This approximation was done by considering solely the endpoint of the curved shock (point B in Fig. 3), which also denotes the beginning of the normal stopping shock.

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Experimental Investigations of Asymmetric Vortex Flows Behind Elliptic Cones at Incidence

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I. Introduction

IN a recent investigation, the low-speed flow past a slender, circular cone at high incidence was studied with respect to leeside vortex-flow asymmetry and its suppression by means of a fin between the vortices.[1] The use of such a fin proved to be effective in establishing, at least nominally, symmetric vortex-flow configurations. It was reported in fairly early work[2] and more recently in Ref. 3, that on slender delta wings in low-speed flow the initially symmetric leading-edge vortices on the leeside became asymmetric at some critical incidence. Therefore, the application of a fin was also considered for suppressing asymmetric vortex flow on slender delta wings. To this end, flow observations were carried out on two slender, sharp-edged delta wings of different aspect ratios A in a water tunnel at high incidence; they revealed that the vortex flow remained symmetric in the incidence range investigated. This result was confirmed in low-speed wind-tunnel tests at a larger Reynolds number. Reported strong vortex-flow asymmetry on a slender delta wing is possibly related to the probably more or less thick, elliptic-cone shape of the tip.[4,5] These findings have recently been confirmed by results reported in Ref. 6.

It is assumed that the flow past a sharp-edged delta wing at incidence, particularly the leeside vortex flow, is representative of the flow past a very thin, flat, delta plate (thickness ratio $\tau = t/b \rightarrow 0$, where t = thickness and b = span); such a very thin, flat, delta plate represents a very thin elliptic cone ($\tau \rightarrow 0$). One could then surmise that there should be some intermediate cone with a certain finite thickness between the thin, flate-plate delta and the thick, circular cone, for which the flow changes from symmetric to asymmetric at a given incidence.

Some light was shed on the development of the vortex configurations on bodies of different relative thicknesses at a given incidence in recent theoretical work by Fiddes and Williams.[7] They presented results of an inviscid-flow study of vortex-flow asymmetry on slender bodies of various cross sections. The separating flow was represented by a vortex-sheet model, and the particular form used was that of Smith.[8] Together with the results obtained by Smith[9] for the separation of a vortex sheet from a smooth surface, Fiddes[10] developed a vortex-sheet model for inviscid flow past slender circular and elliptic cones at incidence. In this inviscid-flow model separation-line positions were specified as a parameter. Solutions were obtained for the flow with symmetric separation-line positions prescribed. Two families of solutions occurred: one for symmetric and one for strongly asymmetric vortex flow.

In Ref. 7, results are reported on the effect of thickness ratio of elliptic cones on vortex-flow asymmetry: The degree of asymmetry is reduced as the thickness ratio is decreased, and at 52% thickness the asymmetry has vanished at the specific incidence chosen. At higher incidences, the thickness ratio needed to suppress asymmetry decreases. These results suggest that on thin elliptic cones, and in the limit on delta plates, vortex-flow asymmetry may not be found. This was confirmed by results when using a simpler line-vortex model.[7]

It was considered to be of interest to check experimentally our earlier-mentioned conclusions and the results of the preceding theory as to the dependence of degree of vortex-flow asymmetry on the cones' thickness ratio. To this end, three elliptic cones of thickness ratios τ = 1.0, 0.65, and 0.40, respectively, as well as a sharp-edged delta wing, with τ varying between 0.09 and 0.18 along the chord, were studied in a water tunnel at high incidence by using a dye flow-visualization technique.

II. Models, Testing Facility, and Flow-Visualization Technique

The models investigated are depicted in Fig. 1. Each model was supported by a thin rod, extending to the rear; the rod, in turn, was fixed at its rear end to a vertical strut system. The water tunnel of

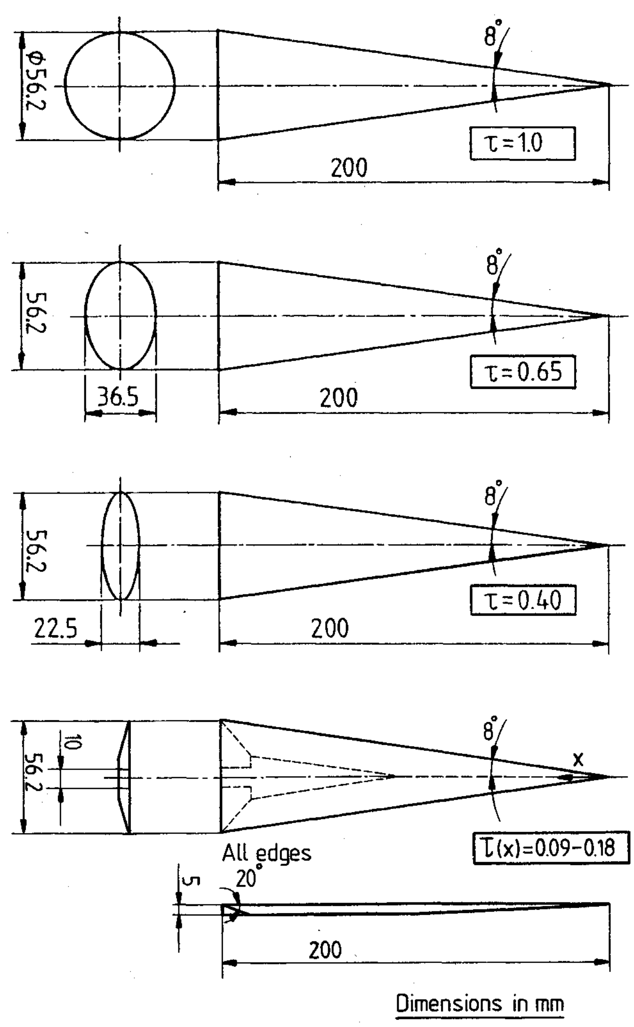

Fig. 1 Plan and rear views of elliptic-cone and delta-wing models.

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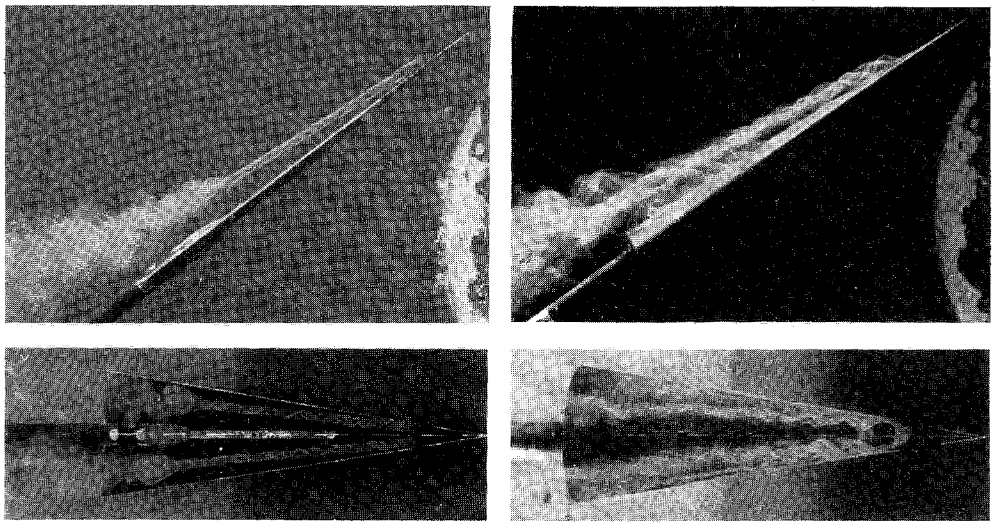
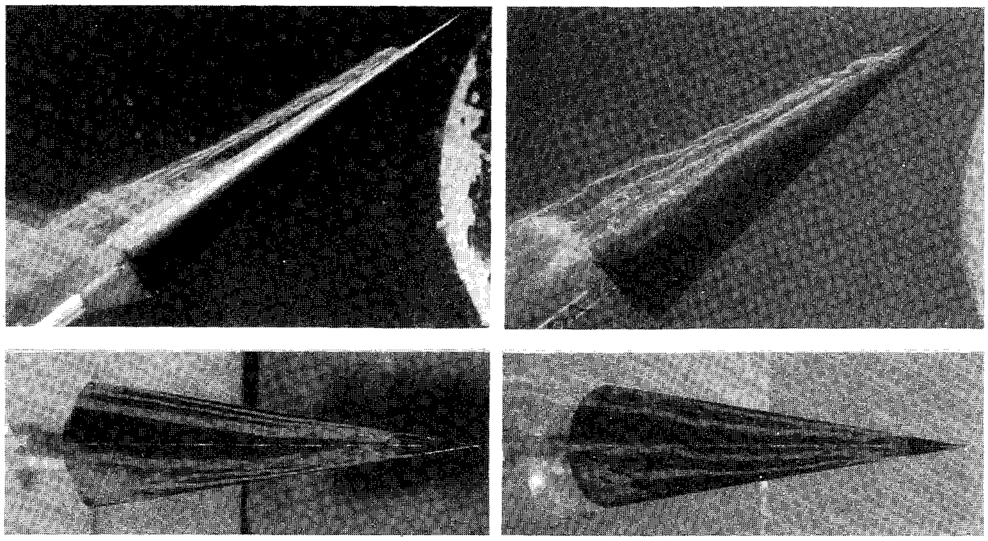


Delta wing, $\tau \to 0$ Cone, $\tau = 0.40$

Fig. 2a Vortex configurations on delta wing and cone with various thickness ratios τ, $Re_L = 2.8\times10^4$, and $\alpha = 38$ deg.



Cone, $\tau = 0.65$ Cone, $\tau = 1.0$

Fig. 2b Vortex configurations on elliptic cones with various thickness ratios τ, $Re_L = 2.8\times10^4$, and $\alpha = 38$ deg.

the DLR Göttingen which was used for the investigations had a closed circuit. The horizontal test section, with a free water surface, has a cross-sectional area of 0.25×0.33 m^2 and a length of 1.25 m. Maximum water velocity in the empty test section is $V_\infty \cong 0.5$ m/s. The tunnel is operated continuously. The pump is driven by a 4-kW electric motor. A flow-visualization technique was used in which small quantities of dye (sodium fluorescein) were applied to the model surface at appropriate locations with the model outside of the test section. After having placed the model into the water, the flow patterns immediately became visible and remained so, typically, for a few minutes. The flow patterns were recorded simultaneously from the side and below, with the aid of two still cameras, on standard color film.

III. Testing Conditions

The flow-visualization experiments were carried out at a water speed $V_\infty \cong 0.14$ m/s. The corresponding Reynolds number, formed with model length L, was $Re_L = 2.8\times10^4$. The angle of incidence was $\alpha = 38$ deg.

IV. Results and Discussions

In Figs. 2a and 2b, from the top and side views, the vortex configurations can be seen on the leeside of the delta wing and the elliptic cones with the thickness ratios $\tau = 0.40$, 0.65, and 1.0 respectively, at an angle of incidence, $\alpha = 38$ deg.

First we consider the results obtained for the elliptic cones at the angle of incidence $\alpha = 38$ deg. The flow-visualization pictures for each geometry show that vortex configuration which had the largest degree of asymmetry recorded during the experiments. Common to all of the cones shown in that particular flow situation is that they exhibit, on the leeside, a set of three vortices on the starboard and port side, respectively.

Circular Cone, $\tau = 1.0$

In Fig. 2b (right-hand side), the flow visualizations obtained show on the leeside in the top view a vortex system consisting of three vortices on the starboard as well as on the port side. This vortex system exhibits a high degree of asymmetry with respect to the vertical plane of symmetry of the cone (lying in the incidence plane). It is shifted to the port side (top view) and at least the innermost, primary vortices lie in the near half at different heights above the cone, as is seen in the side view.

Thick Elliptic Cone, $\tau = 0.65$

On the left-hand side of Fig. 2b, the flow visualization obtained on the thick elliptic cone shows in principle the same vortex system consisting of three vortices on each side of the cone. The degree of asymmetry of the vortex system has decreased, but is still high for the primary vortices.

Thin Elliptic Cone, $\tau = 0.40$

On the right-hand side of Fig. 2a, the flow visualization obtained on the thin elliptic cone again shows, in top view, the familiar vortex system of three vortices on each side of the cone. The primary vortices show a considerable degree of asymmetry; they are turned the opposite way (from a fictitious symmetry configuration) as was the case on the other two cones. Their degree of asymmetry has decreased as compared with the thicker cone of $\tau = 0.65$.

Thin Delta Wing

On the left-hand side of Fig. 2a, the flow visualization obtained on the delta wing exhibits only one vortex, the primary vortex, on each side of the wing. Each of the well-structured vortices terminates in a bubble-like breakdown region, which is followed by irregular flow. The breakdown regions are located clearly asymmetrically with respect to the wing's symmetry plane. From the front of the wing the concentrated, well-structured vortices are nominally symmetric down to the first breakdown bubble. The nonexistence of asymmetric vortex flows on slender delta wings has been discussed in detail in Refs. 4 and 5.

Elliptic Cone, $\tau = 1.54$

The elliptic cone with the thickness ratio $\tau = 0.65$ was turned through an angle of 90 deg to provide an elliptic cone with $\tau = 1.54$. The flow visualizations obtained are not presented here, only discussed. In the initial tests performed it was observed that the vortex system on the leeside was strongly oscillating in the spanwise direction. Two extreme configurations were observed: The flow was first swept to the left side (looking downstream) over the rear part of the core, while at some later state, it has become largely symmetric. From the side, it was observed that one of the vortices intermittently lifted off in the rear part, while the other vortex followed the cone all of the way down to the base. It was found that one extreme configuration of the vortex system is a large liftoff from the cone of the vortex, combined with an extreme spanwise displacement of the vortex system over the rear portion of the cone. The other extreme configuration exists with the main vortices along the cone and in a practically symmetric arrangement.

In a second part of the tests, then, extra attention was given to establish a low disturbance level flow in the empty test section. To this end, the water was circulated in the tunnel (without the model installed) for a relatively long time (approximately 1.5 h). Then the model was brought into the test section with utmost care to minimize disturbance of the flow. Between two tests, periods of water circulation, without the model, of about 5 min were allowed to reduce the disturbance level.

Flow observations from the side now revealed only occasional, slight vortex liftoff over the rear part of the cone; otherwise the primary vortices lie along the cone's leeside surface down to the base. In the top view, the vortex system was observed to distinctly oscillate from one side to the other over the aft portion of the cone, being strongly asymmetric in most cases; no temporarily steady, symmetric configuration was observed. In this test series, with apparently reduced freestream disturbance levels, the (practically) maximum liftoff of a primary vortex is much reduced as compared to that observed under normal operating conditions of the water tunnel. This must be taken into account in further tests.

V. Conclusions

Flow-visualization tests were carried out on three elliptic cones and a delta wing, with thickness ratios τ varying between $\tau = 1$ (circular cone) and $\tau \to 0$ (delta wing) and one inverted cone $\tau = 1.54$, at one angle of incidence $\alpha = 38$ deg, and Reynolds number $Re_L = 2.8\times10^4$. The main result of the study is that the degree of asymmetry of the vortex flows behind the cones decreased as the cones became flatter, i.e., with τ decreasing from $\tau = 1$ to 0.4, and was zero for the delta wing. Our limited experimental results are in qualitative agreement with the results of an inviscid-flow theory by Fiddes and Williams. The outcome of the study suggests an attempt to modify a conventional, thick, axisymmetric missile nose toward a flatter nose, e.g., with elliptic cross sections, to reduce flow asymmetry at high incidence. Such a nose geometry has been proposed in Ref. 11 and will be studied at realistic Reynolds numbers. Furthermore, it has been observed in a specific test series, with apparently reduced freestream disturbance levels, that the liftoff of a vortex from a cone is distinctly reduced, as compared to that under normal tunnel operating conditions. This has to be taken into account in future testing

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Relation Between Spectra of Hot-Wire Signals and Velocity Fluctuations

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Introduction

ONE of the most common methods of measuring turbulence is by the use of a hot-wire anemometer. In a hot-

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