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AERONAUTICAL RESEARCH COMMITTEE.

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THE EFFECTS OF TURBULENCE AND SURFACE
ROUGHNESS ON THE DRAG OF A CIRCULAR
CYLINDER.

By A. FAGE, A.R.C.Sc., and J. H. WARSAP.

OCTOBER, 1929.

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STATION FILE

AERODYNAMIC SYMBOLS.

I. GENERAL

- m mass
- t time
- V resultant linear velocity
- Ω resultant angular velocity
- ρ density, σ relative density
- ν kinematic coefficient of viscosity
- R Reynolds number, $R = lV/\nu$ (where l is a suitable linear dimension), to be expressed as a numerical coefficient $\times 10^6$

Normal temperature and pressure for aeronautical work are 15°C . and 760 mm.

For air under these conditions $\left\{ \begin{array}{l} \rho = 0.002378 \text{ slug/cu. ft.} \\ \nu = 1.59 \times 10^{-4} \text{ sq. ft./sec.} \end{array} \right.$

The slug is taken to be 32.2 lb.-mass.

- α angle of incidence
- e angle of downwash
- S area
- c chord
- s semi-span
- A aspect ratio, $A = 4s^2/S$
- L lift, with coefficient $k_L = L/S\rho V^2$
- D drag, with coefficient $k_D = D/S\rho V^2$
- γ gliding angle, $\tan \gamma = D/L$
- L rolling moment, with coefficient $k_L = L/sS\rho V^2$
- M pitching moment, with coefficient $k_m = M/cS\rho V^2$
- N yawing moment, with coefficient $k_n = N/sS\rho V^2$

2. AIRSCREWS:

- n revolutions per second
- D diameter
- J V/nD
- P power
- T thrust, with coeffic
- Q torque, with coeffic
- η efficiency, $\eta = TV/$



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Summary.—Experiments have been made on that type of flow around a circular cylinder which is peculiarly sensitive to changes in Reynolds' number and for which the drag coefficient falls from 0.6 to 0.2 approximately. A study has been made of the effects on the drag of methodical changes in a turbulence artificially created in the general stream, in the roughness of the entire surface, and finally in the size of local excrescencies formed by generator wires. These methodical changes are shown to produce orderly changes in the drag, and it is concluded that the flow considered although sensitive to such extraneous disturbances is not of a critical nature.

(1) *Introduction.*—It is well known that there is a sensitive range of high values of the Reynolds' number (VD/ν) over which the airflow around a smooth circular cylinder undergoes a marked change; and that associated with this change of flow is a large fall from 0.60 to 0.20 approximately in the drag coefficient, K_D (see Fig. 1). This phenomenon is intimately related with changes of flow in the thin boundary layer situated close to the surface of the cylinder, and in particular to the transition from laminar to turbulent flow which occurs at, or near, the region where the layer separates from the surface*. With an increase in Reynolds' number there is a continuous shift of the point at which separation begins, from a position in front of the equator ($\theta=90^\circ$) to just behind, and the boundary layer itself leaves the surface in a more conformal or easier manner. As a consequence, the pressure in the dead-air region behind the cylinder rises and the drag falls.

(2) Since the flow around a cylinder undergoes such marked changes in character as the Reynolds' number (VD/ν) is altered over the range considered, it appeared likely that considerable changes of flow might also be caused by external agencies such as turbulence in the general stream and surface roughness; and if this were so, indications of such changes would be readily obtained by direct measurements of drag. Some insight into the problem of the effects

*See R. & M. 1179. The Airflow around a Circular Cylinder in the Region where the Boundary Layer Separates from the Surface. By A. Fage.

of turbulence and surface roughness on the airflow around a body should therefore be obtained from experiments conducted on cylinders, especially if the effects are large over the sensitive range of $\frac{1}{2}(VD/v)$, and it was with this idea in mind that the present investigation was initiated.

The Effect of Turbulence.

(3) *Character of Artificial Turbulence.*—Turbulence, although probably on the small scale, is always present in the airstream of a tunnel of standard design. A study of the effect of turbulence on the flow around a body, based exclusively on observations taken in a wind tunnel, must necessarily be restricted therefore to a comparison of the flow characteristics measured in tunnel streams which have been purposely disturbed with the characteristics measured in the ordinary stream. It is however admitted that when the inherent turbulence in the ordinary stream is relatively small the flow characteristics measured in this stream form a basis for comparison, in the absence of the characteristics for a non-turbulent stream. This point of view has been adopted in the present investigation, and for convenience the ordinary stream of the tunnel is referred to as the standard stream.

(4) Artificial turbulence is commonly produced by a rope netting or wire screen placed in a cross section of the tunnel, and at such a distance in front of the model that the flow through the netting (or screen) is not influenced by the presence of the model. It follows on the analogy of the flow behind a circular cylinder, and if the texture of the netting is not too fine, that the eddies generated pass downstream with a frequency proportional to the mean wind speed, and that the size of the eddies depends only on the diameter of the rope used. The velocity disturbances close behind the netting are therefore closely proportional to the mean wind speed. It is known that the eddies created at the netting decay as they pass downstream; and also that since this decay arises largely from the action of viscosity, they take a constant time to die down to a given fraction of their initial intensity* (i.e. maximum velocity). A smaller fraction of the initial energy is dissipated therefore, at a given distance behind the netting, as the mean speed of the stream is increased. It is obvious that an outcome of the eddy dissipation is that the disturbances in the vicinity of a body diminish in intensity down its length (i.e. the down-wind dimension), and that they can only be regarded as reasonably uniform when this length is small compared with the distance behind the netting.

(5) *Drag Experiments.*—At the outset, experiments were undertaken to determine the effect of turbulence on the drag of a smooth

*R. & M. 598. On the Dissipation of Eddies. By G. I. Taylor.

cylinder. The turbulence was artificially induced in the general stream of the tunnel by placing square-meshed rope netting some distance forward of the cylinder under test and covering the whole of the cross section of the tunnel (4ft. side). The diameter of the rope was 0.25 inches and the mesh 1.5 inches. This netting was selected because earlier work by Relf and Lavender* had shown that such netting had a marked influence on the drag of an airship model.

The principal measurements of drag were made on a cylinder of diameter of 6.09 inches mounted in the standard stream, and also in the turbulent stream at distance (S) 36, 48, and 74 inches behind the netting. The cylinder was supported with its axis horizontal and normal to the wind direction by inclined wires attached to two steel bars rigidly fixed to a standard roof balance. To simulate the conditions for two dimensional flow, the cylinder (of length 40 inches) was mounted with small gaps ($\frac{1}{8}$ in.) between extension pieces carried on the walls of the tunnel. It was found that these gaps, although small, caused a departure from the conditions for two dimensional flow. It was decided however not to correct the results given in the paper for the effects arising from this departure, nor for the interference effects due to the tunnel walls, since they do not influence appreciably the character of the turbulence effects. The range of $(V_0 D/\nu)$ covered, V_0 is the speed of the general stream, was from 40,000 to 230,000 and included the sensitive region over which the large fall in K_D occurs.

Measurements were also made on a cylinder of smaller diameter (2.375"), over a range of $(V_0 D/\nu)$ lower than that which could be covered on the 6.09" cylinder.

(6) *Drag Results.*—The values of the drag coefficient K_D estimated from the measurements on the 6.09" and the 2.375" cylinders are plotted against $\log_{10} (V_0 D/\nu)$, where ν is the coefficient of kinematic viscosity (molecular) in Fig. 1. The outstanding features illustrated in this figure are the resemblances in the shape of the drag curves for the turbulent streams to that for the standard stream, and the progressive displacements parallel to the $\log_{10} (V_0 D/\nu)$ base, of these curves from the standard curve, as the screen distance S decreases, i.e. as the turbulence increases. It was anticipated from the work of other investigators† that artificial turbulence would produce a lateral displacement of the drag

*R. & M. 597. The effect of up-wind disturbances in the air current of the channel upon the forces on models with special reference to the effect on the drag of an airship model.

†A list of references to papers on this subject is given in N.A.C.A. Report No. 231.

curve, but it was a matter for surprise that the displacement occurred without any appreciable change of shape in the curve. The significance of this result can be illustrated by the following argument.

Suppose a cylinder were immersed in a hypothetical non-turbulent fluid stream of the same density as air, but of lower viscosity (molecular). Then the curve obtained when values of the drag coefficient K_D were plotted against Reynolds' number $\log_{10} (V_0 D / \nu)$ would coincide with that for a non-turbulent airstream. But if instead of the coefficient of kinematic viscosity of the hypothetical fluid, the value for air had been taken in the estimation of the Reynolds' number, then the shape of the drag curve so obtained would not be altered, but its position would lie to the left, i.e. in the direction of decreasing Reynolds' number, of that occupied by the curve for the non-turbulent airstream. The curves obtained would in fact show precisely the same features as those exhibited in Fig. 1. It appears then that the introduction of turbulence into the stream makes it behave, *in so far as measurements of drag are concerned*, as if it had a viscosity lower than that of a non-turbulent airstream.

(7) Over the range of (VD/ν) from 1.5 to 5×10^4 , the drag of a cylinder is closely proportional to the square of the wind speed, i.e. the drag is independent of the viscosity of the fluid. Artificial turbulence regarded as a mechanism governing the viscosity of a fluid should therefore have no effect on the drag over this range of (VD/ν) . It is noteworthy that the results of the experiments on the 2.375" cylinder given in Fig. 1 support this aspect of turbulent flow.

The Effect of Surface Roughness.

(8) *Nature of a Rough Surface.*—It is customary to regard a surface as smooth when it is so even that no roughness or points are perceptible to the touch. It is known, however, that an examination of such a surface under a microscope would reveal the presence of small excrescences and undulations, that is the surface would appear "rough." The smoothness (or roughness) of a surface is therefore a relative quantity. In problems on fluid motion the surface of a body can be regarded as smooth when the excrescences and undulations are small and of such a character that they do not affect, to any measurable extent, the flow characteristics of the body. Some of the essential differences between the aerodynamical behaviour of surfaces classified as "smooth" and "rough," can be gathered from the papers of Prandtl and of Von Kármán. Thus Prandtl* remarks

*Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen 1927, Vol. 3.

“slightly rough surfaces may be regarded as effectively smooth when the irregularities are completely embedded in the laminar flow. With higher Reynolds’ numbers, when the laminar flow is thinner, such roughnesses may become effective with observed increase in resistance”; and Von Kármán* on the turbulent flow in a pipe says “that a wall can be considered smooth only as long as the differences of level on its surface are small in comparison with the magnitude of the ‘vortices’ which arise as a result of the interchange of momentum due to eddy motion, and taking place from the neighbourhood of the wall outwards towards the centre of the fluid.” Also, according to Von Kármán, “all surfaces may be considered rough when the Reynolds’ number R , is sufficiently high; for the frictional resistance of rough walls is made up essentially of the resistances of all excrescences and these become independent of friction at high values of R .”

(9) *Drag of rough-surfaced Cylinders.*—It has been shown that the peculiar flow around a circular cylinder which is very sensitive to changes of (VD/ν) is also easily affected by turbulence in the general stream. This type of flow should therefore be influenced by surface roughness, since such roughness can be regarded as a mechanism which produces local turbulence. To obtain information on this subject, experiments were undertaken to determine how the drag of a cylinder was influenced by systematic changes in the roughness of its surface. The rough surfaces were obtained by carefully wrapping around the cylinder large sheets of John Oakey’s glass paper, specially supplied by the maker. Five grades of glass paper, specified by the makers as Nos. 0, 1, 2 Fine, 2 Strong, and 3 were used. A rough surface was also obtained with a sheet of 058 Garnet paper. Measurements of drag were made on the cylinder of diameter 6.09” when its surface was roughened with the glass and garnet papers; and also, to obtain the effect of a greater relative roughness, on the 2.375” cylinder roughened with the coarser papers Nos. 2 Fine, 2 Strong and 3. The method of measurement was precisely the same as that for the experiments described earlier.

(10) *Results.*—The values† of the drag coefficient, K_D , obtained are plotted against (VD/ν) in Fig. 2. The systematic change in the shapes of these $[K_D, (VD/\nu)]$ curves with a progressive increase in surface roughness, is there clearly illustrated. It is seen that as the surface is made rougher the fall in K_D occurs at a lower value of

*The Theory of Laminar Flow and the Theory of Turbulence. (Translated T. 2277) (unpublished).

†These results have not been corrected for the effects of the gaps and tunnel walls, since these effects do not modify the conclusions drawn from the analysis.

(VD/ν), and that this fall gradually dies away, and there are indications that if the roughening had been continued, a surface would eventually have been obtained for which there would be no fall in K_D .

It appears, then, that as the surface is roughened the boundary layer is retarded, so that the separation region moves forward, and as a consequence the resistance of the cylinder increases (*see* R. & M. 1179) and also that when the surface is very rough the flow around the relatively large irregular excrescences, and so around the cylinder, is unaffected by a change in a large value of the Reynolds' number.

(11) *Local Roughness*.—Since the effect of roughness depends not only on its texture and gradation but also on the conditions of the local flow, it is of interest to inquire on what part of the surface does a local roughness have the largest effect. The effects, on the drag coefficient of the 6.09" cylinder, of local roughness due to generator strips of No. 2 glass paper are given in Fig. 3. It is there seen that roughening, separately or together, the regions $\theta = (-37.5^\circ$ to $+37.5^\circ)$ at the front and $\theta = (100^\circ$ to $260^\circ)$ at the back of the cylinder produce relatively small effects on K_D compared with those obtained when the whole of the surface is roughened. It would appear then that the flow is particularly sensitive to surface roughness at the regions $\theta = (\pm 37.5^\circ$ to $100^\circ)$, a result to be expected since they include those parts where the flow separates from the surface. It was not possible to obtain by direct measurement the effect of roughening with glass paper these regions of separation because as will be seen later, the front edge of the paper, even if carefully chamfered, would greatly influence the flow and so mask the effect of the roughness.

(12) *Effect of Generator Wires*.—The work with the glass papers gives the effect of a roughness created by innumerable small excrescences of unknown size and shape distributed uniformly over the surface. The cumulative effect due to a continuous interference with the flow of the boundary layer has therefore been measured; but important local interferences with the flow may be concealed. To carry the enquiry a stage further measurements were made of the drag of the 6.09" cylinder, when wires of different diameter placed along generators, similarly disposed with reference to the general stream, were used as local obstructions to the flow in the boundary layer. The speed range covered in these experiments was from 15 to 70 ft. per sec. It is to be inferred from the evidence given in R. & M. 1179, that the separation of the boundary layer from a 6.09" cylinder begins near $\theta = \pm 70^\circ$ at 15 ft. per sec. and $\theta = \pm 92^\circ$ at 70 ft. per sec. The first series of measurements were made with wires at the generators $\theta = \pm 65^\circ$, because it was expected that, since these positions are just forward of the separation regions, the effect of the wires on the flow would be large. The selected

diameters (d) of these wires were 0.001, 0.002, 0.005, 0.010, and 0.020 inches respectively. At $\theta = \pm 65^\circ$ the average thickness δ of the boundary layer can be taken as 0.035" over the speed range 15 to 70 ft. per sec. The average values of (d/δ) were therefore 0.03, 0.06, 0.14, 0.29 and 0.57, so that each of the wires was totally immersed in the boundary layer.

(13) The results obtained from the drag measurements are given in Fig. 4. It will there be observed that an orderly change in the shape of the drag curves occurs as the diameter of the generator wires is progressively increased. It is also especially noticeable that even the finest wires of diameter 0.001" (that is, only 3 per cent. of the thickness of the boundary layer) has a large effect. That these 0.001" wires do have an effect does not appear to be open to doubt for several check observations of drag with and without the wires in place were taken. The effect of these fine wires is in fact almost the same as that produced by the standard rope netting situated at a distance of 80 inches forward of the cylinder (compare Figs. 1 and 4).

(14) *Comparison of Pressure Curves.*—The curves of Fig. 5 disclose the fact that a large change in the drag coefficient, K_D , due to generator wires is associated with a marked change in the pressure distribution around the cylinder. The full line curves in this figure represent the pressure distribution taken around a bare cylinder of diameter 8.9" at the wind speeds 22.0, 26.9, 39.2 and 57.9 feet per second, whilst the dotted curves represent the corresponding distributions with wires of diameter 0.012" at the generators $\theta = \pm 65^\circ$. The average value of δ at $\theta = \pm 65^\circ$ can be taken as 0.049" over the speed range from 22.0 to 57.9 ft. per second, so that the value of (d/δ) is 0.24. At the bottom of Fig. 5 is a table which gives the values of K_D estimated from the pressure distributions. It will be seen in this figure that when the values in the table show the generator wires to have a large effect on K_D , there are also marked changes in the corresponding pressure distributions; and this is especially noticeable at the lower speeds 22.0 and 26.9 feet per second.

It is of some interest to note that the effect of the 0.012" wires on the estimated K_D of the 8.9" cylinder was found to resemble closely (the absolute values were somewhat different) that obtained on the 6.09" cylinder with generator wires of diameter 0.008" (*see para. 12*).

(15) *Large Wires.*—The preceding work relates to fine wires totally immersed in the boundary layer of a cylinder. Pressure distributions around the 8.9" cylinder were also measured with stouter wires at $\theta = \pm 65^\circ$. These wires had diameters of 0.048" and 0.079", the corresponding average values of (d/δ) being 0.98 and

1.61. The 0.048" wires were therefore just immersed in the boundary layer, whilst the 0.079" wires projected about 0.68 beyond. The effect of these wires on the pressure distributions are illustrated in Fig. 6. It will be noticed for each wire that the pressure observations taken at the three speeds 22.0, 39.2 and 57.9 ft. per sec. fall very closely on a common curve (shown dotted). There are therefore no systematic changes either with wind speed or with wire diameter. It would seem then that wires of diameter greater than the thickness of the boundary layer, when placed at the generators $\theta = \pm 65^\circ$, cause the boundary layer to leave the surface, and it is possible that when this happens the flow is not appreciably influenced by the actual diameter of the wires.

(16) It must not be inferred, however, that if the wire diameter is greater than the thickness of the boundary layer, the layer will necessarily leave the surface, for obviously the effect of a wire depends not only on its diameter but also on its position, that is, on the conditions of the local flow. Thus, it would be expected that the disturbance created by a given pair of generator wires would become less severe as they are removed away from the regions where the boundary layer separates from the surface. This is strikingly illustrated in Fig. 7, where it will be seen that wires of diameter 0.016, 0.032 and 0.048 inches placed at the generators $\theta = \pm 25^\circ$, where the average value of the thickness of the boundary layer is 0.032 inches, have practically no effect on the pressure distribution.

(17) Finally, it is desired to direct attention to an important conclusion which can be drawn from the investigation. The experiments have dealt with the effects of methodical changes (1) in a turbulence artificially created in the general stream, (2) in a roughness of the entire surface, and (3) in the size of local excrescences formed by generator wires, on a flow which is itself easily affected by a change of (VD/ν) , and it has been shown that these methodical changes produce orderly changes in the drag coefficient (see Figs. 1, 2, and 4) and it would appear that these orderly changes in response to systematic changes in the disturbing influences preclude any idea that the flow which has been considered is of a critical nature even although it is sensitive to extraneous disturbances.

DRAG COEFFICIENTS FOR CYLINDERS IN A 4 FT. TUNNEL.

k_D uncorrected for wall and gap effects.

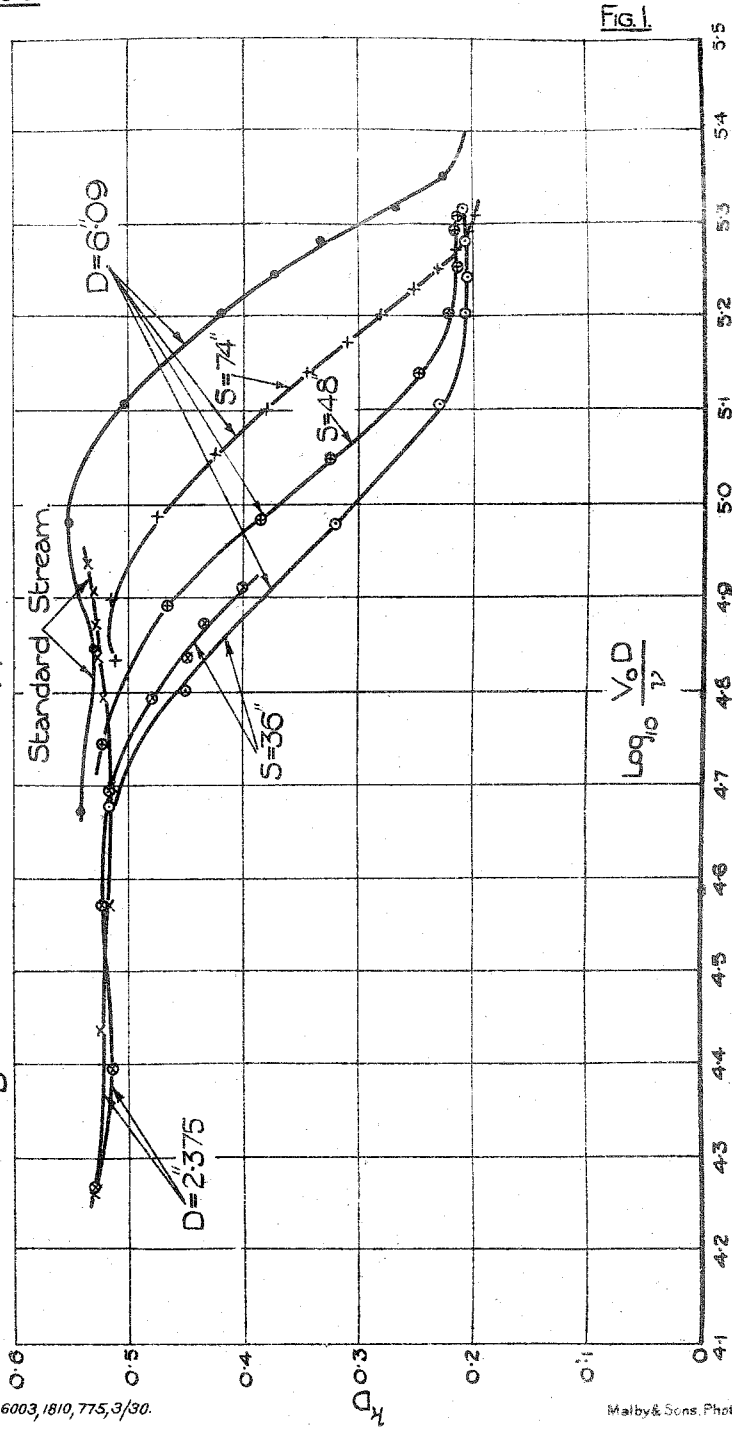
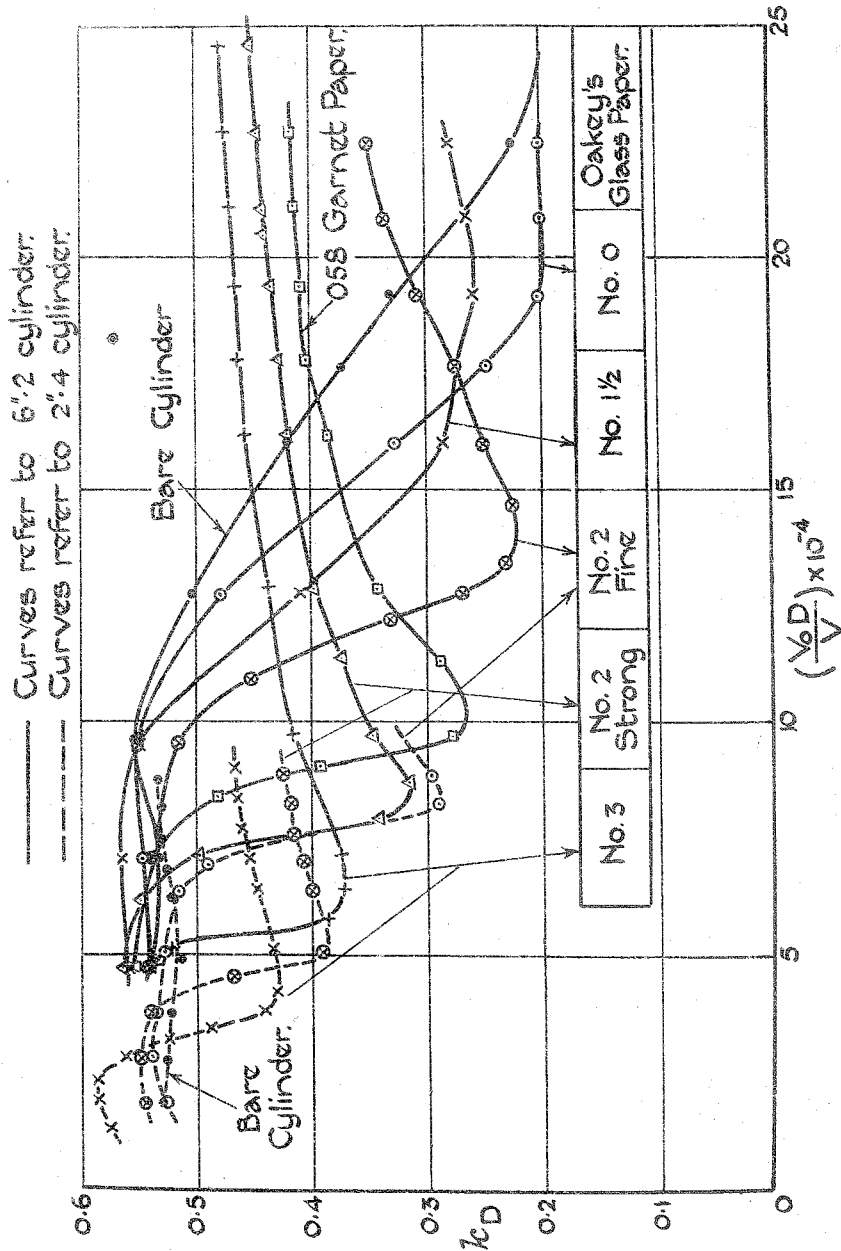


Fig. 1

EFFECT ON k_D OF ROUGH SURFACES. FIG.2.

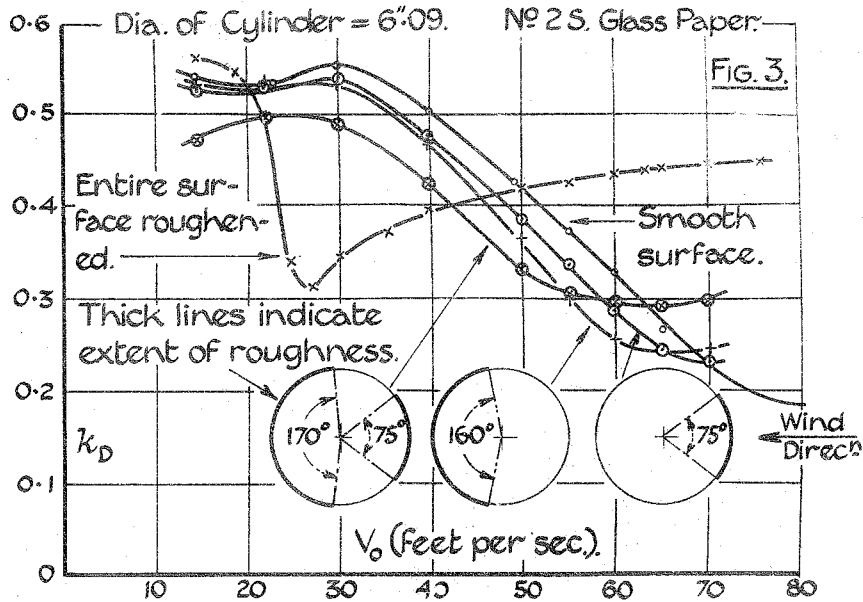
Results uncorrected for Gap and Tunnel Wall effects.



R.&M.1283.

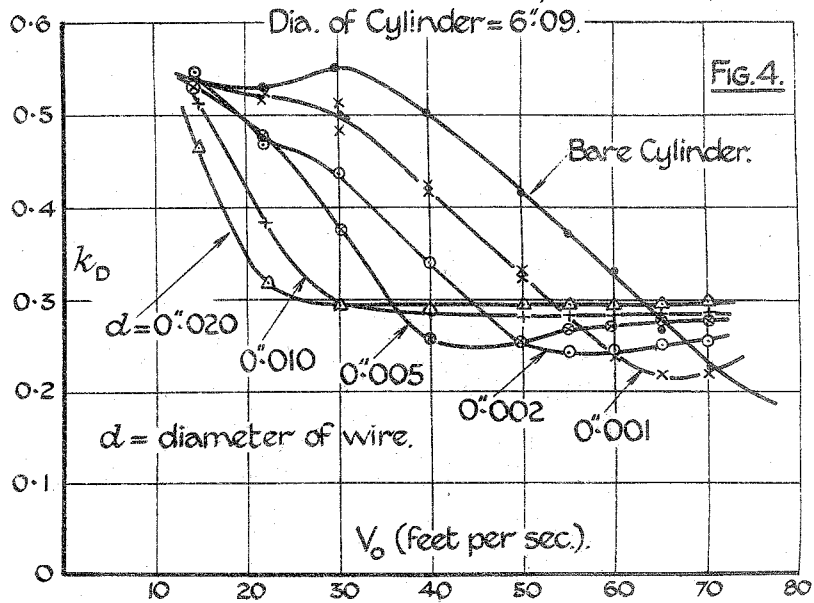
EFFECT ON k_D OF A LIMITED ROUGH SURFACE.

FIGS. 3 & 4.



EFFECT ON k_D OF WIRES AT $\theta = \pm 65^\circ$

Results uncorrected for Gap & Wall effects.

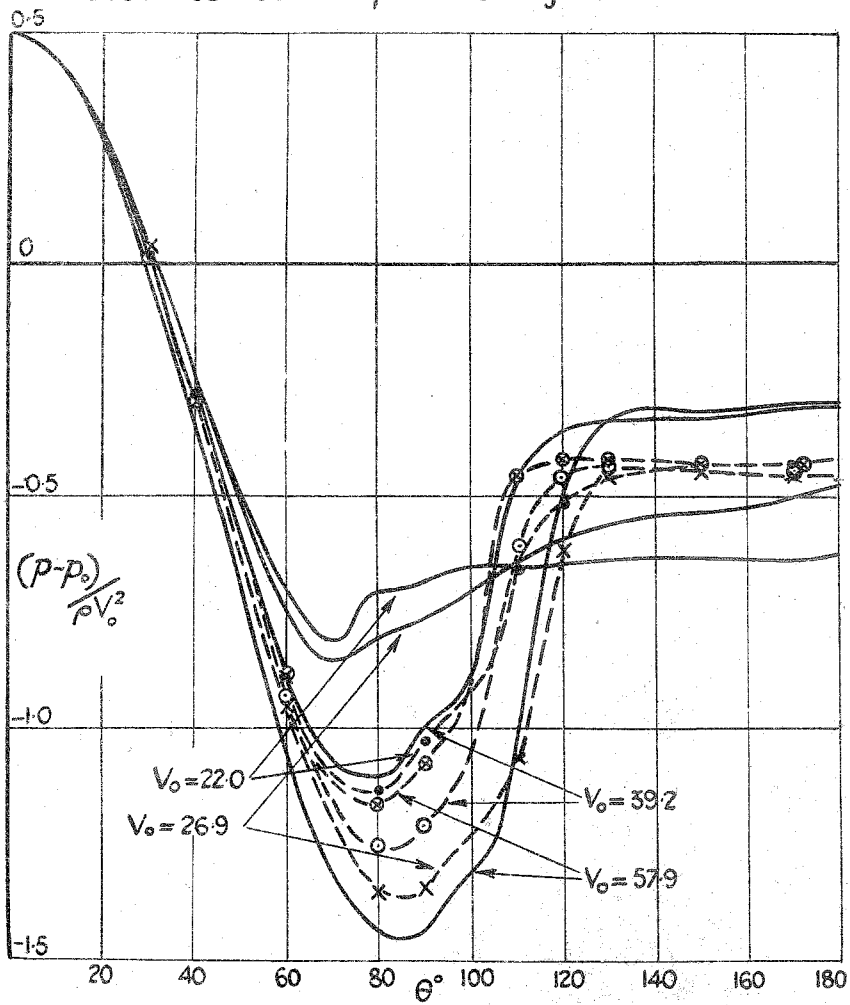


R&M.1283.

FIG. 5.

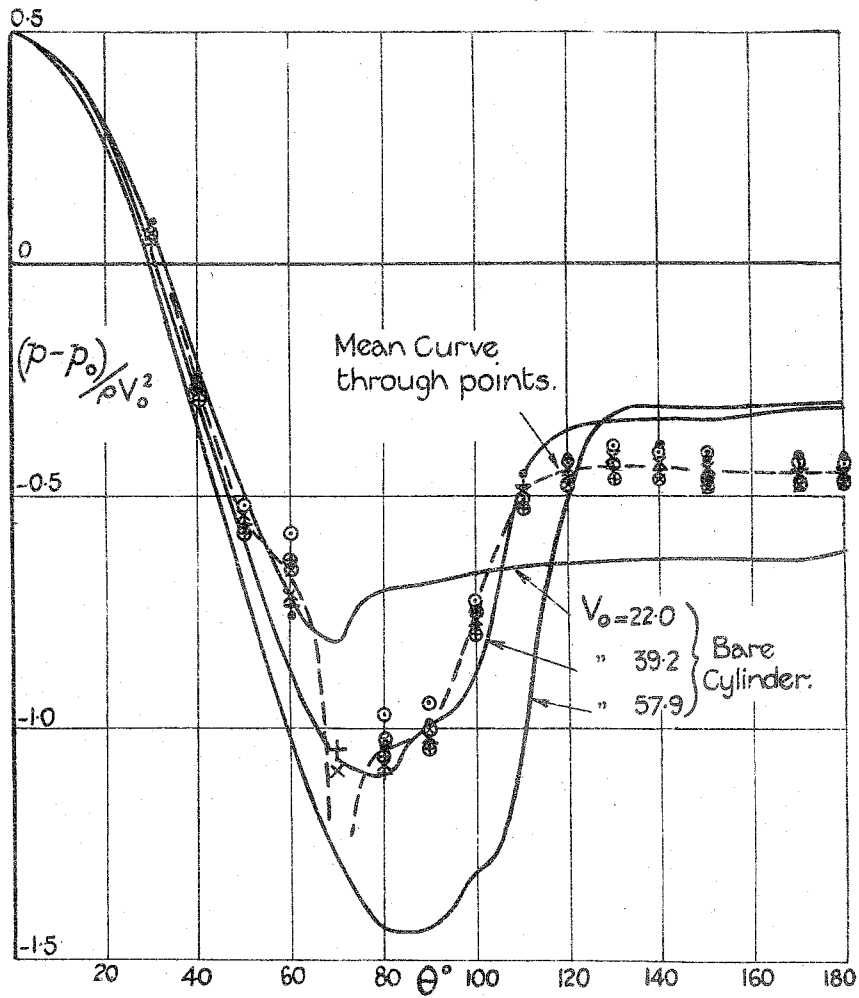
DIAMETER OF CYLINDER = 8.9 INCHES.
 0.012 INCHES. WIRES AT $\theta = \pm 65^\circ$

Full-line curves refer to Bare Cylinder.
 Dotted curves with points to Cylinder with wires.



V_0 ft per sec.	22.0	26.9	39.2	57.9
K_D , Bare cylinder	0.63	0.51	0.23	0.19
K_D , Cylinder with wires	0.36	0.39	0.35	0.34

DIAMETER OF CYLINDER = 8.9 INCHES.
WIRES AT $\pm 65^\circ$



Key for Points.			
Wire diam. Inches.	V_0 (ft per sec)		
	22.0	39.2	57.9
0.048	•	X	+
0.079	⊙	⊗	⊕

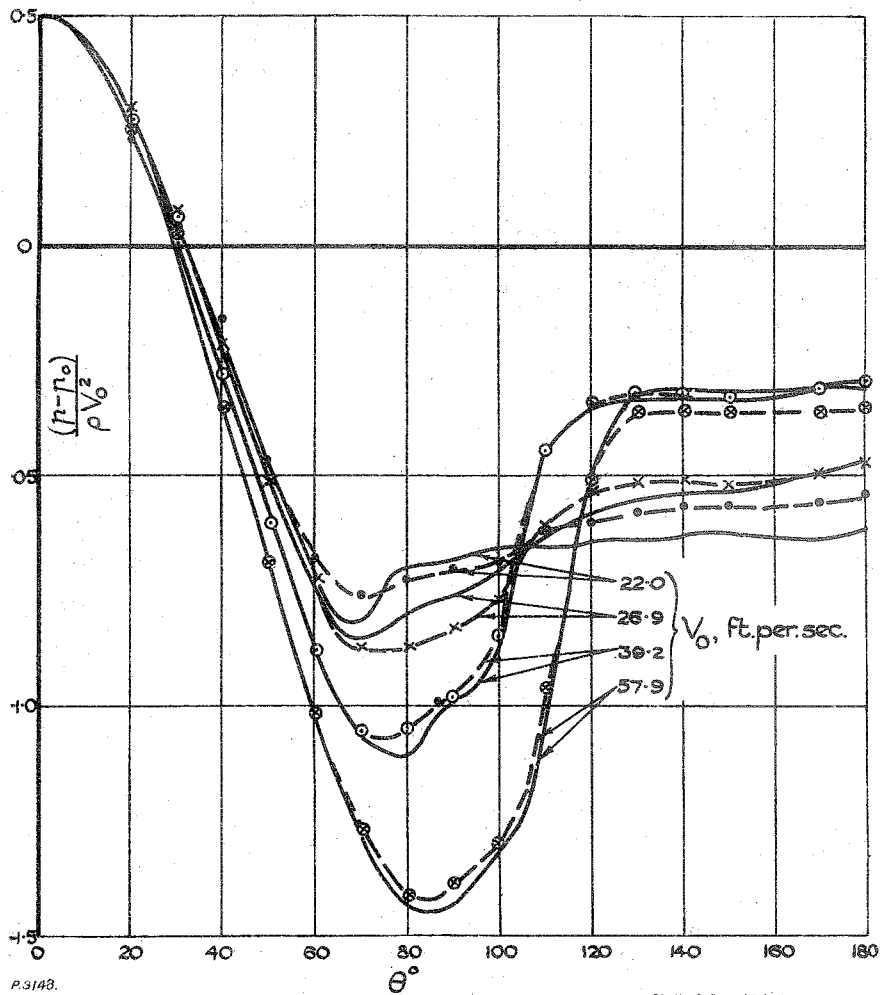
R.&M.1283.

DIAMETER OF CYLINDER = 8"9

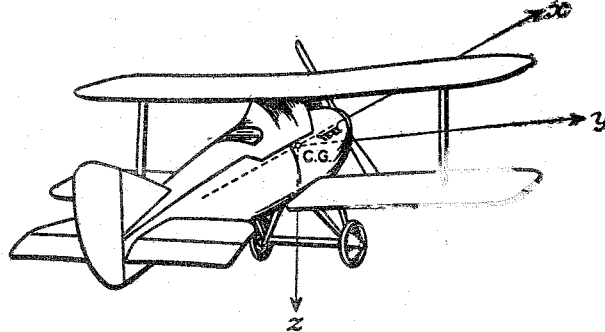
FIG. 7.

WIRES AT $C = \pm 25^\circ$

Points on dotted curves give mean values for cylinder with wires of diameters, 0.016, 0.032 and 0.048 inches.
Full-line curves refer to bare cylinder.



SYSTEM OF AXES.



Axes	Symbol Designation Positive direction	x longitudinal forward	y lateral starboard	z normal downward
Force	Symbol	X	Y	Z
Moment	Symbol Designation	L rolling	M pitching	N yawing
Angle of Rotation	Symbol	ϕ	θ	ψ
Velocity	Linear Angular	u p	v q	w r
Moment of Inertia		A	B	C

Components of linear velocity and force are positive in the positive direction of the corresponding axis. Components of angular velocity and moment are positive in the cyclic order y to z about the axis of x , z to x about the axis of y , and x to y about the axis of z .

The angular movement of a control surface (elevator or rudder) is governed by the same convention, the elevator angle being positive downwards and the rudder angle positive to port. The aileron angle is positive when the starboard aileron is down and the port aileron is up. A positive control angle normally gives rise to a negative moment about the corresponding axis. The symbols for the control angles are :-

- ξ aileron angle
- η elevator angle
- η_T tail setting angle
- ζ rudder angle

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