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SUMMARY

An hypothesis advanced originally to explain computational observations is supported by theoretical considerations: The asymmetric mean flow observed on bodies of revolution at moderate to high angles of attack is the result of a convective instability of an originally symmetric flow to a time-invariant space-fixed disturbance. Additionally, the time-dependent fluctuations characteristic of the flow at higher angles of attack (up to 90°) are the result of an absolute instability of an originally steady flow to a small temporal disturbance of finite duration. Within a common domain, the instability mechanisms may coexist.

The experimentally confirmed existence of bistable states, wherein the side-force variation with nose roll angle approaches a square-wave distribution, is attributed to the dominant influence of a pair of trailing vortices from the ogival forebody. Their existence is made possible by the appearance of foci of separation in the skin-friction line pattern beyond a critical value of angle of attack. The extreme sensitivity of the asymmetric flow orientation to nose geometry, demonstrated experimentally, is attributed to the presence of an indeterminate phase in the family of possible solutions for the three-dimensional wave system.

INTRODUCTION

It is well known that when a body of revolution is inclined at a sufficiently high angle to an oncoming stream, the steady-state component of the flow over the body becomes asymmetric with respect to the angle-of-attack plane. The origin of the asymmetry has remained a mystery for many years, but recent advances based on computational results have opened the path toward a rational explanation of the phenomenon.

In references 1 and 2, a time-accurate, thin-layer Navier-Stokes code was used to investigate the three-dimensional flow fields over ogive-cylinders (L/D = 6.5 to L/D = 12.5) at several angles of attack. At α = 40°, the mean flow was found to be symmetric. Placement of a small space-fixed and asymmetrically disposed perturbation near the tip of the body caused the mean flow to become asymmetric. Upon removal of the perturbation, the mean flow returned to a symmetric state (cf. fig.1, taken from ref. 1). At α = 60° and α = 80°, without a fixed perturbation at the tip, a small temporal disturbance of finite duration was sufficient to set off an unsteady flow involving vortex shedding, which evolved to a finite-amplitude fluctuation around a symmetric mean flow. At α = 80°, the Strouhal frequency was about 0.2, which is consistent with the value expected from vortex shedding in the case of flow past a two-dimensional cylinder under the same oncoming flow conditions (cf. fig. 2, taken from ref. 2). At α = 60°, when a permanent disturbance was also added near the tip, a pair of asymmetrically disposed vortices emerged near the nose, and correspondingly, the fluctuating flow developed an asymmetric mean component, just as at α = 40° (cf. fig. 3, taken from ref. 2).

Degani (ref. 2) recognized the relevance of the concepts of convective and absolute instability to the observed flow behavior, and advanced an explanation of the observations in terms of the two categories. He suggested that the asymmetric mean flow observed in the moderate to high angle-of-attack range was the result of a convective instability of an originally symmetric flow to a time-invariant, space-fixed disturbance. On the other hand, Degani suggested that the periodic fluctuations characteristic of the flow at higher angles of attack (up to 90°) were the result of an absolute instability of an originally steady flow to a small temporal disturbance of finite duration.

In references 3 to 6, various shear flows were studied by means of linear stability analysis techniques. Typically, the linear analysis of a flow that is unstable to a class of disturbances allows one to characterize the initial growth of the disturbed flow subsequent to a perturbation. The terms convective and absolute instability were coined to distinguish between the two classes of instability as determined by examining the eigenvalues of the stability analysis. The specifics of the stability analysis are beyond the scope of this paper, but in any event, it is believed that if the presence of an absolute instability is indicated, the fluctuations that are triggered by a short-duration excitation will persist and grow to an equilibrium state even after the excitation has been removed. In contrast, if the presence of a convective instability is indicated, the initially growing fluctuations that are triggered by a short-duration excitation will be washed downstream and, in the absence of further excitation, the flow will return to its original unperturbed state.

The notion of instability, either of the convective or the absolute type, is a mathematical construct. In the computational realm, it is possible to follow the mathematical prescription and, at least in principle, prove that an observed flow actually represents the stable state resulting from the response of an unstable original flow to a disturbance. A similar proof in the experimental realm would be considerably more difficult, in view of the necessity of providing a disturbance-free environment in which the original flow could persist until it was deliberately disturbed. In reference 7 (an experimental companion piece to ref. 2), the aim was more limited. One of its implicit objectives was to demonstrate that the experimentally obtained observations and measurements on a pointed body of revolution at incidence were consistent with the explanation advanced in reference 2 of the computational observations in terms of convective and absolute instabilities. Another objective was to address a set of issues that had been raised previously by the results of other experimental investigations. In particular, the question of whether bistable states existed (refs. 8-11), and if so, under what conditions, was addressed. Additionally, some of the issues raised by previous investigators (refs. 10-13) about the role played by the tip geometry in determining the asymmetric orientation of the flow field were confronted.

The study undertaken here is intended as an analytical counterpart to references 2 and 7. The discussion is aimed at providing a theoretical basis, both to the explanation of the computational observations in reference 2 and the experimental observations in reference 7.

THEORETICAL CONSIDERATIONS

This section contains ideas from a forthcoming article by D. C. Hill and M. Tobak on the stability of flow past an inclined cylinder. The features that we believe need to be captured in a theoretical treatment are evident in the set of flow-visualization photographs provided by Ramberg (ref. 14). In figure 4, these features are emphasized schematically, and, at the same time, the problem is simplified by allowing the pointed cylinder to be infinitely long.

In figure 4, one sees that there are three distinct regimes of flow. The first is far enough downstream from the nose that the influence of the nose on the flow there is negligibly small. Accordingly, the flow in regime (1) is essentially the flow past an inclined cylinder, for which the independence principle (ref. 15) holds. In the crossflow direction normal to the cylinder axis, we have simply the two-dimensional flow past a cylinder. It has now been verified both theoretically (ref. 16) and experimentally (ref. 17) that the steady two-dimensional flow past a cylinder becomes unstable beyond a crossflow Reynolds number of about 50. As a result of the instability, the disturbed flow grows up to a new equilibrium state that replaces the original steady flow.

The event is describable by means of bifurcation theory. When, as here, the steady flow is replaced by one containing a periodic time-dependent component, the event is known as a Hopf bifurcation. Physically, the periodic time-dependent component manifests itself by the appearance in the wake of vortex shedding parallel to the cylinder axis. Computations by Yang and Zebib (ref. 6) have confirmed that when the disturbance exciting the instability has an antisymmetric component relative to the symmetry plane and is situated in the near wake (the region enclosing the separation bubble), the instability is absolute. A disturbance of finite duration is sufficient to set off the vortex shedding which continues indefinitely.

Regimes (2) and (3) both lie between the nose and regime (1), and hence the nose influences their corresponding flows. The principal change is that the instability mechanism becomes three-dimensional, allowing flow properties to become quasi-periodic functions of the axial coordinate. In regime (2), the periodic time-dependent shedding of vortices continues as before, but, owing to the presence of the nose, the vortices are inclined obliquely to the cylinder axis. Close to the cylinder, the set of obliquely shedding vortices composes a wave system that is propagating upstream relative to the body surface. One member of this system has a wave speed of zero relative to the surface, and this defines regime (3), the asymmetric steady-state component. Thus, the source of the asymmetry in the steady flow that is observed in experiments with inclined bodies of revolution may be attributed to a three-dimensional outgrowth of the instability mechanism that causes the appearance of vortex shedding in the two-dimensional flow past a cylinder. In contrast to the two-dimensional case, however, the three-dimensional wave system requires continuous excitation to persist; that is, the instability is convective, as will be demonstrated later.

In Ramberg's experiments, which involved bodies of high fineness ratio, (L/D ~100), all three regimes are easily identifiable in the flow-visualization pictures, although the extent of regime (1) diminishes rapidly as α approaches zero. In experimental studies involving bodies of lower fineness ratio, such as the one studied in reference 7 ($L/D = 16$), at low to moderate values of α regime (1) is virtually nonexistent, because the influence of the nose extends over the length of the body. In the virtual absence of regime (1), there is no source of periodic fluctuations to excite regime (2), so that it also is virtually nonexistent. Hence, at moderate values of α, the flow is dominated by regime (3), the asymmetric, steady-state component. The presence of regime (1), and with it, regime (2), becomes identifiable only after α has become sufficiently large (in ref. 7, $\alpha \sim 65°$). Notice that within this latter range, while regime (3) would be absent in the absence of a fixed perturbation at the nose, the three-dimensional component represented by regime (2) still would be present, forced by regime (1), as would be evident by the presence of a fluctuating flow (having two dominant frequencies) around a symmetric mean flow. Regime (1) then becomes predominant as α approaches 90°, squeezing regimes (2) and (3) into an ever-diminishing zone just behind the nose.

Let us now study the development of the three-dimensional wave system more closely. To show why the instability mechanism that sets it off must be convective, consider the following thought experiment. Suppose we have, simply, the flow past an infinitely long inclined cylinder, and that the cylinder is equipped with a small retractable pin located at a point on the leeward side, asymmetrically disposed with respect to the angle-of-attack plane (i.e., the symmetry plane in the crossflow direction). When the pin is inserted into the flow, there first will be a transient response that is eventually replaced by an equilibrium state. The equilibrium state will consist again of the same three regimes that were observed to characterize flow past the inclined pointed cylinder. Regime (1) will prevail in a zone far enough downstream of the pin to escape its influence. Regimes (2) and (3) will exist together in the intervening zone between the pin and regime (1). The steady flow component corresponding to regime (3) may differ in form from the flow characterizing its counterpart on the inclined pointed cylinder, but its origin is the same, nevertheless. If the pin is now retracted, after a transient period, we must have the stable equilibrium state for flow past an inclined cylinder, a state which can sustain only parallel vortex shedding. Both the steady and time-dependent components of the three-dimensional wave system must vanish. This demonstrates that the three-dimensional wave system requires continuous excitation to persist; that is, its instability mechanism is convective.

INTERPRETATION OF RESULTS

Convective and Absolute Instabilities

Theoretical analysis fully supports the hypothesis advanced in reference 2. Each of the computational observations leading to the hypothesis can be given a firm theoretical basis. The asymmetric mean flow (fig. 1) observed in the moderate angle-of-attack range is the result of a convective instability of an originally symmetric flow to a time-invariant, space-fixed disturbance. The virtual absence of time-dependent fluctuations in this range is consistent with the absence of regime (1), in view of the finite length of the body. At higher values of α, when regime (1) is present, in the absence of a fixed perturbation at the nose, the observed fluctuating flow around a symmetric mean flow (fig. 2) is the result of an absolute instability of an originally steady symmetric flow to a small temporal disturbance of finite duration. In effect, the disturbance triggers regime (1), which in turn acts as a forcing to sustain regime (2). This is also the situation for the solid curve in figure 3(a) and in figure 3(b). Adding a fixed perturbation at the nose (dashed curve, fig. 3(a) and fig. 3(c)) then triggers regime (3). This demonstrates that the instability mechanisms triggering regimes (1) and (3) may exist either separately or together. In the absence of an external periodic source, however, it appears that regime (2) cannot persist without the presence of regime (1) to continually excite it.

Results of the experimentally obtained observations and measurements of reference 7 also are consistent with the hypothesis and provide an indirect confirmation of it in the following sense. It was demonstrated experimentally (cf. fig. 5, taken from ref. 7) that when the nose geometry was made symmetric with respect to one or more planes, orthogonal orientations of these planes with respect to the angle-of-attack plane were coincident with the occurrence of zero-crossings in the side-force variation with nose roll angle. That is, an imposed symmetry at the nose with respect to the angle-of-attack plane suppressed the appearance of the asymmetric flow field. This indirectly confirms the theoretical assertion that the development of an asymmetric flow field is the result of an instability, requiring an asymmetrically disposed, space-fixed disturbance to trigger it.

Bistable States

The experimental results of reference 7 confirmed the existence of bistable states both for bodies having " natural" tips and tips with imposed symmetry planes. As an aid in understanding the conditions that bring about bistable states, it may be helpful to consult the results of reference 18, which show in considerable detail how the stationary component of the three-dimensional wave system develops downstream from the nose. Drawn from the original photographic evidence, a set of sketches of the topology of the flow in crossflow planes at a succession of closely spaced streamwise stations is presented. The crossflow planes are oriented normal to the free-stream direction.

One sees that the stronger of the two primary vortex structures grows continually in successive stations downstream, assimilating the newly formed vortical structures that are born beneath it. The growth of this structure eventually reaches a saturation point. The other vortical structure then becomes dominant and undergoes a similar history of growth to saturation. The two vortical structures gradually lose their link to the structures beneath them as the angle of attack increases and eventually become the trailing vortex system of the ogival forebody.

In a set of experimental results obtained under similar conditions, it is this pair which can be identified in the hot-wire survey plots of reference 19 (cf. fig. 6) and in the smoke/laser sheet pictures of reference 7 (fig. 7). These results, obtained for $\alpha = 55°$, must also be associated, however, with another factor which has already entered at a slightly lower value of α. Surface oil-flow visualization studies (not reported in refs. 7 or 19) reveal the presence of foci of separation in the skin-friction line patterns at angles of attack beyond about $\alpha = 50°$. An example for $\alpha = 55°$ is shown in figure 8 (Degani, D. and Zilliac, G. G., unpublished data, 1988). A focus is visible (with a second barely discernible) on the line of separation just aft of the ogive/cylinder junction. A similar focus appears on the line of separation on the other side, forward of the ogive/cylinder junction.

We make the following conjectures regarding their function. First, by considering the analogous situation for a finite-length wing or body, we argue that the foci play the same role in the two cases: They act as the anchor points that allow the stream surfaces containing the cast-off vortical structures to roll up in the wake and form the trailing vortex system. An attempt to portray schematically how a pair of foci might carry out this role on an ogive-cylinder is shown in figure 9. Alongside is a sketch which we have used as a model, depicting how foci carry out the same role on a finite-length wing or body (cf. ref. 20). Notice that the ogive-cylinder may require an additional pair of foci to originate the lines of separation on the cylinder.

Second, we argue that by allowing the stream surfaces containing the pair of cast-off vortical structures to roll up in the wake, the foci enable the formation of a trailing vortex system which is virtually independent of the details of the nose geometry. The change in surface flow topology thereby signals a significant change in the properties of the flow field. Before the foci appear, flow-field properties vary continuously with variations of the roll-angle position of the nose. After the foci appear, the discontinuous behavior characteristic of bistable states becomes possible. The following argument suggests that it is the freeing of the pair of cast-off vortical structures that accounts for the onset of bistable states.

In the early stage of development (incidence angles below the critical value for the appearance of foci, or near the nose), all of the new vortical structures are linked and they influence each other. When the nose is rolled to a new position, all of the structures move accordingly, so their net contribution to the side force varies continuously with variation of the roll-angle position of the nose.

In the later stage of development (incidence angles beyond the critical value for the appearance of foci, and downstream of the foci), where the stream surfaces containing the pair of cast-off vortical structures have rolled up to form the trailing vortex system, the situation is different in two respects. First, because the influence on side force of the remaining linked vortices decays with distance downstream, the pair of trailing vortices emanating from the tip becomes the dominant factor in determining the magnitude and sign of the side force. Second, this pair of vortices no longer responds to the particular orientation of the nose, but only to the ability of the nose to set the right-hand or left-hand pattern of the flow field behind it. A simple application of the Biot-Savart law in a crossflow plane will suggest that the trailing vortices are able to find stable positions at which the balance of forces on them is zero, allowing them to remain stationary relative to the cylinder and to each other. Thus, as long as the flow-field pattern does not change hand as the nose is rolled to new positions, the side-force contribution attributable to the pair of trailing vortices remains virtually constant. Then, this side-force contribution abruptly shifts to the opposite sign when the pair of trailing vortices responds to a change in hand of the flow-field pattern by shifting to its mirror image orientation relative to the angle-of-attack plane (cf. fig. 7). These two factors appear to be sufficient to explain why the side-force variation characteristic of the later stage of development approaches a bistable state, having virtually a square-wave variation with roll-angle position of the nose.

We note that for a finite-length body, the flow at low to moderate values of α is dominated by the early stage of development, whereas the later stage becomes dominant as α approaches 90°. The side-force variation with roll-angle position of the nose changes accordingly from continuous at low to moderate α to a square-wave pattern for larger α, after the first appearance of foci in the skin-friction line pattern. Finally, we note again that as α approaches 90°, regime (3), the regime consisting of an asymmetric steady flow, becomes confined to an ever-diminishing zone just behind the nose. The magnitude of the square-wave pattern of side force characteristic of this regime therefore approaches zero as α approaches 90°.

The existence of extremes of side-force magnitude that are independent of tip geometry and of a maximum of all extremes both are consistent with the virtually independent behavior of the pair of trailing vortices that we have postulated. The magnitude of their contribution to the side force was said to be independent of the tip geometry, to become dominant as α increases, but to approach zero as α approaches 90°. Hence, it is natural that a maximum of all magnitudes should exist at some particular value of α.

Nose Geometry

It is true that nose geometry is the dominant factor in determining the leeward-side vortex orientation. The orientation's sensitivity to even the minute changes in nose geometry caused by the accumulation of dust particles was clear testimony to that. An explanation of this extreme behavior on the basis of theory may become possible as a result of further study of the three-dimensional wave system that composes regime (3) of our description of the flow field. We can already see that, in general, there will be a family of possible solutions whose dependence on the axial coordinate will be wave-like, containing an indeterminate (open) phase. From the infinity of possible solutions, the particular tip geometry will pick out the one having the appropriate phase. Hence, every alteration to the tip will alter the phase accordingly. The sensitivity of the flow field to size, location, and form of perturbation may find an explanation on this basis.

The application of theory may also clarify the role of other perturbations in triggering the asymmetric flow field when tip perturbations are absent. Theory suggests that a minute perturbation at the tip will activate growth of the asymmetry in the flow field immediately behind it, which in turn will activate that of the succeeding flow field, and so forth downstream. In the absence of a tip perturbation, any one of these activated flow fields could be considered an appropriate trigger for succeeding flow fields. To achieve the same effect as the tip perturbation, however, it is clear that a downstream trigger would have to be very large. This discussion suggests that to each position of the body there corresponds a critical dimension, characterizing the size of a disturbance at that site just sufficient to set off the instability in the flow field behind it.

CONCLUSIONS

The analysis carried out here was intended to provide a theoretical basis to the explanation in terms of convective and absolute instabilities of the computational observations contained in reference 2 and to the experimental observations contained in reference 7. Both pertain to the phenomena of the flow about an ogive-cylinder of finite length placed at incidence to an oncoming stream. Principal conclusions of the analysis follow.

1. Theoretical considerations support the hypothesis advanced previously on the basis of computational observations: At moderate angles of attack, where the nose influences flow over the entire body, the observed asymmetric mean flow is the result of a convective instability of an originally symmetric flow to a permanent disturbance applied at the tip, asymmetrically disposed with respect to the angle-of-attack plane. At higher angles of attack, where the flow over the aft part of the body escapes the influence of the nose, the original steady symmetric flow is additionally absolutely unstable to a temporal disturbance of finite duration, applied asymmetrically with respect to the angle-of-attack plane. Triggering the absolute instability results in the appearance of both parallel and oblique vortex shedding. The fluctuations may occur about a symmetric mean flow in the absence of a fixed asymmetrically disposed disturbance, or about the asymmetric mean flow resulting from the convective instability triggered by the presence of such a fixed disturbance at the tip.

2. The experimentally confirmed existence of bistable states, wherein the side-force variation with nose roll angle approaches a square-wave distribution, is attributable to the dominant influence of a pair of trailing vortices from the ogival forebody. Their formation and virtual freedom from the influence of the particular nose geometry is made possible by the appearance beyond a critical value of the angle of attack of foci of separation in the skin-friction line pattern.

3. At low to moderate incidence angles, the extreme sensitivity of the asymmetric flow orientation to nose geometry (demonstrated experimentally) is attributable to the presence of an indeterminate phase in the family of possible solutions for the three-dimensional wave system.

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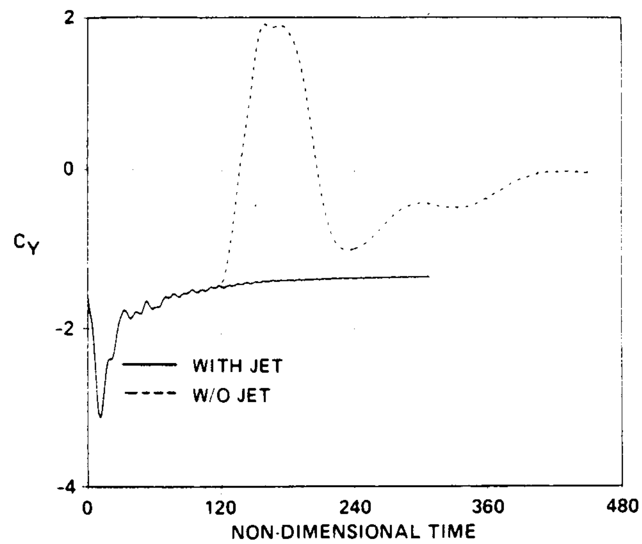


Figure 1.– Side-force coefficient history, $M_\infty = 0.2$, $\alpha = 40°$, $Re_D = 26{,}000$ (ref. 1).

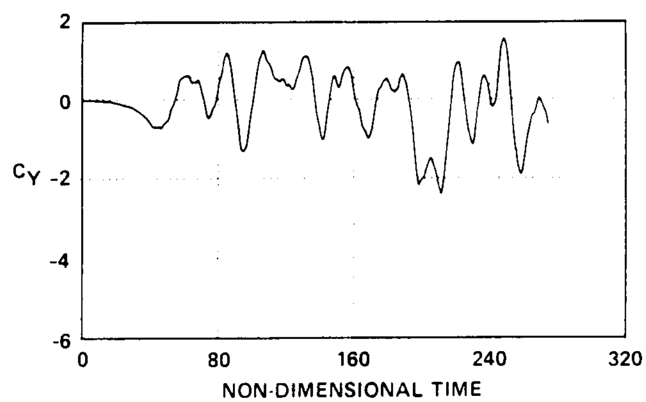
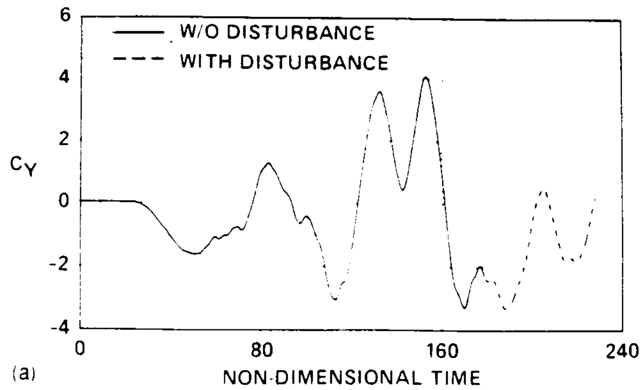
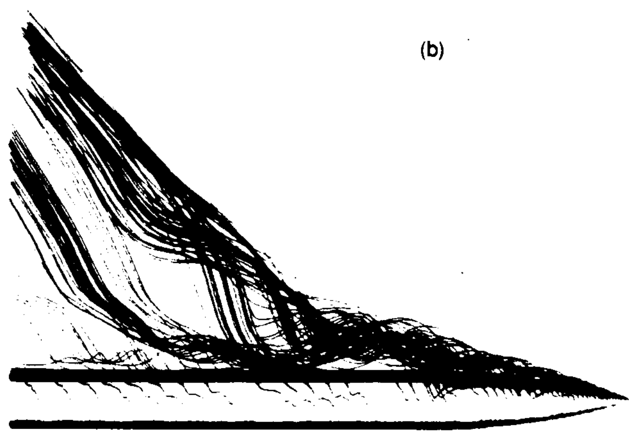


Figure 2.– Side-force coefficient history, $\alpha = 80°$, $M_\infty = 0.2$, $Re_D = 200{,}000$ (ref. 2).





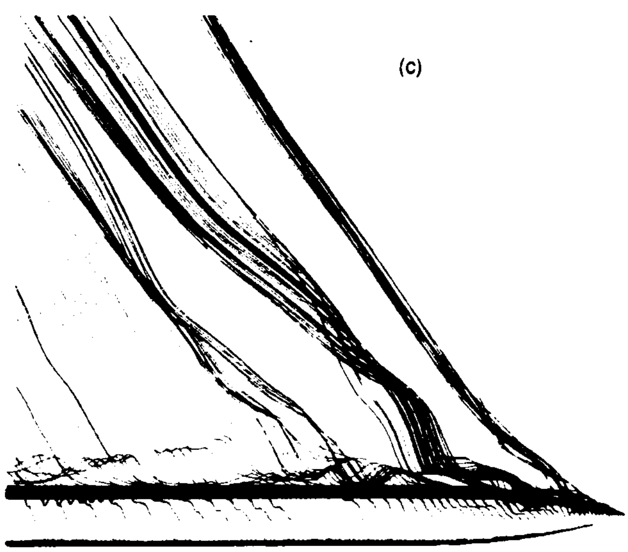


Figure 3.– Side-force coefficient history, $\alpha = 60°$, $M_\infty = 0.2$, $Re_D = 200{,}000$ (ref. 2). a) Side-force coefficient, b) off-surface streamlines without disturbance, c) off-surface streamlines with disturbance.

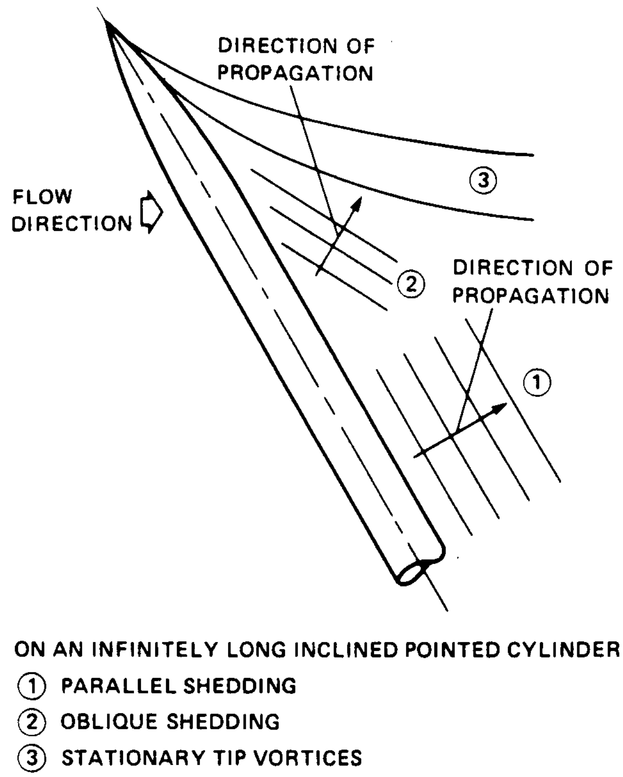


Figure 4.– Leeward-side flow regimes.

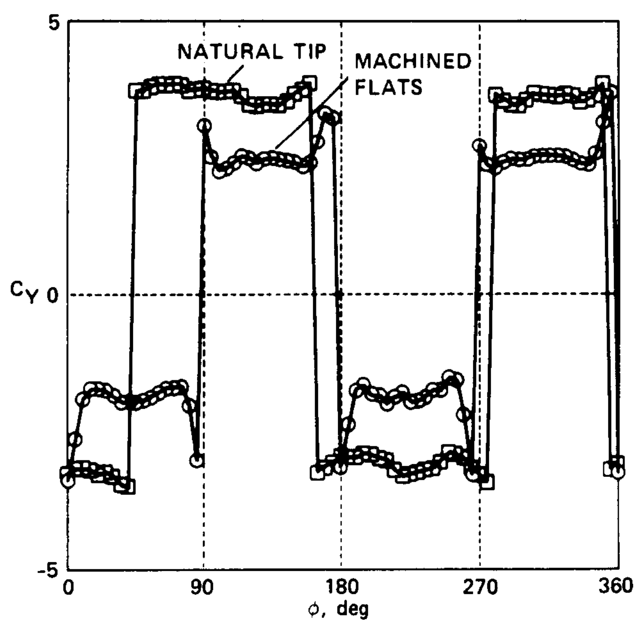


Figure 5.– Side force versus nose roll angle. Natural tip and tip with microscopic machined flats, $Re_D = 30{,}000$, $\alpha = 53°$ (ref. 7).

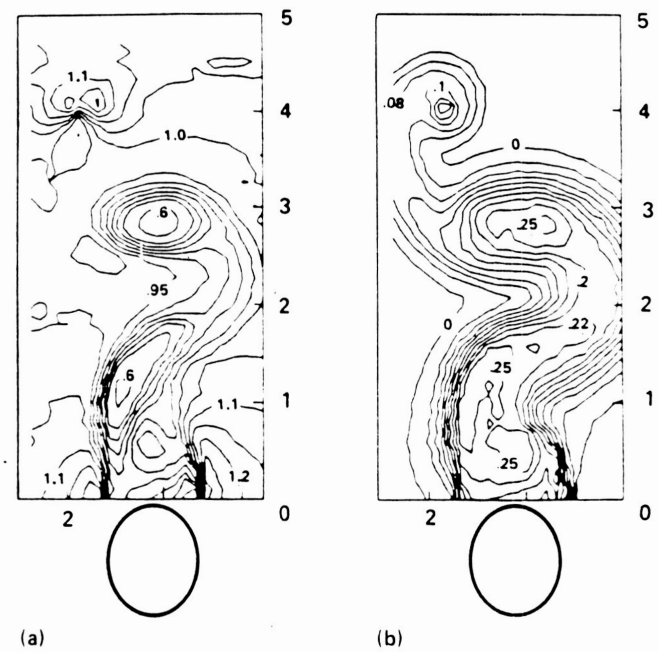


Figure 6.– Hot-wire survey of a plane. $X/L = 0.55$, $\alpha = 55°$, $Re_D = 26{,}000$ (ref. 19). a) Mean velocity, b) RMS velocity.

Figure 7.– Smoke-laser sheet visualization of flowfield, $\alpha = 55°$, $Re_D = 30{,}000$ (ref. 7). a) Left hand, $C_Y = 3.79$, b) right hand, $C_Y = -3.57$.

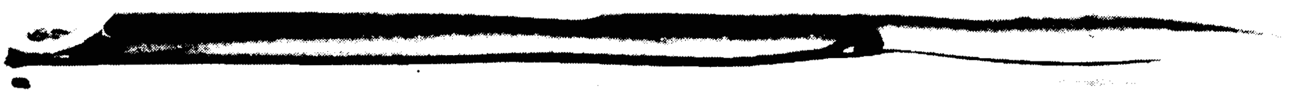
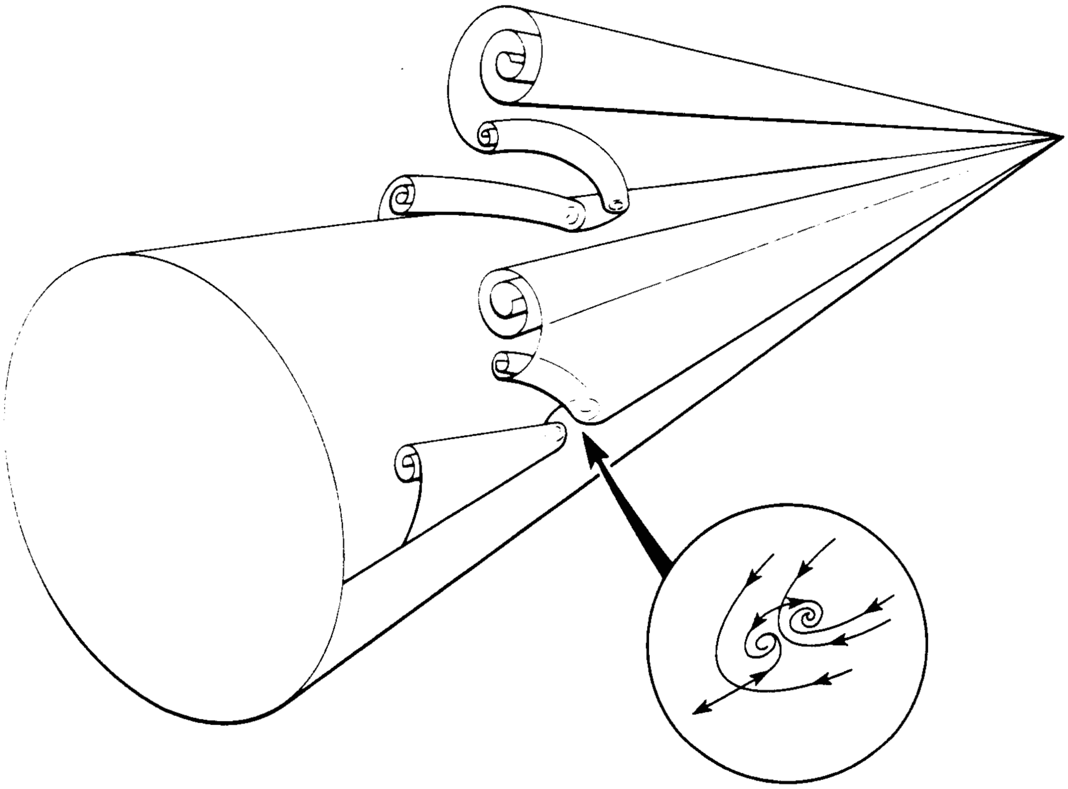
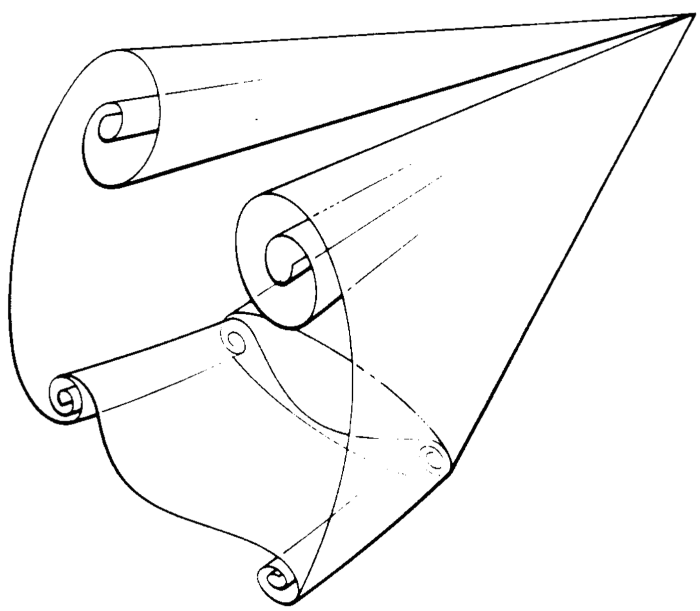


Figure 8.– Surface oil-flow visualization, Re_D = 26,000, α = 55° (Degani, D. and Zilliac, G. G., unpublished data, 1988).



(a)



(b)

Figure 9.– Conjectured mechanism for formation of trailing-vortex system on a) ogive-cylinder, and b) finite-length wing or body.

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16. Abstract

An hypothesis advanced originally to explain computational observations is supported by theoretical considerations: The asymmetric mean flow observed on bodies of revolution at moderate to high angles of attack is the result of a convective instability of an originally symmetric flow to a time-invariant space-fixed disturbance. Additionally, the time-dependent fluctuations characteristic of the flow at higher angles of attack (up to 90°) are the result of an absolute instability of an originally steady flow to a small temporal disturbance of finite duration. Within a common domain, the instability mechanisms may coexist.

The experimentally confirmed existence of bistable states, wherein the side-force variation with nose roll angle approaches a square-wave distribution, is attributed to the dominant influence of a pair of trailing vortices from the ogival forebody. Their existence is made possible by the appearance of foci of separation in the skin-friction line pattern beyond a critical value of angle of attack. The extreme sensitivity of the asymmetric flow orientation to nose geometry, demonstrated experimentally, is attributed to the presence of an indeterminate phase in the family of possible solutions for the three-dimensional wave system.

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