application of Eq. (1) along conical rays then yields the reflected expansion impingement boundary in the plane of the flap.

The calculated boundaries are compared with some experimental observations based on pressure measurements and oil flow visualization in Fig. 3 at varying incidence angle. The expansion impingement boundary may be approximately located by the isobar which terminates the plateau region and marks the beginning of pressure fall (Fig. 3a). The oil flow (Fig. 3b) provides a direct visualization of the reflected-expansion footprint as a curved band across the oil streaks.

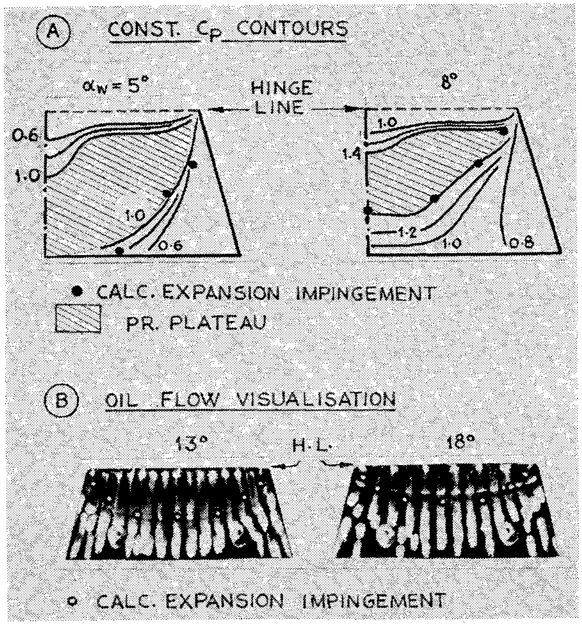

Fig. 3 Prediction of reflected expansion impingement boundary over flap surface.

In general, good agreement with the calculated points is evident in spite of the presence of some flow separation.

The aerodynamic load on the flap surface may now be estimated. The initial flap pressure P_{f_1} between hinge-line and expansion impingement is obtained through two-dimensional shock compression of the mean (i.e., area-averaged) delta wing pressure (P_w) (conveniently approximated by the oblique-shock value for attached shock, and by tangent-cone pressure with detached leading-edge shock).[4] A discontinuous and complete adjustment of pressure to the final value P_{f_2} (given by oblique shock compression of the freestream through deflection angle $\alpha_F + \delta_F$) across the impingement boundary is assumed.

Balance measurements of the normal force, axial force, and pitching-moment coefficients of the flapped delta wing are compared with estimates in Fig. 4. The figure shows that the inclusion of the reflected wave effect significantly improves the agreement between experiment and calculation. The break in balance data near $\alpha_w = 13°$ coincides with the predicted oblique shock detachment for freestream deflection through angle $(\alpha_w + \delta_F)$.

In conclusion, a simple method for estimating the impingement boundary of the reflected expansion arising from shock interaction on a flapped delta wing and the resulting hypersonic aerodynamic coefficients has been presented. This study also suggests that as a consequence of the three-dimensional shock interaction, the outboard portions of the trailing-edge flap on a delta wing are relatively less effective since they derive the least benefit from the compression field of the wing.

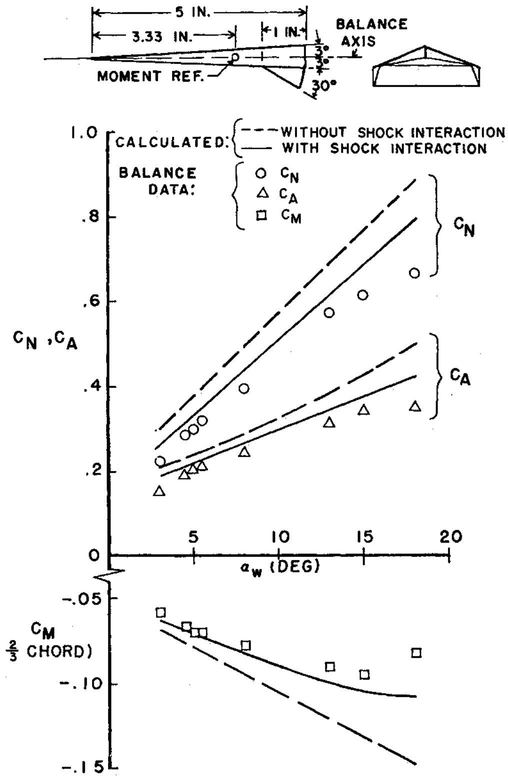

Fig. 4 Prediction of flapped delta aerodynamic coefficients with shock interaction effect.

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