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FLOW SEPARATION ON YAWED CYLINDERS : PRESSURE AND WAKE SURWAYS

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Abstract

The flow around a circular cylinder between parallel walls is experimentally investigated both in surface pressure and into the wake. The results show a strong analogy with the properties of cone- and ogee- cylinders, i.e. a pseudoperiodic vortex wake and a weavy separation line. Particular interest was dicated to the case of 60°sweep angle, where the largert aspect ratio (21) could be obtained.

Introduction

It is well known that a "nosed" cylinder and some other slender bodies may show non symmetric separation and wake. From the experiments of Thomson and Morrison(1) till to the last tests of Hartmann, many flow properties and coufigurations were tested, showing generally a lack of symmerty in a wide range of angles of attack.

It is therefore an interesting question to see whether this asymmetry is related to some nose singularity or condition , or it is a much more general property of almost any slender body. On one hand, the fact that, while rotating the models, the asymmetry is switching from one condition to another suggests that it might be related to the nose shape. On the other hand,it is difficult to think about a rather regular vortex sheet leaving the body separation line. At low angle of attack a straight separation line was observed by Poll (3), but it does not mean that further Kelvin-Helmholtz instability will not roll-up the wake into discrete vortices. And there is no reason to say that far downstream the wake will not obey to the usus1 von Karman street stability condition.

Starting from this consideration ,it was therefore interesting to investigate what would happen with a completely different initial condition, i.e. a straight wall parallel to the onset flow. If we add the hope of getting something similar to "infinite yawed cylinder",it is quite obvious to test at rather high aspect ratios.

This is therefore the general outline of a set of tests carried on in the attempt to give either answer to the questions or suggestions for further investigations.

Symbols

Alfa - angle between flow and V_{oo}in the V_{oo}-Y plane
Beta - angle between flow and V_{oo}in the V_{oo}-Z plane
D - cylinder diameter (6cm) and reference length
V_{oo} - asymptotic velocity vector
Y - coordinate nurmal to axis and V_{oo}
Z - coordinate along the axis

1) Experimental setup

The models were made by acrylic tubes of 0.06 m of diametre, one for each specific test.

The first model was fitted with 118 pressure taps spaced by 1/4 diametre, aligned on a cylinder generator. Each pressure tap was connected to a Scanivalve system and finally to a pressure transducer. In this way it was possible to measure the whole pressure field on the cylinder surface.

A second model was used both for flow visualization and for wake measurement. A third one is now under eqiopment for shear stress measurement on the body surface.

The wind tunnel is a rectangular, closed test section open circuit facility. Its cross-section is 0.5 x 0.7 square meters and the typical speed is 20 meter per second. This leads to a Reynolds Number about 100 000.

Special transparent walls with elliptic holes were manufactured to host the models, in order to have an accurate wall-model intersection. This has obviously limited the tests to a discrete number of sweepback angle. We tested 0° for a general check, and then only 30°;45° and 60°, this latter being the maximum allowable by the test-section size.

Being in the fully laminar regime, we tried to rotate the model around its axis, on the basis that it had no nose: at least any asymmetri trigger could be related to wall and not to nose imperfections and would not rotate with the model.

In any case each test was conducted without any flow interruption, because we wanted to avoid a stochastic trigger of instability which could changê for a tunnel stop and restart.

2) First tests

Although yet published in (4), let us summarize the results of the pressure tests, because their comment is the basis of the present research.

It has been noted that, in fact, the pressure is asymmetric and, far from the upstream wall, quite antisymmetric. This may be shown , for example, by the pressure distribution on two cylinder generators in symmetrical position with respect to the planr which is defined by the onset flow vector and the body axis.

In Fig. 1 such a pressure plot is shown in dimensionless form for the tested configurations.

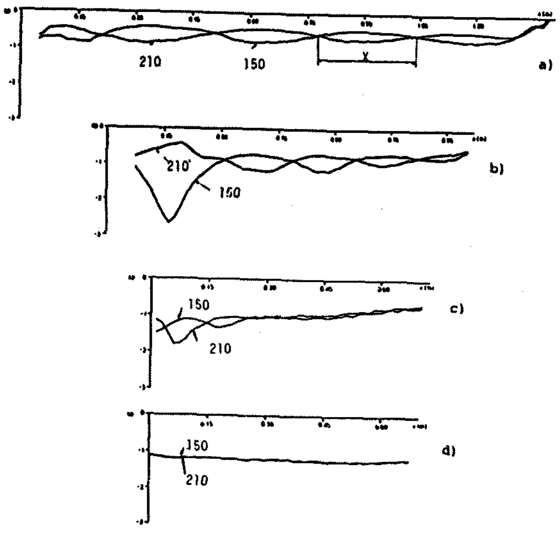


Fig. 1 Pressure coefficients along 210° and 150° generators. Sweepback angle: a) 60° ; b) 45° c) 30° ; d) 0°

It could be noted that for no sweep the pressure is constant, as predictable in two-dimensional flow. For 30° sweep, at the left of the plot corresponding th the upstream side, there is a remarkable asymmetry, which soon disappears althoughthe pressure is no more constant. Thi is sign of a certain three-dimensionality of the stream. It is the first evidence that we cannot superimpose axial and cross-flow as in the classical swept wing theory.

At 45°degrees, there is a large pressure peak which may be explained as the "capture" of the separation horseshoe vortex on the side wall. One of the two branches of the horseshoe vortex goes along the cylinder for a while. After this phenomenon,which is shurely related to the presence of the sidewall and was yet clear at 30°, there is an antisymmetric pressure distribution whose amplitude is decaying as we approache the opposite sidewall. Also the average pressure seems to be slightly decreasing, as observed for 30°, but less evident.

On the other hand , at 60° sweepback, there is no remarkable peak on the first sidewall, the average pressure is not clearly decreasing and the pressure antisymmetry is quite clear and maybe of rather constant amplitude.

At that point we can answer to the first basic question:"even with no nose, the stream past a sweptback cylinder may be antisymmetric as the one of "nosed" cylinders"

The second conclusion is that even if all known stability criteria says that the laminar boundary layer is stable, the flow is unstable although in space and not in time.

At his point a further question arises:

"is the asymmetry decreasing to zero as could be suspected by "nosed" cylinder experiments or can it reach some asymptotic value"

3) Further analysis of the first results

Beyond what was yet published on the first pressure tests, it is time of further observations.First is the decrease in asymmetry of nosed cylinders and of the 45°sweep experiment between parallel walls.

On a nose or an ogee, there is a "conical" growth of a pair of vortices on the"conical" forebody: thus the first shedded vortices might be stronger then the following andtheir induced velocity may alter boundary layer separation. As this is decreasing, asymmetry may also decrease.

In the 45° experiment, the wall separation horseshoe vortex may have the same effect.

Therfore separation and pressure might show no significant asymmetry, while Kelvin-Helmholtz instability may introduce antisymmetrical flow in the far wake.

It is therefore necessary to separate the concepts of antisymmetric separation from the one of " von Karman like" wake.

At that point it is clear that the pressure experiments are not sufficient to produce the required information: we need to know the separation behaviour and the vortex strength in the wake.

4) Further plans for experiments

A complete set of experiments will require the knowledge of the wake and the complete wall stress distribution.

The measurement of skin friction is a rather complicated thing in laminar flow. In turbulent flow it is easy to assume the Coles' law of the wall and use any kind of pressure measurement in the wall layer, ralating it to skin friction.

For laminar flow, the velocity profile near the wall is connected to the pressure gradient by the usual law:

$$\mu(du/dy)= dp/dx$$

therefore any skin friction measurement by means of a velocity measurement close to the wall is also related to the local pressure gradient.

This is apparently no problem , because the pressure field is well known by the first tests, but resulted in a very difficult task for calibrating the probes.

The data obtained are up to now too scattered to be a basis for sound conclusions.

Further investigation is therefore required.

5) The wake surway

A) Instrumentation

The instrumentation for wake surway is related to the physical quantity of interest, i.e. the vortex strength.

Anyone knows the problems related to measure vorticity, like instrumental perturbations and vortex breakdown. therefore it was decided to measure the circulation around the vortex cores without accepting any value very close to the core itself. This procedure seemd to be simple and useful to answer to the main questions left open about the wake.

Therefore it was necessary to measure single velocity components or flow angles, in order to integrate them and finally get the circulation around simple rectangular paths.

The choice was a five tube pressure probe, which has rather small cross-sensitivity. Four tubes are welded around a central one, in order to measure total pressure and flow direction.

The square front tubes grant small angular sensitivity and therefore easier data reduction.

The probe was calibrated in three direction , one parallel to a pair of tubes, the second to the other pair and a third along the bisector.
Simple parabolic interponalions were taken for all other angles.

In this way, although with some loss in accuracy it is possible to grant unique result from the five pressure measurements.

The overall resolution is not better then 2° in any range of angles within ± 30°, wich is reasonable in preliminary tests.

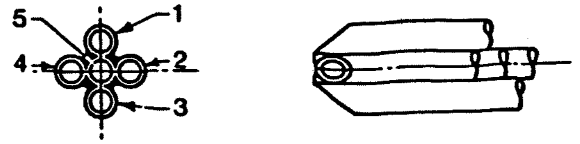
Each pair of pressure tubes is connected to a separate pressure transducer, to avoid zero errors, which are much worse then lack of accuracy for large angles in integrating velocity components.

The central tube was connected to a pressure transducer which could measure the difference from total and tunnel static pressure.

This again is not a mean of obtaining local velocities, but a loss in total pressure is indicating the locaion of the probe in the vortex core and therefore a suspicious measurement.

B) Experimental setup

The probe was mounted on a two-axes transversing gear, driven by a data acquisition computer.



The 5-tube probe

One of the axes was parallel to the cylinder axis and is referred in the text as Z coordinate.
The other one is normal to onset flow and cylinder axis and is referred ad Y coordinate.

An Z-Y mesh was explored in steps of 1/6 of cylinder diametres in the Y direction and 2 diameters in the Z direction.

C) Data reduction

Direct trapezoid rule integration over 30 steps in the Y direction was used to calculate the potential along the Y axis for different Z stations.

Plots of potential are shown in fig. 2, where the most significant result is shown.

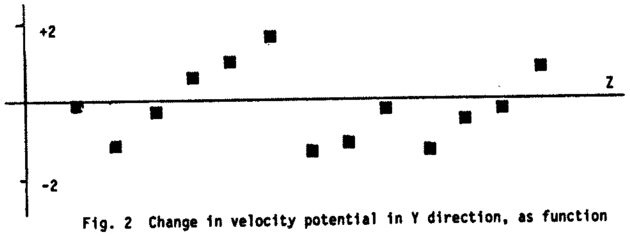


Fig. 2 Change in velocity potential in Y direction, as function of Z

The measuring station is 5D downstream,in order to investigate the wake where it is almost aligned to the onset flow direction V_{∞}

Another reason for this choice is that at that stati it is reasonable to assume that the pressure is only slightly different from static pressure and the velocity outside the vortex cores might be evaluated by simple total pressure measurement. This may avoid the necessity to align probes to the local flow direction in a range of ± 30° to obtain first-approximation data.

6) ANALYSIS OF THE RESULTS

a)Circulation If we look at Fig. 2, where the change in potential is plotted versus the Z direction, (Z=0 7D from sidewall) we note that, between Z=6D and Z=7D there is a strong jump. This is interpreted as a vortex which is leaving the body. We can also note two other jumps after Z=1 and Z=9.

Apart of the jumps, the slope of this Z-wise increase in potential is almost constant, this leading to the idea of similar flow properties along the axis. Although this is not a strict confirm of the tendence towards a steady periodic condition, shurely is one of the things which could lead to this conclusion.

b)Velocity vector We can now observe the velocity vector just ahead and after the largest potential jump in circulation, as one of the most significant features of the wake.

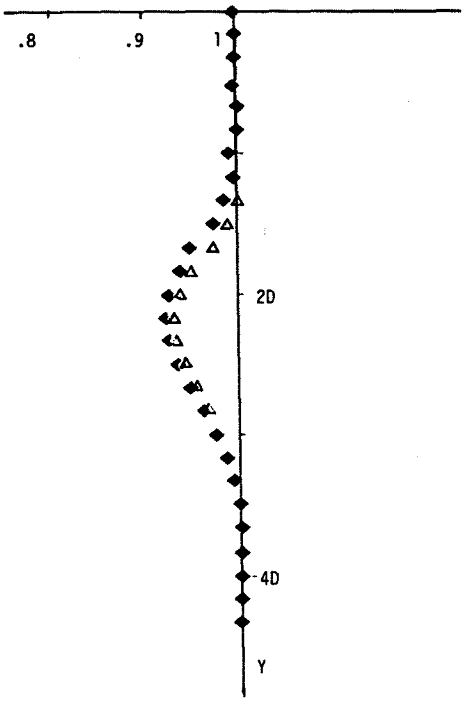


Fig. 3 The velocity defect upstream (open symbol) and downstream (closed symbol) the main vortex

First of all, in Fig. 3 there is a plot of the velocity defect upstream and downstream the jump. It could be noted that there is no significant change between the two sections. Therefore the energy loss is not changing too much. A second consequence is that the probe did not cross the vortex core and therefore the other measurement are reliable.

Referring now to the plots of velocity direction of Fig.5 , where the angle alfa formed by the velocity vector with respect to the onset flow in the plane V_{oo}- Y,and beta in the V_{oo}-Z are plotted versus the Y direction, we may observe that the angle alfa is quite antisymmetric inside the wake, while the angle beta isdifferent in the two stations outside the wake and almost coincident in the middle. Therefore the flow is "skewed"in the axial direction outside the wake, as we can expect from potential flow theory and vortex induction, and the wake itself is deflected in the normal (Y) direction.

In terms of usual "nosed" cylinders, the two deflections are associated to changes in momentum and therefore to forces. Deflection in alfa means sideforce and deflection in beta means lift and lift-dependant drag. A defect in velocity modulus is mainly associated to parasitic drag.

Therefore the lift and total drag ar not too much affected by the vortex shedding, and are mainly associated to the simple existance of vortices, while the sideforce is quite changing along the axis.

Fig.4Shows the location of maxima and minima of velocity defect and flow directions. Again it is possible to observe a clear jump in the location of the maximum beta, which corresponds to the vortex position. The angle alfa has a much more variated and periodic aspect, as it is related to the side deflection of the flow.

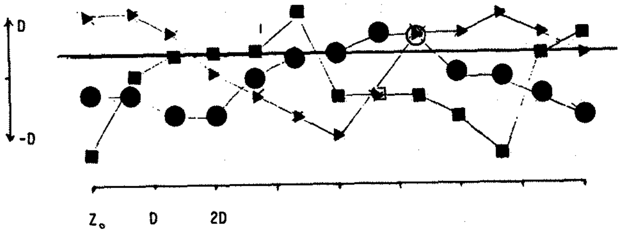


Fig. 4 Y location of maxima and minima: cercle-velocity
square- alfa
triangle - beta

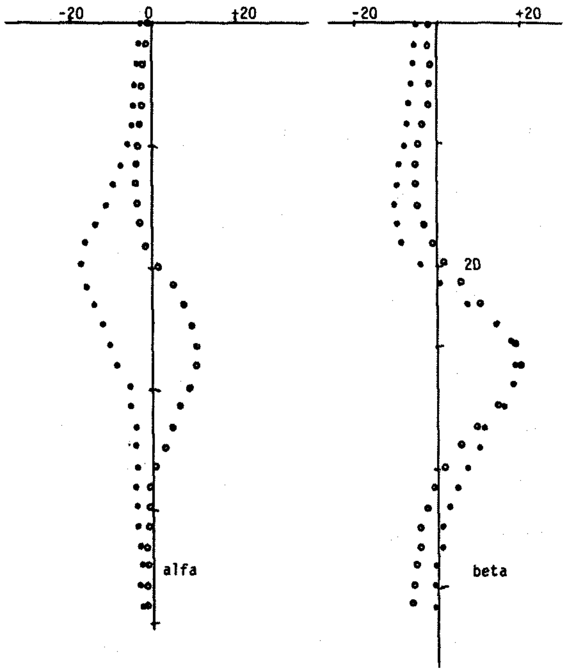


Fig. 5 The change in alfa and beta upstream and downstream the vortex. Open symbols upstream.

7) CONCLUSIONS

The first conclusion is the need of testing in a certain renge of Reynolds Numbers and with possibly higher aspect ratios, to be shure to avoid large wall interference on the wake development.

The experimental technique although simple, has shown the possibility of obtaining a lot of information, if associated with suitable data reduction.

The results have confirmed that the flow on simple bodies might be rather complicated and probably on very long bodies in sweeped configuration the flow is periodic. Maybe this is not interesting for long cylinders, but will give a better insight into the mechanism of separation bubbles in sweptback wings, on leading edges and in flap slots. It is important to obtain slight improvements in wing performances, both in maximum lift and cruise drag.

Of course, the flowfield measurement close to the body and the shear stress evaluation is the next goal of the research.

The last remark is that a more complete set of data could be a good case for numerical code validation, but this set is at least a first one for comparing to Navier-Stokes solution.

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