Prediction of Aerodynamic Out-of-Plane Forces on Ogive-Nosed Circular Cylinders

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This paper describes an empirical method for predicting the aerodynamic out-of-plane forces and moments on circular cylindrical bodies with tangent-ogive noses. The method is derived from experimentally determined distributions of out-of-plane force over the cylindrical body. It is applicable to incompressible flow conditions and is based mainly on experimental results where the boundary layer over the body was laminar at separation. An examination of the available experimental data on overall out-of-plane forces and moments suggests that some of this data may have been affected by a form of unsteadiness which is determined by the test facility. The predictions of the present method show good agreement with the limited amount of experimental data which is considered to have general significance.

Nomenclature

C_{of}	= coefficient of out-of-plane force per unit length based on cross flow dynamic pressure and cylinder diameter
C_{of_B}, C_{of_D}, C_{of_F}	= values of C_{of} at points *B, D* and *F*, respectively, of the characteristic distribution (Fig. 1)
C_{OF}	= coefficient of overall out-of-plane force based on freestream dynamic pressure and $\pi D^2/4$
C_{OM}	= coefficient of overall out-of-plane moment based on freestream dynamic pressure and $\pi D^3/4$.
D	= diameter of cylinder
F_N	= nose fineness ratio, L_N/D
L	= overall length of the model
L_N	= length of the nose
P, Q	= quantities which determine the shape of the first half cycle, [Eq. (1)]
R	= cylinder radius
Re	= Reynolds number, $D \csc\alpha U/v$
Re_D	= Reynolds number, DU/v
t	= flow development time for an impulsively started cylinder
$\bar{t}$	= Vt/R for an impulsively started cylinder, $x \tan\alpha/R$ for an inclined cylinder
$\bar{t}_A$, $\bar{t}_B$, etc.	= values of $\bar{t}$ at points *A, B,* etc. of the characteristic force distribution (Fig. 1)
$\bar{t}_{CE}$	= $\bar{t}_E - \bar{t}_c$
$\bar{t}_{EG}$	= $\bar{t}_G - \bar{t}_E$
U	= freestream velocity for an inclined cylinder
V	= freestream velocity for an impulsively started cylinder
x	= axial distance from nose apex
α	= angle of inclination to the freestream velocity
v	= kinematic viscosity
ξ	= $(\bar{t}-\bar{t}_A)/(\bar{t}_C-\bar{t}_A)$
ξ_B	= $(\bar{t}_B-\bar{t}_A)/(\bar{t}_C-\bar{t}_A)$

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Introduction

THE existence of aerodynamic side forces on slender axisymmetric bodies at high angles of inclination has been known for a number of years. It is an intriguing fluid mechanical problem and it is of practical importance to the control of certain missiles and in the recovery from spin of some aircraft. Since the bodies under consideration are axisymmetric, there is no aerodynamic significance in the plane of inclination of the body with respect to the freestream direction. Therefore, in this paper the terms inclination and out-of-plane force and moment are used in place of incidence, side force and yawing moment respectively.

These out-of-plane forces are generated by a complex wake which includes a pattern of asymmetrically shed vortices. The complexity of this flowfield suggests a complex force distribution along the axisymmetric body. A detailed investigation of the pressure and force distributions on the cylindrical part of an inclined ogive-cylinder in conditions of laminar separation has been reported in Ref 1. This experimental investigation leads to a number of important conclusions; those of particular relevance are now summarized. 1) There exists an oscillatory distribution of local out-of-plane force along the body which has a characteristic form. 2) The form of the force distribution is similar to, but not identical with, that suggested by the impulsively started flow analogy (which relates the development of flow along the axis of the body to the flow development with time in an impulsively started two-dimensional flow[2]). 3) Serious unsteadiness of the flow pattern is a common occurrence. This unsteadiness involves a switching of the flow pattern from one of its bistable states towards and sometimes into the other state. This unsteadiness can greatly reduce the time-averaged value of the out-of-plane force. A major cause of the unsteadiness is freestream turbulence. 4) The time-averaged value of out-of-plane force often varies with roll angle. This results from variations in the unsteady flow behavior with roll angle, produced (presumably) by small variations in body geometry. 5) If Reynolds number is based on the length $D\csc\alpha$ and freestream velocity, then the state of the boundary layer at separation is approximately independent of the angle of inclination.[3,4]

These conclusions have important implications for both experimental and theoretical work on this problem. According to conclusion 3), serious flow unsteadiness will be experienced in all wind tunnels except those with very low turbulence levels (the approximate theoretical model of the switching behavior which was developed in Ref. 1 suggests that a turbulence intensity of less than 0.1% is needed before a reasonably undisturbed flow can be achieved). Further, this unsteadiness can result in a time-averaged force which can take any value between equal positive and negative limits which correspond to the undisturbed conditions. The actual value recorded will depend on the freestream turbulence and the roll angle of the model. A further source of switching which can affect the recorded value of the time-averaged force is vibration of the model, which is liable to occur unless the model is rigidly mounted. It therefore follows that many of the published results for time-averaged force will be valid only for the particular conditions under which they were obtained and will have limited general application. This observation helps to explain the discrepancies and inconsistencies which exist in the literature. It also means that great care must be exercised in selecting experimental results for the purpose of testing a prediction method. Such a prediction method can only hope to consider the undisturbed flow condition, since the unsteadiness depends on freestream turbulence and minute geometric effects; the prediction of which would seem to be beyond the scope of present knowledge. It should also be noted that according to conclusion 5) above, the use of a Reynolds number based on cylinder diameter (which has been almost universal) means that the condition of the boundary layer at separation can change with angle of inclination, adding further to the difficulties of interpreting the results.

As far as the theoretical work is concerned, the inexactitude of the impulsively started flow analogy, stated in conclusion 2) previously, is relevant. All the published methods[5-9] for out-of-plane force use this analogy. Now, although the limitations of the analogy are not yet completely clear, it has been demonstrated in Ref. 1 that it is certainly incorrect in certain respects. Consequently, any theoretical method based on the analogy will contain at least some inherent inaccuracy. A further point to be made is that all the existing methods (except that due to Lamont and Hunt,[6] which is inaccurate in other respects) involve calculating the force on the body from vortex strengths which are either estimated or generated by a discrete vortex computation. An indication of the uncertainties present in these calculations is given by the fact that the methods disagree fundamentally over the expression to be used to relate vortex strengths to the net force. The problems encountered with such methods are perhaps not surprising since they are effectively attempting to predict the lift force developed in a time-dependent flow over a cylinder and this has not yet been done with complete success even for fully developed Karman vortex shedding, in spite of the heroic efforts of Sarpkaya,[10] Gerrard,[11] and others.

Thus, although the vortex models are attractive in the sense that, in principle, they can be applied to a wide range of flow conditions and geometries, their accuracy is sufficiently uncertain so that there is a place for more restricted but firmly based empirical methods. In this paper, such a method is described, based on the experimental results of Ref. 1. It is appropriate for incompressible flows with laminar separation from cylindrical bodies with tangent ogive noses. It is strictly valid only for the loads on the constant diameter section but evidence is presented that the method works quite well for the loads on the noses also.

Prediction Method

The prediction method is based on experimentally determined distributions of force along the axis of a circular cylinder fitted with tangent ogive noses of fineness ratios, F_N, of 3, 2.5, 2, and 1. These force distributions were obtained by integrating the circumferential pressure distributions measured on an extensively pressure tapped model[1] under conditions of laminar separation. The maximum freestream Mach number was 0.2. The prediction method uses simple expressions to represent these force distributions and integrates them to give out-of-plane forces and moments.

There are, however, certain features of the results which require preliminary comment. First, considerable unsteadiness was experienced under some conditions, resulting in reduced values of time-averaged force. Values corresponding to the unswitched state were obtained with the aid of a limited number of time-dependent measurements: this prediction method is based on these unswitched values. Second, it was found that a strong dependence on Reynolds number exists at inclinations above about 55°, the amplitude of the out-of-plane force reducing and the spacing of the distribution increasing with increasing Reynolds number even for laminar separation. The prediction method makes use of the highest values of amplitude and their corresponding spacing. No Reynolds number dependence has been built into the method because it was also found that the range of Reynolds numbers over which the reduction occurs depends on the scale of the model.[1]

Characteristic Force Distribution

The results of the pressure plotting experiments show that the distribution of out-of-plane force along an inclined cylinder has a characteristic form which occurs at all angles of inclination up to the region extending from 65° to 80°, where the time-averaged force disappears. The characteristic form of the distribution of C_{of} (the coefficient of out-of-plane force per unit length) is illustrated in Fig. 1 where the abscissa is the impulsive flow analogy parameter $\bar{t}=x\tan\alpha/R$. The coefficient C_{of} is based on cross flow dynamic pressure and cylinder diameter. This form is similar to that suggested by the simplest form of the impulsively started flow analogy.[6] However, only three significant half cycles of the oscillatory distribution are present, instead of the infinite number suggested by the analogy. Also unlike the simple analogy, the amplitude and spacing of this characteristic force distribution vary with inclination angle α and nose fineness ratio, F_N. The approximate expressions used to represent these variations are described in the following two sections. The experimental values of Ref. 1 do not always define the variations in amplitude and spacing unambiguously, but they do, on the whole, enable sensible approximations to be constructed.

Variation of Amplitude

The simple impulsively started cross flow analogy suggests that the amplitude of the characteristic out-of-plane force distribution along an inclined circular cylinder is independent of inclination. The experimental results agree with this suggestion for inclinations below that at which asymmetric flow begins on the nose. Above this inclination the peak out-of-plane force at point B of Fig. 1, C_{of_B}, increases with inclination as progressively more of the asymmetric flow development occurs on the nose. This increase in C_{of_B} continues until a maximum value is reached when point B is close to the nose-cylindrical junction. Its value then falls rapidly until the characteristic distribution disappears completely at very high angles of inclination. The variation of C_{of_B} with inclination for various nose fineness ratios can be reduced to a common form embodying these features, if it is related to the value of $\bar{t}$ at the end of the nose, $2F_N\tan\alpha$. This common form is shown in Fig. 2. The curve used for $2F_N\tan\alpha>\bar{t}_A$ is a third-order polynomial which passes through unity at $\bar{t}_A$, through zero at $\bar{t}_C$ and has a specified maximum value at $2F_N \tan\alpha=8.6$. The manner in which the maximum value, and the values of $\bar{t}_A$ and $\bar{t}_C$ are determined are described below.

The experiments showed that the maximum value of C_{of_B} is greater with the $3D$ ogive nose than with the $2D$ nose. The straight line which passes through these two values is $1+0.4F_N$. Although only based on two points, this straight line approximation produces good results when incorporated in the prediction method for out-of-plane force, even when extrapolated to predict the out-of-plane force and moment on a cylindrical body with a nose of length $3.5D$.

The values of C_{of_D} and C_{of_F} must be considered in order to complete the definition of the amplitude of the characteristic force distribution. Despite the variation of C_{of_B} with inclination and nose fineness ratio, the ratio of C_{of_D} to C_{of_B} ap-

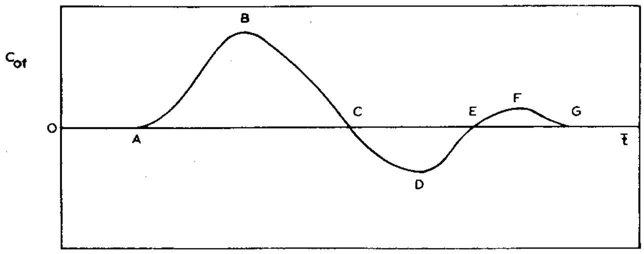

Fig. 1 Characteristic distribution of out-of-plane force along the body.

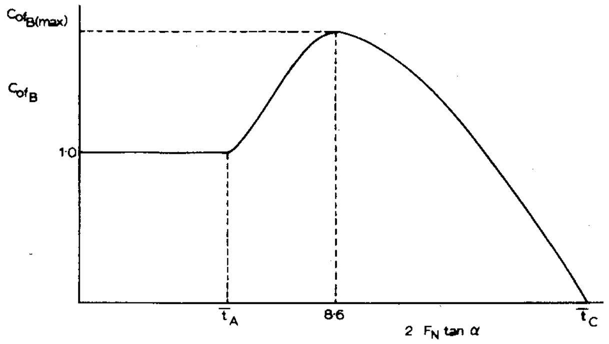

Fig. 2 Sketch of variation of C_{OF_B} with $2F_N\tan\alpha$.

pears to remain reasonably constant throughout. The experimental values of C_{of_D}/C_{of_B} fall in a band of about ± 0.05 about an average level of -0.6. This average value is used in the prediction method. Information on C_{of_F} is far more limited. However, the experimental results suggest that C_{of_F}/C_{of_B} is approximately equal to 0.3. In this way the amplitude of the whole out-of-plane force distribution can be related to the value of C_{of_B} at each inclination.

Variation of Spacing

The distributions of out-of-plane force were initally obtained as variations with x/D where x is the distance along the model measured from the nose apex. Although the distributions were all of the same form, the spacing varied strongly with inclination. Relating the distribution to $\bar{t}$ as suggested by the impulsively started flow analogy, greatly reduces the dependence on inclination but does not eliminate it completely. The spacing between node points tends to increase with inclination and the positions of the onset of asymmetry $\bar{t}_A$ and of the first node point $\bar{t}_C$ are found to depend on both α and F_N. This behavior can be accounted for in the following manner.

The value of $\bar{t}_C$ was found to increase with inclination for tests with all the ogive noses according to the expression $11+4.7\tan\alpha$ until a point is reached where the value of $\bar{t}_C$ remains constant or falls slightly with increasing inclination, Fig. 3. In the prediction method, this behavior at larger angles is approximated by a constant value which is given by the empirical expression $21-2F_N$ (see Fig. 16 of Ref. 1).

The value of $\bar{t}_A$ varies with inclination in a somewhat similar manner to $\bar{t}_C$. Thus, $\bar{t}_A$ increases with increasing inclination according to the straight line $3+0.05\alpha$ until it reaches a constant value at high angles of inclination. This constant value is approximately given by the straight line $7-F_N$.

The spacing of the second half cycle $\bar{t}_{CE}$ was found to increase with inclination. As in the case of $\bar{t}_C$, this increase is proportional to $\tan\alpha$. The experimental variation of $\bar{t}_{CE}$ found in tests with all four ogive noses is represented in the prediction method by the straight line $4+2.6\tan\alpha$ (see Fig. 17 of Ref. 1). The spacing of the third half cycle $\bar{t}_{Eg}$ of the characteristic out-of-plane force distribution was more dif-

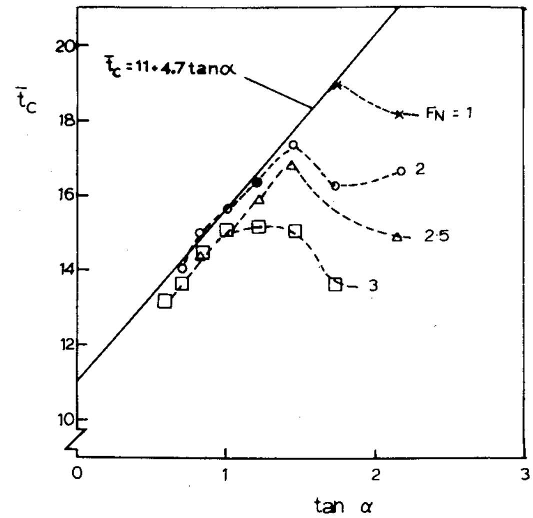

Fig. 3 Variation of first node point with inclination.

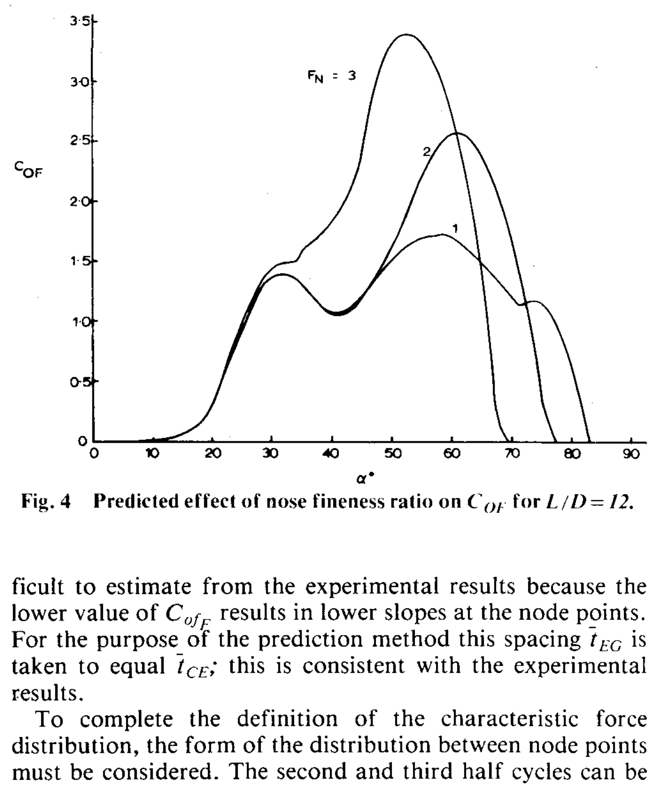

Fig. 4 Predicted effect of nose fineness ratio on C_{OF} for $L/D=12$.

ficult to estimate from the experimental results because the lower value of C_{of_F} results in lower slopes at the node points. For the purpose of the prediction method this spacing $\bar{t}_{EG}$ is taken to equal $\bar{t}_{CE}$; this is consistent with the experimental results.

To complete the definition of the characteristic force distribution, the form of the distribution between node points must be considered. The second and third half cycles can be taken as sinusoidal, but this is not the case for the first half cycle. Point B, the point of the first peak of C_{of}, occurs after the midpoint of the half cycle. The form can be approximated by a distorted sine wave given by

$$C_{of}=P(\pi\xi)^{Q}\sin(\pi\xi) \qquad (1)$$

where $\xi\equiv(\bar{t}-\bar{t}_A)/(\bar{t}_C-\bar{t}_A)$, $0<\xi<1$ and P and Q are defined by requiring the expression to have a maximum value equal to C_{of_B} at the point $\bar{t}=\bar{t}_B$. The variation of $\bar{t}_B$ was found by plotting the spacing ratio ξ_B against inclination. It can be represented, with some scatter, by the line $0.6+0.1\cos 2\alpha$.

Evaluation of Overall Force and Moment

The expressions for amplitude and spacing which have been discussed above enable the distribution of local out-of-plane force coefficient, C_{of}, along the body to be constructed for a given inclination and given nose fineness ratio. Hence the overall out-of-plane force and moment can be obtained by integrating that part of this distribution which is present on the body at a particular angle of inclination. The extent of the distribution present is determined by finding the value of $\bar{t}=L \tan\alpha/R$ at the rear of the model. The contributions of each of the half cycles or of such parts of them as are present on the body are evaluated separately and then summed. The treatment of the first half cycle is made easier by the use of the simple but accurate approximation $\pi(\xi-2\xi^3+\xi^4)$ in the place of $\sin(\pi\xi)$ in Eq. (1). Further details of the calculation method are given by Lamont.[12]

The prediction method is now complete. As an example, Fig. 4 shows the predicted effect of nose fineness ratio on the overall out-of-plane force coefficient C_{of} for an ogive/cylinder with an overall fineness ratio of 12. It can be seen that the force coefficients are similar for all the noses up to 30° inclination. At higher inclinations, the increase in out-of-plane force, produced by having asymmetric flow on the nose, becomes larger and occurs earlier as the nose fineness ratio increases. The figure also shows that the out-of-plane force disappears at progressively lower inclinations as F_N is increased. A further point of importance is that Fig. 4 shows that a continuous evolution of the flow pattern with angle of inclination results in an out-of-plane force which always has the same sign; a brief consideration of the relative sizes of the integrated forces due to the first and second half cycles shows that this must always be the case. It thus appears that experimentally observed changes in sign which have been reported previously are due to a switch in the sense of the preferred flow pattern.

Comparison of Prediction Method with Experimental Results

In this section, comparisons are made with independent tests on ogive/cylinders in which overall forces and moments were measured. The comments made in the Introduction explain the problems caused by freestream turbulence in such testing. Details of freestream turbulence intensity are given in Ref. 13 while Ref. 1 quotes both turbulence intensity and scale. Apart from these, none of the published papers gives information about freestream turbulence, and it is thus difficult to judge directly how much the results have been influenced by unsteadiness. However, an indirect test can be applied via the roll angle dependence. Since a variation with roll angle is caused by different levels of switching, it follows that a strong variation is an indication of substantial unsteadiness and the time-averaged results will not be a reliable indicator of the undisturbed value. Conversely, results which are independent of roll angle probably (but, unfortunately, not certainly) mean that little switching is occurring and that the results are a reliable measure of the steady flow value. Applying this test to the published experimental results, the most reliable are those which Coe, Chambers, and Letko[14] obtained on a tangent-ogive model . These results will therefore be used as a check for this prediction method.

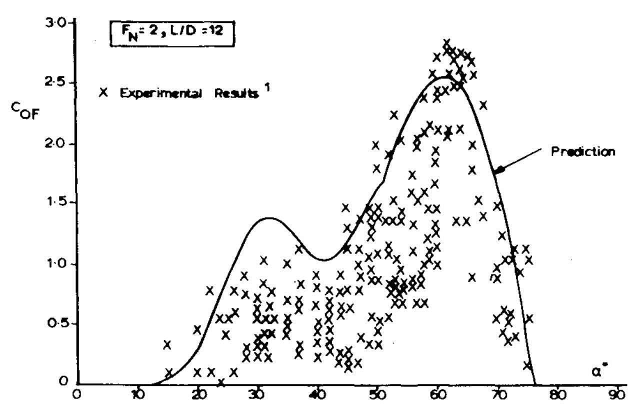

Fig. 5 Comparison of predicted values of C_{OF} with experimental results from Ref. 6.

In addition to Ref. 14 the results of Refs. 6 and 13 will be compared with values from the prediction method. The results of Ref. 6 are used, despite their large scatter, because the experimental conditions in which they were obtained are known and it has been confirmed that their scatter is due to different levels of switching.[12] Time-dependent tests indicate that the highest values correspond very closely to undisturbed flow conditions. As far as Ref. 13 is concerned, the low turbulence intensity (<0.2%) suggests that the results may be only mildly affected by unsteadiness.

The model used in Ref. 6 had an overall length of 12 diameters which included a 2 diameter ogive nose. The comparisons between the prediction method and the experimental results for out-of-plane force and moment are shown in Figs. 5 and 6. The wide scatter of the experimental points is a result of transient flow effects which differed between tests at different roll angles and in different parts of the tunnel. The prediction method aims to predict the maximum out-of-plane force at a particular inclination, thus its variation with inclination should form an envelope to the experimental results. It can be seen that the predicted force and moment curves are each close to such an envelope. In particular, note that the

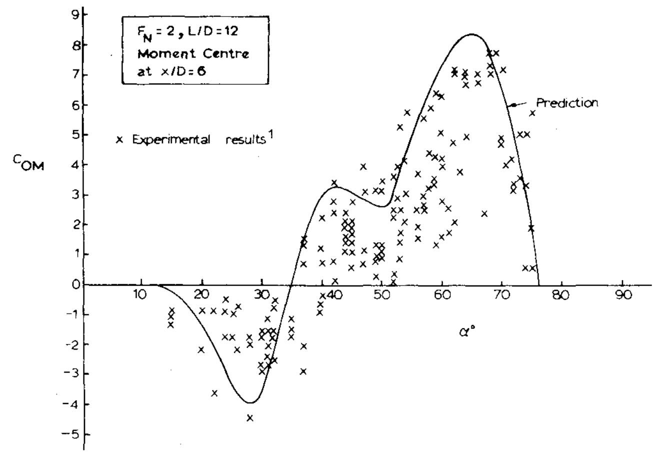

Fig. 6 Comparison of predicted values of C_{OM} with experimental results from Ref. 6.

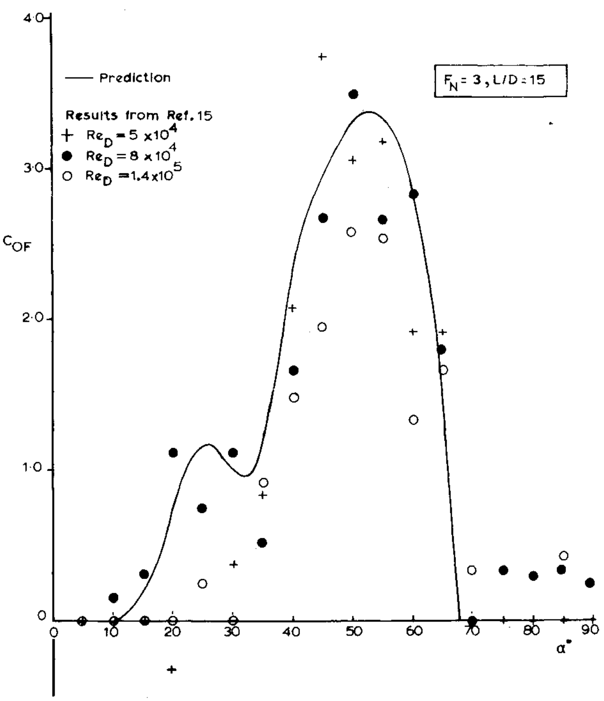

Fig. 7 Comparison of predicted values of C_{OF} with experimental results from Ref. 13.

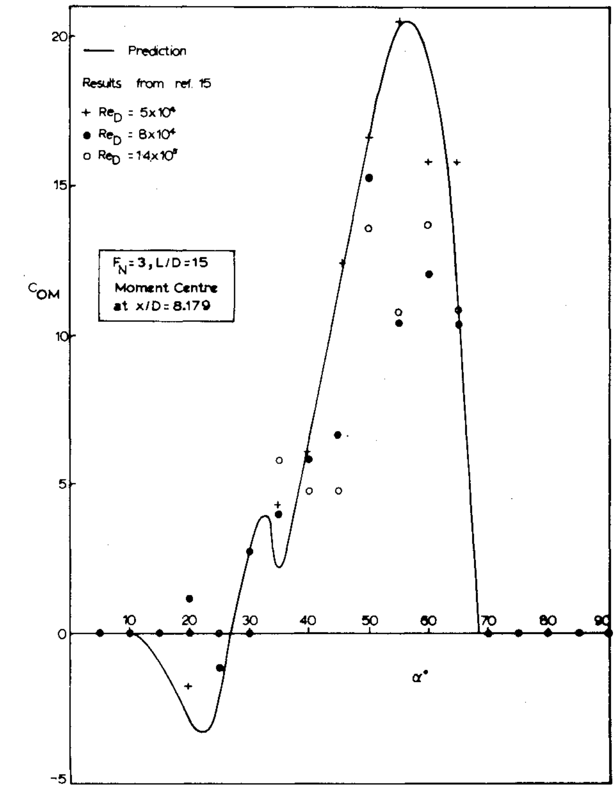

Fig. 8 Comparison of predicted values of C_{OM} with experimental results from Ref. 13.

peak values of both the experimental and the predicted force occur at 62° inclination. Although there is a discrepancy of 10% between these maximum values of out-of-plane force, it would be advisable to await further experimental results before making adjustments to the prediction method, since the accuracy of the experimental method used in these tests was not high.

The results of Smith and Nunn[13] were obtained on a model of overall length equal to 15*D*, including a 3*D* ogive nose. Three values of Reynolds number (based on body diameter) were used, namely 5×10^4, 8×10^4, and 1.4×10^5. These values correspond to Reynolds numbers based on $D\csc\alpha$ of 1×10^5, 1.6×10^5 and 2.8×10^5 at $\alpha=30°$. Therefore, it is probable that laminar separation was occurring on their model at inclinations above 30°. Figures 7 and 8 compare Smith and Nunn's results with the predicted values. Once again, the predicted curve forms an approximate envelope to the experimental force and moment values. The predictions of the form and maximum values of the experimental results for both force and moment are good. When Figs. 7 and 8 are compared with Figs. 5 and 6, it can be seen that the prediction method has correctly reproduced the effect of nose fineness ratio on the maximum values.

The model used by Coe, Chambers, and Letko[14] consisted of a 3.5*D* tangent ogive nose which was tested both with and without a 3.5*D* cylindrical afterbody. Reynolds numbers based on maximum body diameter ranged from 1.5×10^5 to 3.5×10^5. These are equivalent to Reynolds numbers based on $D\csc\alpha$ between 2.1×10^5 and 5×10^5 at 45° inclination. There is no consistent variation between the results at different Reynolds numbers and the separation may be taken to be laminar in all cases at inclinations above 45°. The model nose length of 3.5*D* is beyond the range covered in our experiments, but the expressions which represent variation with nose fineness ratio can be extrapolated to $F_N=3.5$. The most appropriate experiments to use for comparison are those in which the afterbody was fitted. Even this model, however, is very different to those used in our test since the nose length is

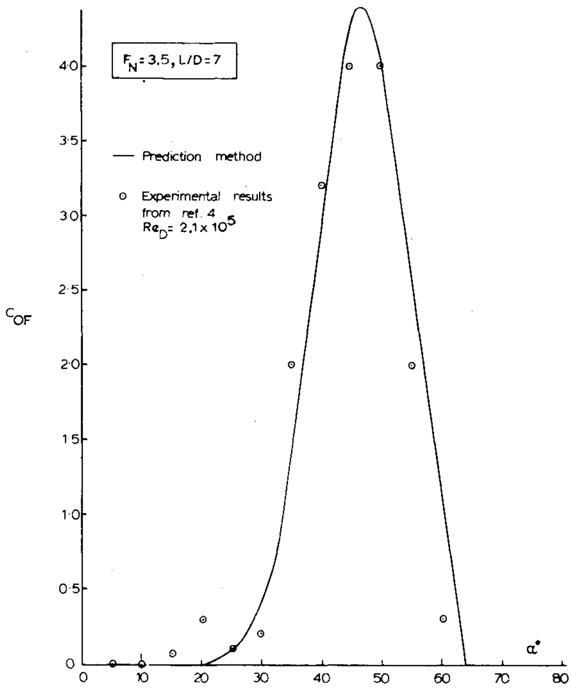

Fig. 9 Comparison of predicted values of C_{OF} with experimental results from Ref. 14.

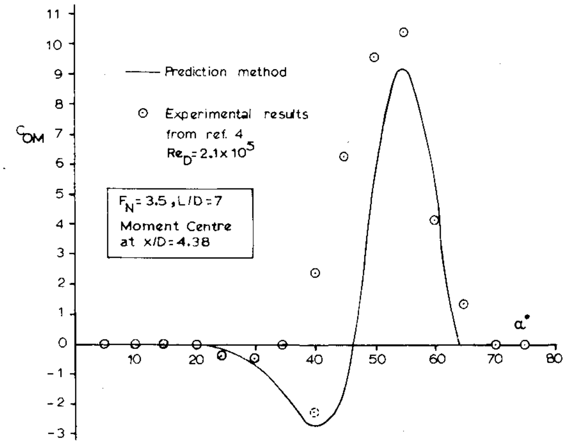

Fig. 10 Comparison of predicted values of C_{OM} with experimental results from Ref. 14.

50% of the total length. This situation exposes a possible weakness in the current method. Surface pressure measurements were taken on the cylindrical part of our model but not on the nose. Consequently, in the implied force distribution used in the prediction method, no distinction is made between that part which occurs on the nose and that part which occurs on the afterbody. This is probably not serious when a missile shape is being considered but is certainly questionable for an aircraft configuration, such as that used by Coe, Chambers, and Letko.[14] Nonetheless, Fig. 9 shows that the prediction method is very successful in predicting the overall out-of-plane forces. The prediction of the out-of-plane moment shown in Fig. 10 is not quite as good but is still very encouraging. In view of this problem of handling the nose, the tests conducted by Coe, Chambers, and Letko without the afterbody represent an extreme case for this prediction method. Despite this, Figs. 11 and 12 show that quite good agreement is still achieved.

Extension of the Method to Turbulent Separation

The experimental work of Ref. 1 dealt exclusively with laminar separation over an inclined cylinder. However, there

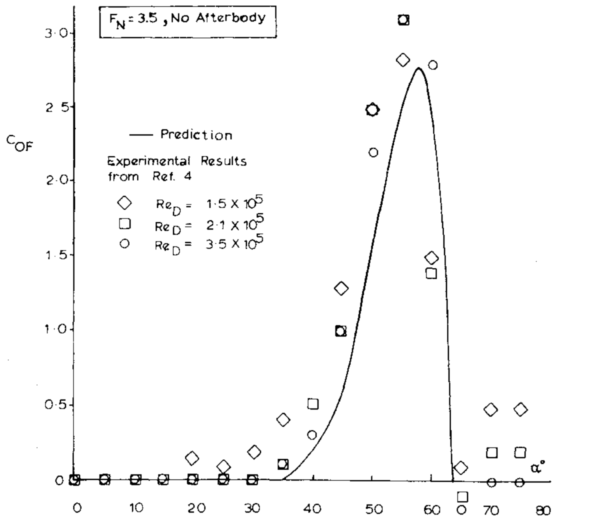

Fig. 11 Comparison of predicted values of C_{OF} with experimental results from Ref. 14.

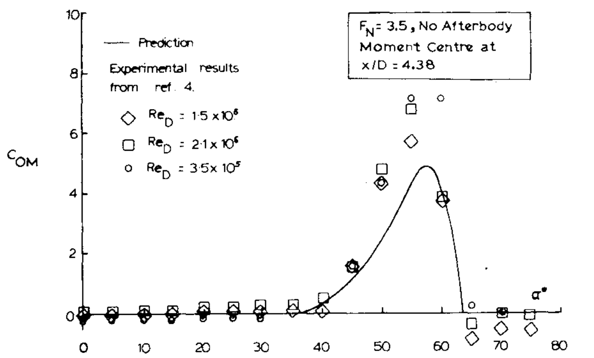

Fig. 12 Comparison of predicted values of C_{OM} with experimental results from Ref. 14.

will be many practical situations, particularly at low to moderate inclinations, where the flow over an inclined cylinder will have a turbulent separation. For completeness, the ideas developed in this work for laminar separation are used to construct an approximate prediction method for turbulent separation conditions from such experimental data as is available in the literature. Bostock[4] measured surface pressures on a model with turbulent separation at angles of inclination up to 30°. These results show that there are characteristic distributions of both out-of-plane force and in-plane normal force which are similar in form to those obtained with laminar separation.

The value of C_{of_B} for turbulent separation is taken from Bostock's work to be 0.8 which is slightly less than the value of 1.0 found with laminar separation. Bostock's results suggest that the ratio of peak out-of-plane force coefficients of the first three half cycles can be taken to be the same as for laminar separation, and that the ratio $(\bar{t}_B - \bar{t}_A)/(\bar{t}_C - \bar{t}_A)$, which gives the shape of the first half cycle, is approximately constant at 0.6, at least for angles of inclination up to 30°. Bostock's results for $\bar{t}_A$ and $\bar{t}_C$ may be approximated by $\bar{t}_A = 3$ and $\bar{t}_C = 9$, both independent of inclination. The values of $\bar{t}_{CE}$ and $\bar{t}_{EG}$ were both found to be 3.5.

These values for turbulent separation were substituted into the prediction method and values of C_{OF} and C_{OM} were calculated for an ogive/cylinder of overall length *12D* and nose length *1D*. When compared with results for laminar separation on the same body, these results show a lower critical inclination for the appearance of the out-of-plane force and moment and substantially reduced maximum values. This is in agreement with the observations of Pick.[15]

Bostock's experimental results were obtained with an ellipsoidal nose of length *1.25D*. Under the conditions of his work, the onset of asymmetry occurs on the cylindrical afterbody. Now, in the results obtained with laminar separation, the magnitudes of the local force distribution are independent of nose shape so long as the flow on the nose is symmetrical. It seems reasonable to assume similar behavior with turbulent separation. This suggests that the predictions under conditions of turbulent separation will be valid for angles of inclination up to a maximum of $\tan^{-1}(\bar{t}_A/2F_N)$ where $\bar{t}_A = 3$. It is unfortunate that there does not appear to be any relevant data which can be used for comparison with the predictions of this extension to the method.

Conclusions

1) An empirically based prediction method has been formulated from local force distributions obtained by Lamont and Hunt.[1] It aims to predict the out-of-plane forces and moments for undisturbed flow conditions. It should be valid for any inclination up to 90°, for tangent-ogive nosed cylinders with nose fineness ratios between 1 and 3.5 under conditions where the flow is incompressible and the boundary layer is laminar at separation. The limited meaningful comparisons which can be made with measured overall forces and moments show good agreement.

2) The predictions of the method show the increase in overall force with nose fineness ratio which has been reported by several workers. However, they also show that changes in sign of the overall force on a particular body (which have also been reported) cannot be produced by a continous evolution of the flow pattern, but must be due to a switch in its sense.

3) A preliminary extension of the method to conditions of turbulent separation has been made using data obtained by Bostock.[4] The range of validity is limited to conditions where the flow over the nose is symmetric. The predicted overall out-of-plane force is lower if the separation is turbulent than if it is laminar. This is in agreement with the experience of most experimental workers.

4) An examination of the available experimental data on overall out-of-plane forces and moments in the light of recent work[1] suggests that some of this data may have been affected by a form of unsteady flow which is determined by the test facility and that such results will therefore not have general validity.

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