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THE MAGNUS FORCE ON SPINNING CYLINDERS

NOTS 1784

27 JUNE 1957

U.S. NAVAL ORDNANCE TEST STATION, INYOKERN, CHINA LAKE, CALIFORNIA

This report, a preprint of a paper presented at the Aerodynamics Session, Twenty-Fifth Annual Meeting of the Institute of the Aeronautical Sciences, is published by the Research Department. It consists of cover and 10 leaves. From the original printing of 45 copies, this document is

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Technical Director

THE MAGNUS FORCE ON SPINNING CYLINDERS

By

Ray W. Van Aken
and
Howard R. Kelly
Research Department

NAVORD REPORT 5583
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U N C L A S S I F I E D

FOREWORD

The work reported here was performed by the Ballistics Division of the Research Department during the period of January 1955 to January 1957, under Bureau of Ordnance Task Assignments NOTS A3d-441-3 and NO-803767-73001/01-054.

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THE MAGNUS FORCE ON SPINNING CYLINDERS

by

RAY W. VAN AKEN
and
HOWARD R. KELLY
U. S. Naval Ordnance Test Station

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THE MAGNUS FORCE ON SPINNING CYLINDERS

by

Ray W. Van Aken* and Howard R. Kelly**

U. S. Naval Ordnance Test Station

ABSTRACT

Results of recent experiments conducted in the Convair wind tunnel and the University of Notre Dame smoke tunnel on spinning cylinders are presented. It is shown that at low spin rates the Magnus force may be positive or negative, depending on the Reynolds number, and this variation corroborates data obtained by Lafay and Betz. In the present investigation, the Reynolds number range has been greatly extended and the systematic variation of Magnus force with this parameter is demonstrated. The effect of critical Reynolds number is discussed and a correlation of the Magnus force with the nature of the flow as observed in a smoke tunnel is given.

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INTRODUCTION

The purpose of this paper is to summarize recent experiments on the classical Magnus effect. These experiments have shown a distinct pattern in the behavior of Magnus force with different Reynolds numbers. The pattern, at least for moderate spin rates, is found to agree quite well with all known experimental results, and thus serves to unify the experimental work in this field.

The classical Magnus effect refers to the lift on a spinning sphere, or cylinder, that moves through a fluid in a direction perpendicular to the axis of spin. The effect was named for G. Magnus, who made the first convincing demonstration of the pressure difference on the two sides of a rotating cylinder. [1] This tended to substantiate earlier statements by Robins [2] that the dispersion of cannon balls was probably due to spin.

Lord Rayleigh [3] noted that the behavior of tennis balls and golf balls could be explained in part by the Magnus effect. He developed the well-known explanation of the Magnus force in which the potential flow about a cylinder is added to a flow with circular streamlines to obtain a flow with circulation (Fig. 1). He realized that his mathematical treatment was valid only for non-viscous flows, and could only serve as an idealized model for the study of real flows. It has remained the "ideal" Magnus effect and, in spite of considerable discrepancies when compared with "real" Magnus effects, has been very useful as a model for airfoil theory.

The practical applications of Magnus force have been limited. Two of the better-known examples are the Flettner rotor ships described by Prandtl,[4] and the explanation of the long range obtainable with dimpled golf balls.[5] The Magnus force upon which the stability of spinning rockets and projectiles depends is purposely excluded, since this is usually of a different nature. These rockets and projectiles usually fly at small angles of yaw, in which case the so-called Magnus effect is due to boundary-layer asymmetry.[6-8] This effect has not yet been described in terms of circulation. If any circulation is present, it is entirely within the boundary layer. An intermediate case is now arousing interest. The Magnus effect at moderately large angles of yaw may well be considered as a combination of the effects of boundary-layer asymmetry and circulation.

The investigations being reported in the present paper are an indirect result of the study of rockets at large angles of attack. Some experiments were made by the Naval Ordnance Test Station in the Convair subsonic wind tunnel in 1953, with angles of yaw up to 90 degrees. The measured forces at 90 degrees were orders of magnitude too large to be explained by any existing data on spinning cylinders. End effects on the finite-length models would be expected to decrease, rather than increase, the force. The only obvious reason for the discrepancy was

the high Reynolds number of 840,000 for the rocket tests as compared to Reynolds numbers of about 100,000 for most cylinder tests of other investigators. A systematic investigation of the effects of high Reynolds numbers on the Magnus force on spinning cylinders was then initiated, and the principal results to date are reported in the following paper.

REVIEW OF PREVIOUS EXPERIMENTS

Magnus first demonstrated the existence of pressure differences on opposite sides of spinning cylinders, but the first quantitative measurements were probably made by Lafay.[9, 10] Some of his data for smooth cylinders are reproduced here in Fig. 2. Positive and negative lift coefficients agree with the positive lift convention shown in Fig. 3. Lafay's results show a variation of initial slope with Reynolds number, but the most important result was the demonstration of negative Magnus force. Many writers since have been unaware of his results or have chosen to ignore them. At the other extreme, a recent text-book[11] shows the negative Magnus effect as being the normal effect at low spin rates. It is now known that the negative Magnus effect is only normal at low spin if the Reynolds number is near the critical value.

There was a flurry of activity in the nineteen twenties, including experiments by Reid[12] at the NACA, Betz[13] at Göttingen, Thom[14-16] at Edinburgh University, and Maccoll[17] at Glasgow University. Some of the results found by Lafay, Betz, and Thom are shown in Fig. 4. It is notable that there is very close agreement between three curves, one from each experimenter. These curves are at approximately the same effective Reynolds number, while the extra curve from Thom is at a lower Reynolds number and the curve from Lafay showing negative lift is at a considerably higher Reynolds number. Further results by Thom are shown in Fig. 5. These show a hint of agreement with Lafay at higher Reynolds number and a pronounced increase in lift coefficient at very low Reynolds number. The data from Lafay and Thom are not truly two-dimensional, which probably accounts for the variation in initial slope in Lafay's curves, at different Reynolds numbers. Betz found that disc-shaped end plates, rotating with the cylinder, improved his results. These facts agree quite well with present knowledge, though the significance was apparently not recognized at the time. The experiments of Reid do not completely agree with present results, probably because he had some difficulty in measuring the small forces at low spin rates. Maccoll's experiments were with spinning spheres, and exhibited negative Magnus force at low spin rates.

Interest in this subject was low for a number of years, but has recently been growing. Davies [5] experimented with golf balls by dropping pre-spun balls in a wind tunnel and tracing the trajectories. He showed that negative Magnus forces occurred at low spin rates if the ball was

perfectly smooth, but the standard dimpled bals always showed a positive Magnus effect. Using his measured lift coefficients, he predicted that the dimpled balls would have twice the range of smooth ones. Recently, Swanson [18] at the Case Institute of Technology has completed a program in which Magnus forces vere measured on a spinning cylinder. Three coaxial, tandem cylinders were used, with forces measured only on the central section, in order to obtain an approximation to a two-dimensional flow. This should provide more precise data than the simple cylinders of Lafay and Thom or the cylinders with end discs, used by Betz. Swanson's data have not yet been published, to the present authors' knowledge. It is only known that the data clearly exhibited sudden dips from positive to negative Magnus force, but were limited to sub-critical Reynolds numbers.

Meanwhile, some critical reviews and other papers concerning the Magnus effect have appeared. Ahlborn, [19] in 1930, criticized the work of Prandtl and Betz, with regard to their belief in the Flettner rotor principle. Stefan [20] carried out some experimental work with bodies of revolution at various angles of attack as a Master's thesis at the University of Minnesota. Popular articles have appeared recently in national magazines, [21, 22] and a very thorough analysis of the existing knowledge of the Magnus effect was made by Buford [23] at the Aberdeen Proving Ground in 1954. He reproduces photographs obtained by Prandtl[24] of the flow about spinning cylinders using the aluminum powder-water technique. The Prandtl photographs provide excellent detail of the wake and have been reproduced[25] several times.

Each of the experimental programs mentioned has made a definite contribution, but only the experiments of Davies even suggested the effect of super-critical Reynolds numbers. The change in the drag coefficient of non-spinning cylinders at the critical Reynolds number has been known for many years, but the presence of a significant effect on Magnus force was apparently not suspected.

DESCRIPTION OF EXPERIMENTAL WORK

An important consideration in performing experiments on spinning cylinders is the effect of the ends. It is desirable that this effect be made as small as possible so that the results are representative of a true two-dimensional cylinder. Three approaches to minimizing the end effects are:

1. Construct the cylinder with a high length-diameter ratio so that the end effects are small in comparison with the total force.
2. Use end disks which spin with the cylinder.
3. Have three cylinders spinning and measure forces only on the center cylinder.

The third method will give the most accurate results; however the complexities of synchronizing the speeds of the cylinders and measuring the forces are much greater than in the first two methods. At Case Institute the three-cylinder method was used[18] after more than a year of development work.

The experimental methods of other investigators were discussed previously. Two types of experiments were performed on the work reported here: force studies at Convair and flow visualization studies at Notre Dame.

CONVAIR FORCE STUDIES

The Convair subsonic wind tunnel[26, 27] has an 8-by 12-foot test section and is capable of speeds to 300 ft. per sec. Figure 6 shows the experimental set-up. Ground boards have been installed in the test section to form a two-dimensional channel. The ground boards enclose struts which support the cylinder and transfer the forces to the Baldwin-Southwark hydraulic balance located beneath the tunnel floor. The cylinders were spun by two 15 hp. electric motors mounted on the struts and enclosed in the cylinders projecting from the ground boards. Figure 7 shows details of the cylinder mounting. The cylinder is mounted on a shaft between the motors and rides in bearings fastened to the struts. Disk-shaped end plates 10 inches in diameter are fastened on the cylinder. Non-rotating dummy cylinders were used as a wind shield for the shaft and permitted the rotating cylinder to be located outside the boundary layer on the ground boards. Some runs were made without the end plates in order to determine their effect. Figure 8 indicates there is a loss of lift when end cylinders are used and this loss is greater at higher spin ratios. Low cylinder speeds were measured by a strobotac located above the test section. Observations were made on the "V" inked on the cylinder. Higher speeds were measured by a Berkeley time-interval counter. The cylinders tested were 4, 6, and 8 in. in diameter and 30 and 60 in. in length. The two lengths were used to evaluate the end effects. Surface finish of the cylinders varied from 14 to 50 micro inches.

Cylinder speeds were varied from 0 to 12,000 r.p.m. and air speeds from 50 to 300 ft. per sec. The Reynolds number range was from 99,000 to 1,187,000. Measurements made with a turbulence sphere indicate that the turbulence factor was very close to unity. A further indication of the low turbulence level may be seen from the plot of zero-spin drag against Reynolds number (Fig. 9) which gives a critical Reynolds number of about 375,000. In order to investigate the effect of turbulence, three grids of varying mesh were used. Both lift and drag forces were measured, but only the lift data are presented (Fig. 10) in this paper, with the exception of the zero-spin drag (Fig. 9, 11).

NOTRE DAME FLOW VISUALIZATION STUDIES

The Notre Dame tests provided flow pictures and force information at low Reynolds numbers. The Notre Dame smoke tunnel [28-30] has normally a 2-by 2-ft. test section and can produce air speeds of 30 to 170 ft. per sec. Smoke is produced by burning wheat straw with insufficient air. Figure 12 shows the tunnel and associated equipment. On the right is the smoke generator. Smoke is led from the generator to the manifold on the left, just upstream of the screens, and introduced into the flow thru the bank of nozzles. Multiple screening and a 12 to 1 contraction ratio result in a very low turbulence level, with turbulence factor essentially equal to one. The cylinder tested was 4 in. in diameter and 28 in. long and had a surface finish on the order of 15 micro inches. No end plates were used. The Reynolds numbers were all subcritical and ranged from 47,300 to 302,000. Cylinder speeds were varied from 0 to 1900 r.p.m. Lift and drag were measured by a strain-gage balance. Only the lift data (Fig. 13) are presented. The smoke filiments were introduced at the center of the cylinder in order to minimize the effects of the ends. Photographs of the flow field were taken by electronic flash. For each test condition two photographs were taken: one with the camera axis on the cylinder top and one with the camera axis on the cylinder bottom. The top and bottom sections were then spliced together. Pertinent pictures are shown in Fig. 14-18.

RESULTS OF THE EXPERIMENTS

The lift data obtained in the Convair wind tunnel are shown in Fig. 10. Here, the lift (or Magnus force) coefficient C_L is plotted against the ratio of peripheral velocity V to freestream velocity U with Reynolds number as a parameter. The lift coefficient is based on the projected frontal area of the cylinder and freestream velocity. Corrections to the velocity due to blocking were found to be less than 1% and were neglected. The Reynolds number is based on the cylinder diameter. In examining the data of Fig. 10 we must bear in mind the role of the critical Reynolds number. The critical Reynolds number is here defined to be the Reynolds number at which the drag coefficient of a nonrotating cylinder decreases abruptly, due to the difference in flow separation with laminar and turbulent boundary layers. The critical Reynolds number Re_c depends primarily on the turbulence level of the flow and surface roughness of the cylinder. Figure 9 indicates a critical Reynolds number of about 375,000. Refering again to Fig. 10 we see that at Re = 101,000 the lift coefficient is always positive and agrees with the data of Betz (Fig. 5). At Re = 202,000 the initial slope is about the same but the curve experiences an excursion into the negative region. As Re approaches Re_c the drop to negative values occurs at smaller spin ratios until at a Reynolds number near the critical (403,000) the curve appears to start out negatively. At supercritical Reynolds numbers the curves all have

higher initial slopes about equal to π and experience dips which occur at increasing spin ratios with increasing Reynolds numbers. The curve at Re = 1,176,000 is expected to dip at a higher spin ratio. The low supercritical Reynolds number (454,000) curve enters the negative region, but all the others remain positive. A discussion of the shapes of the curves will be given later. Two interesting features of the curves in Fig. 10 are the apparent convergence of all the curves after the dip to a slope of about π which is parallel to the initial slope at high Reynolds numbers and the near-common crossing of the spin ratio axis at a spin ratio of about 0.5.

Attempts were made to obtain very high lift coefficients. By using the 8 in. cylinder and a low airspeed (50 ft. per sec.) high spin ratios could be obtained. Results obtained at high spin ratios are shown in Fig. 19. A lift coefficient of 10.4 has been measured at a Reynolds number of 198,000 and a spin ratio of approximately 5.6 (8000 r.p.m. and 50 ft. per sec.). It is believed that higher lift coefficients could be obtained by carefully arranging the experiment.

The effects of changing the turbulence level were investigated by placing a screen at the entrance to the two-dimensional channel. The turbulence factor was increased to 2.35 and the critical Reynolds number decreased to about 150,000 (Fig. 11). A comparison of the lift coefficients with and without the screen is shown in Fig. 20. Both curves have very nearly the same initial slope. The Reynolds number is 591,000 for both curves. The behavior of the without-screen curve is consistent with the trend as shown in Fig. 10. The with-screen curve is at a much greater value of Re/Re_{crit} due to the reduced critical Reynolds number and hence does not exhibit a dip.

Lift data obtained at Notre Dame are given in Fig. 13. All the Reynolds numbers are subcritical. Even without correcting for end effects the curves exhibit the same trends as the data obtained at Convair. Photographs (Fig. 14-18) of the smoke flow were taken at five flow conditions as shown in Fig. 13. In the pictures the air flow is from the left and the cylinder rotation is clockwise (Fig. 3). Figure 14 is typical of the flow field at high spin ratios and positive lift. In Fig. 15 we have the zero-spin case. The laminar boundary layer (subcritical Reynolds number) separates at points approximately 80° - 85° from the forward stagnation point agreeing with previous data (Goldstein [25] p. 152).

A condition of positive lift is shown in Fig. 16. The separation point on the top surface has moved downstream (away from the forward stagnation point) while the separation point on the bottom surface has moved slightly towards the forward stagnation point. Figure 17 shows the conditions for negative lift. The boundary layer separation on the top surface is still laminar and occurs at about 90°. On the bottom surface we now have a turbulent separation. There will be a turbulent

separation on the bottom whenever there is negaive lift. The maximum negative lift will occur when the turbulent separaion point has moved the furthest from the forward stagnation point. As the spin rate is increased the magnitude of the negative lift decreases until a condition of zero circulation and zero lift is reached. This condition is shown in Fig. 18. The turbulent boundary layer separation has moved forward and is near the point of laminar separation. As the spin rate increases the lift force again becomes positive.

In a recent note [31] Krahn gives a qualitive explanation for the dips and negative force coefficients. He bases his theory on the transition effect from a laminar to a turbulent boundary layer. For a non-spinning cylinder the laminar boundary layer will separate (Fig. 21) at a point 82° from the forward stagnation point (Fig. 15). If the boundary layer is turbulent the separation occurs somewhere between 122 and 130° (Goldstein [25] p. 438). Laminar separation occurs on both sides of the nonspinning cylinder at subcritical Reynolds numbers and turbulent separation at supercritical Reynolds numbers.

If the cylinder is now allowed to spin at an increasing rate, the separation points on top and bottom will tend to shift in the direction of spin, producing an asymmetry in separation with a resulting circulation and positive Magnus force. The spin, however, will cause the relative flow velocity to increase on the bottom and decrease on the top of the cylinder. This can lead to a sudden change from a laminar-type separation to a turbulent-type on the bottom for subcritical flow, or from a turbulent-type separation to a laminar-type on the top for supercritical flow. An increase in spin with constant Reynolds number corresponds to a horizontal traverse of Fig. 21, with the sudden changes occurring at the lower or upper boundary of the shaded region. The shaded region represents a condition of laminar separation on top of the cylinder and turbulent separation on the bottom. The area above the shaded region corresponds to turbulent separation on both sides and the area below to laminar separation on both sides. Crossing the boundary of the shaded region will correspond to the sudden dips in lift coefficient found in Fig. 10 and 13. A special case is that of flow at the critical Reynolds number, where negative lift occurs immediately at even the least values of spin.

Krahn's results are found to be qualitatively correct, but Fig. 22 shows that his estimates differ from experiment quantitatively. Here we have indicated the spin and Reynolds number of the beginning of each sudden dip in lift coefficient on the same diagram as the boundary curve predicted by Krahn. Data from the Convair and Notre Dame tests are presented. We are not prepared to offer a substitute for Krahn's method that will completely explain the discrepancies between his predictions and the experimental results. Perhaps application of the methods developed by Gustafson [32] might yield better agreement.

CONCLUDING REMARKS

The effect of Reynolds number on the Magnus force coefficient can be summarized in terms of Fig. 23 and Fig. 5. At low (subcritical) Reynolds number the curve begins with a small slope, then steepens, and reaches a maximum value of about 10 at a spin ratio of 4, according to theory.[23] Our results indicate (Fig. 19) that the maximum is reached at a spin ratio of about 6. As the Reynolds number increases, the same general curve is followed, except that a sharp dip is found just before the curve steepens. This dip becomes more pronounced until, at the critical Reynolds number, it occurs immediately at zero spin. At Reynolds numbers slightly above critical, a steep curve both precedes and follows the dip, with both steep portions having a slope near the value π. It might be expected that at extreme values of Reynolds number this high slope could be maintained until the "perfect" Magnus coefficient of 4π was reached, but this has not been verified as yet.

The difference in initial slopes at low and high Reynolds numbers may very well be related to the greater efficiency of turbulent boundary layers in transmitting vorticity into the flow outside the boundary layer to produce circulation at low spin rates. If this is true, then for lower and lower Reynolds numbers, the initial slope should again steepen, since viscous flow theory predicts an increasing importance of viscous effects and their transmission into the flow as the Reynolds number decreases. This is partially borne out by Thom's data in Fig. 5.

Some items for future research are:

1. Investigation of compressibility effects.
2. Investigation of Magnus effects at higher Reynolds numbers and spin ratios.
3. Study of the case of the inclined spinning cylinder (angles of yaw less than 90°) where there is a combination of Magnus and boundary layer displacement effects.

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REFERENCES

1. Magnus, G.: Poggendorf's Ann. d. Physik Chemie 88, 1 (1853).

2. Robins, B.: New Principles of Gunnery. London 1842.

3. Rayleigh: On the Irregular Flight of a Tennis Ball. Messenger of Math. 7, 14, 1877.

4. Prandtl, L.: Application of the "Magnus Effect" to the Wind Propulsion of Ships. NACA TM 367 (Translation).

5. Davies, John M.: The Aerodynamics of Golf Balls. Journal of Applied Physics, Vol. 20, No. 9, Sept. 1949.

6. Martin, John C.: On Magnus Effects Caused by the Boundary-Layer Displacement Thickness on Bodies of Revolution at Small Angles of Attack. BRL Report No. 870, June 1953. Revised, June 195[illegible]

7. Kelly, Howard R.: An alytical Method for Predicting the Magnus Forces and Moments on Spinning Projectiles. U. S. Naval Ordnance Test Station, Tech. Memo. 1634, August 1954.

8. Kelly, Howard R. and G. Robert Thacker: The Effect of High Spin on the Magnus Force on a Cylinder at Small Angles of Attack. U. S. Naval Ordnance Test Station, NAVORD Report 5036, February 19[illegible]

9. Lafay, M. A.: Sur l'Inversion on Phénomène de Magnus. Comptes-Rendus, Vol. 151, P. 867, November 1910.

10. Lafay, M. A.: Contribution Experimental a l'Aerodynamique On Cylinder. Revue Mechanique, 30, 1912.

11. Rauscher, Manfred.: Introduction to Aeronautical Dynamics. John Wiley and Sons, New York, 1953.

12. Reid, Elliott G.: Tests of Rotating Cylinders. NACA TN 209, December 1924.

13. [illegible]oetz, A.: The "Magnus Effect," the Principle of the Flettner Rotor. Zeits. d. Ver. deuts. Ing., Jan. 1925. Translated as NACA TM 310.

References, (Con't.)

14. Thom, A.: Experiments on the Air Forces on Rotating Cylinders. ARC R and M No. 1018, February 1925.

15. Thom, A.: The Pressures Round a Cylinder Rotating in an Air Current. ARC R and M No. 1018, November 1926.

16. Thom, A.: Experiments on the Flow Past a Rotating Cylinder. ARC R and M No. 1410, March 1931.

17. Maccoll, John W.: Aerodynamics of a Spinning Sphere. Jour. of the Royal Aero. Sci., Vol. 32, p. 777, 1928.

18. Private communication with Prof. R. E. Bolz of Case Institute.

19. Ahlborn, F.: The Magnus Effect in Theory and in Reality. NACA TM 567 (translation).

20. Stefan, Karl H.: Magnus Effect on a Body of Revolution at Various Angles of Attack. Master's Thesis, Dept. of Aero. Engr., University of Minn., 1949.

21. Life Magazine: Camera and Science Settle the Old Rhubarb About Baseball's Curve Ball. Vol. 35, Life. pp. 104-107, 27 July 1953.

22. Smith, Stanley E.: Watch Those Curves. Argosy, Vol. 342, No. 3, p. 41, March 1956.

23. Buford, William E.: Magnus Effect in the Case of Rotating Cylinders and Shell. BRL Memo Report No. 821, July 1954.

24. Prandtl, L.; and Tietjens, O. G.: Applied Hydro-and Aerodynamics. Mc Graw-Hill Book Co., Inc. New York, 1934.

25. Goldstein, S. (Ed.): Modern Developments in Fluid Dynamics, 2 Vols. The Clarendon Press, Oxford, 1938.

26. Mason, Jack: Consolidated Vultee's New Aeronautical Laboratory. A Sherman Fairchild Publication of the Institute of the Aeronautical Sciences, New York, August 1946.

27. Wind Tunnel Group, Convair Wind Tunnel Handbook, Volume I, Convair Rept. ZT-043, April, 1955.

28. Brown, F.N.M.: Fundamental Flow Patterns, Aircraft Engineering (London), Vol. 28, No. 331, pp. 313-317, Sept. 1956.

29. Brown, F.N.M.: An American Method of Photographing Flow Patterns, Aircraft Engineering (London), Vol. 24, No. 280, pp. 164-169, June 1952.

30. Brown, F.N.M.: A Photographic Technique for the Mensuration and Evaluation of Aerodynamic Patterns, Photographic Engineering, Vol. 4, No. 3, pp. 146-156, 1953.

31. Krahn, E.: Negative Magnus Force. Journal of the Aeronautical Sciences, Vol. 23, No. 4, p. 377, April 1956.

32. Gustafson, Torsten: On the Magnus Effect According to the Asymptotic Hydrodynamic Theory. NACA Translation of "Uber den Magnuseffekt nach der Asymptotischen Hydrodynamischen Theorie." Hakan Ohlssons Buchdruckerei, Lund 1933.

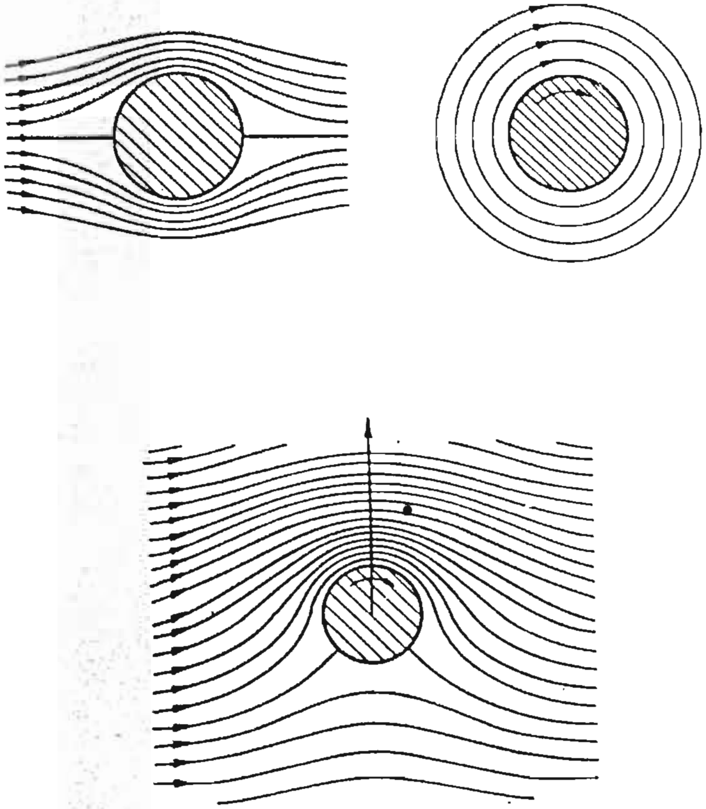

FIG. 1. Superposition of flows.

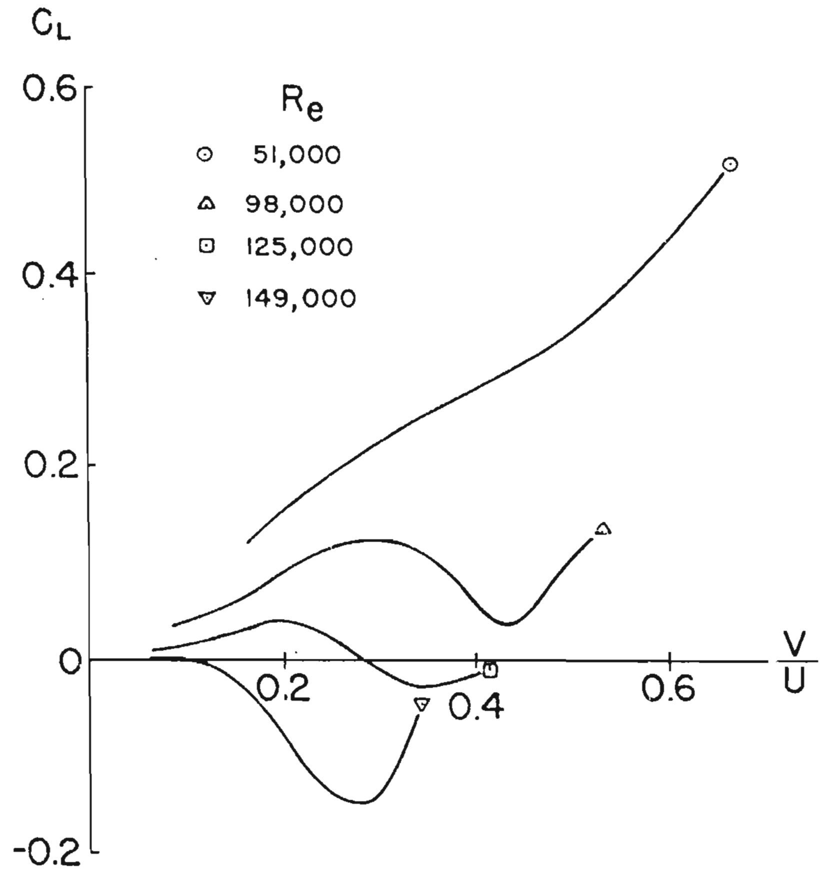

FIG. 2. Lafay's lift data for smooth cylinders.

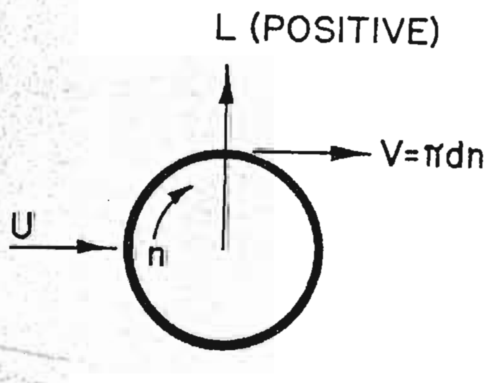

FIG. 5. Sign convention.

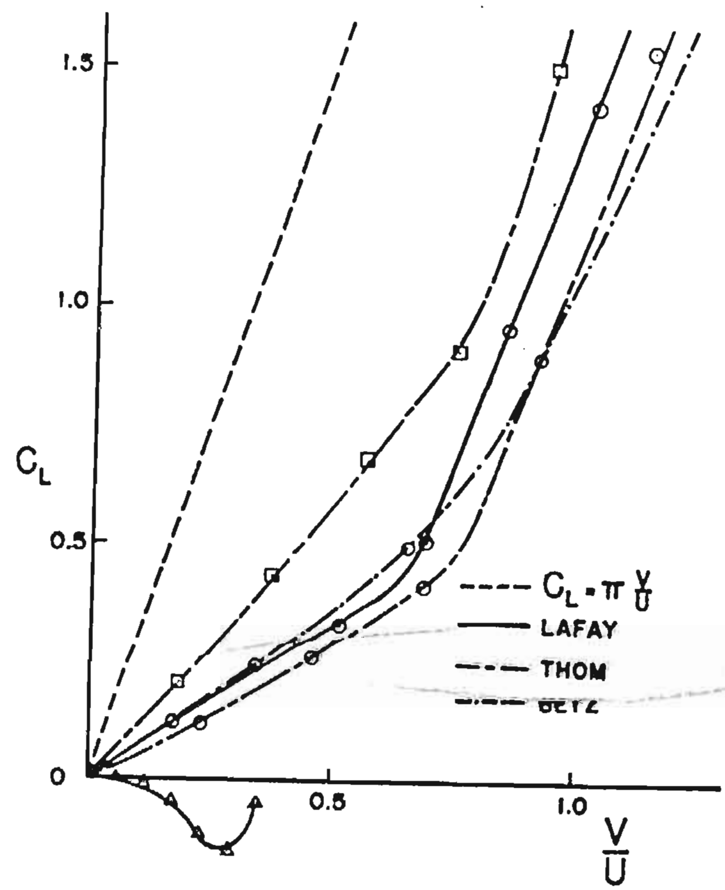

FIG. 4. Some results of Lafay, Thom, and Betz.

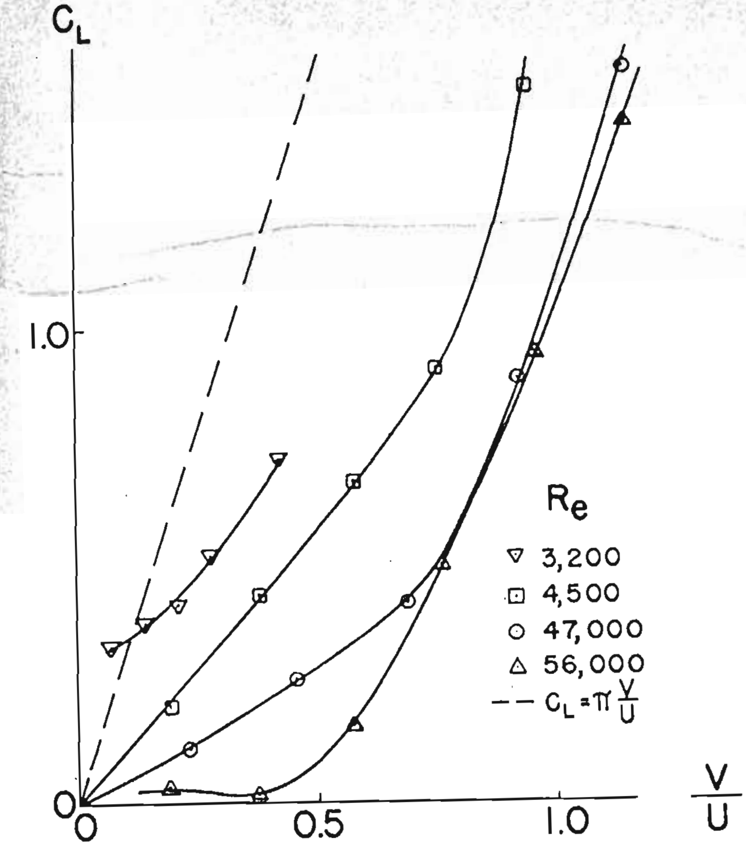

FIG. 5. Thom's data.

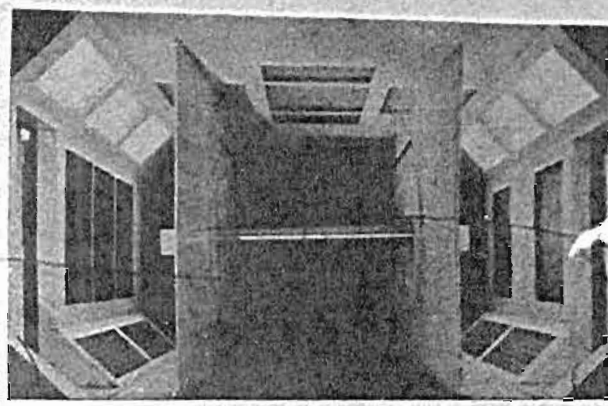

FIG. 6. Convair wind tunnel with ground boards and 8 in. cylinder installed.

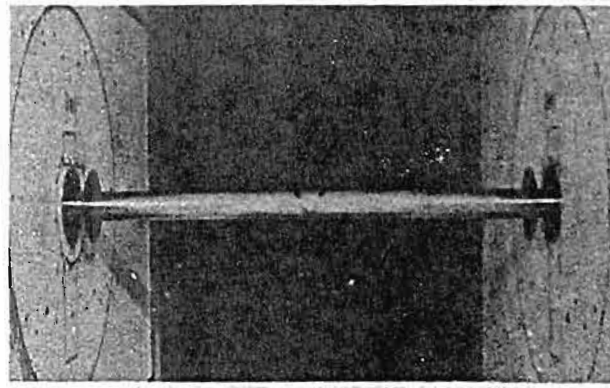

FIG. 7. Close-up of 4 in. cylinder with end plates.

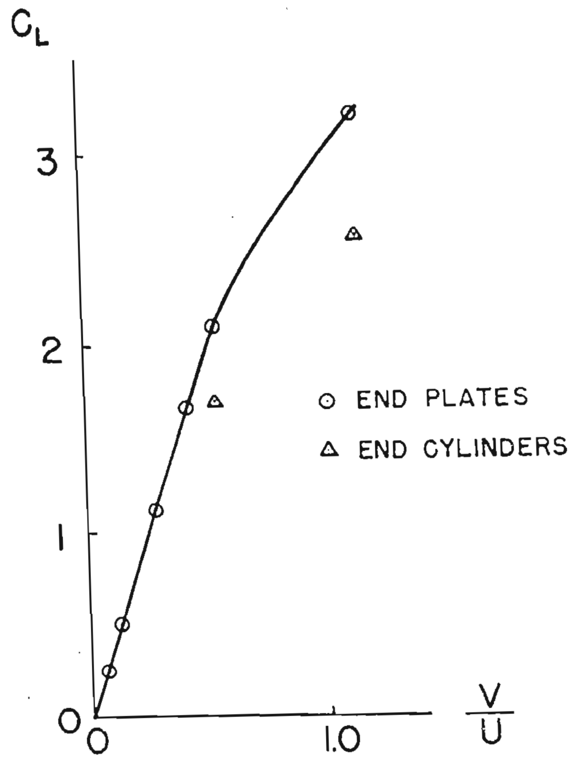

FIG. 8. Comparison of lift coefficients obtained with end plates and end cylinders.

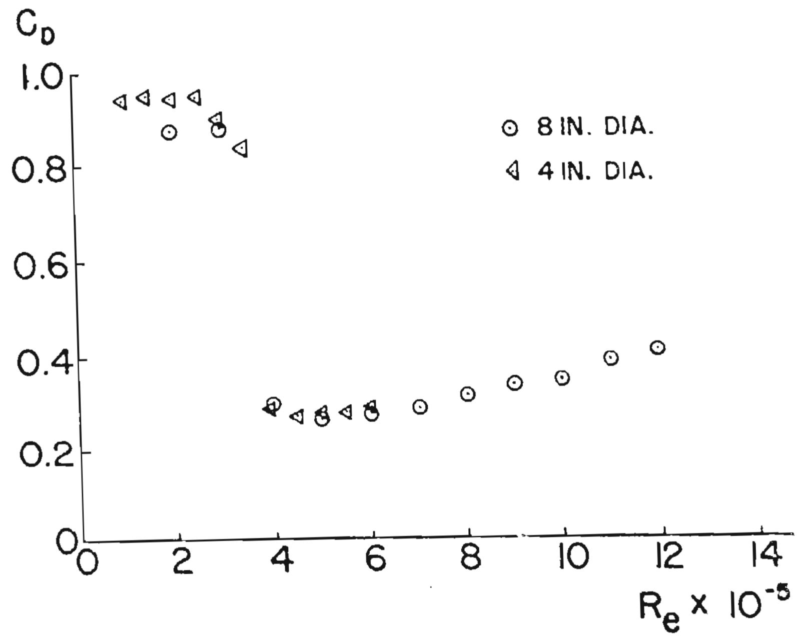

FIG. 9. Zero-spin drag coefficient.

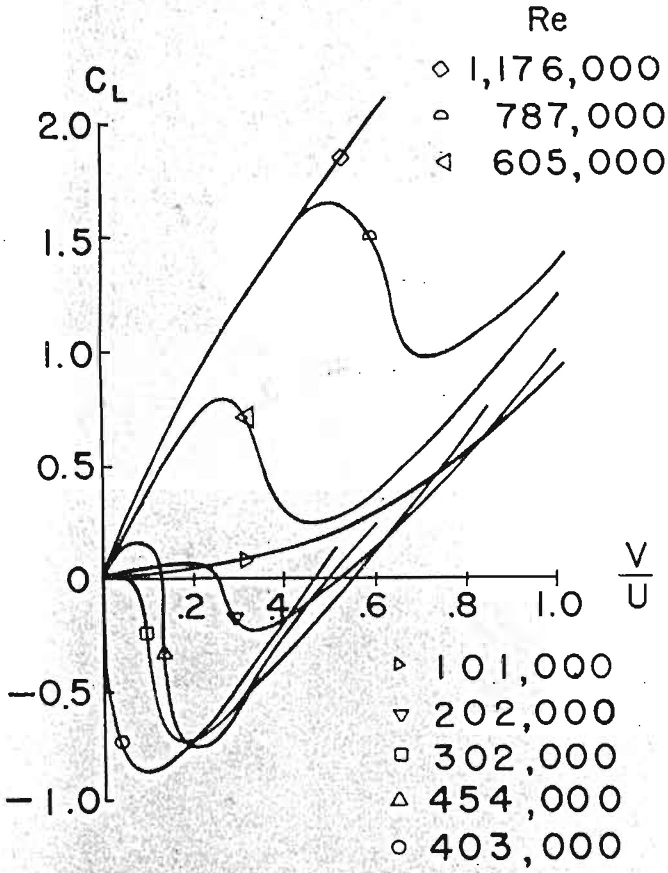

FIG. 10. Lift coefficients obtained at Convair.

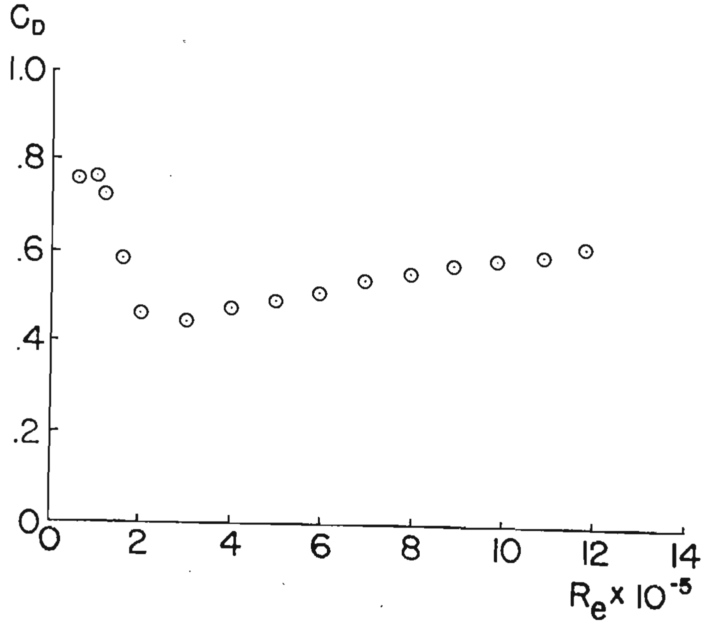

FIG. 11. Zero-spin drag coefficient with turbulence grid installed.

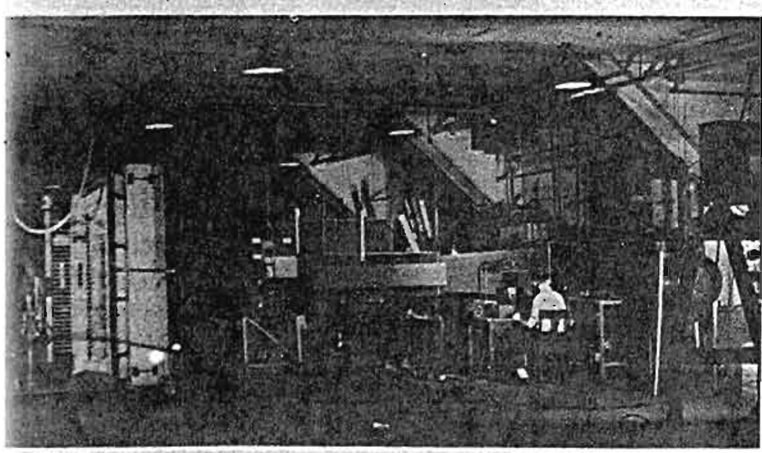

FIG. 12. Notre Dame smoke tunnel.

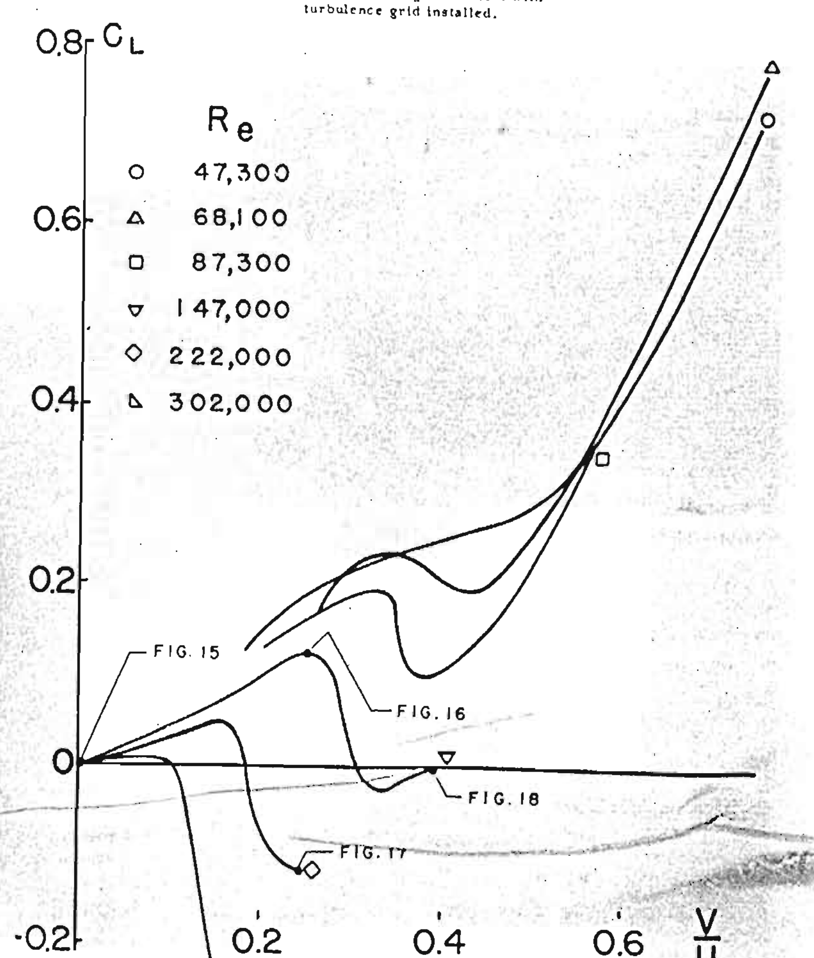

FIG. 13. Lift coefficients obtained at Notre Dame.

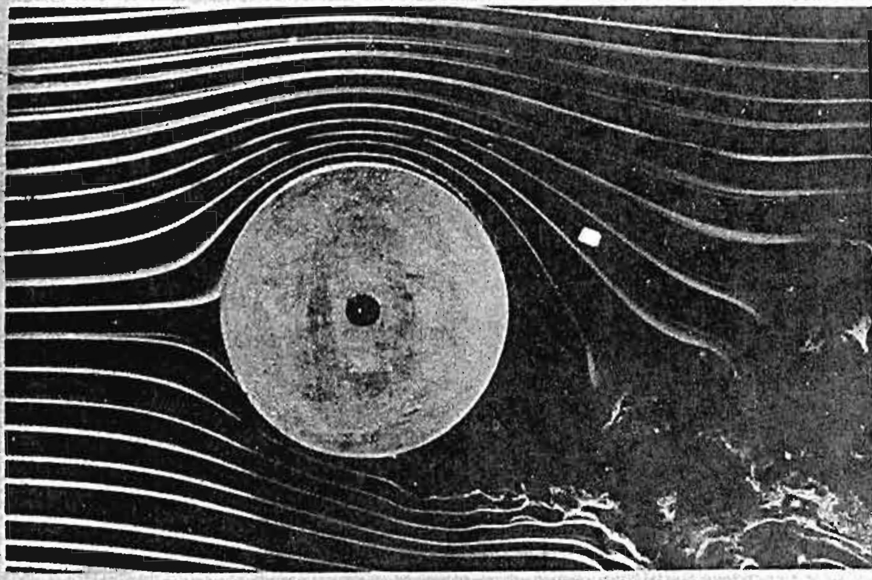

FIG. 14. Flow pattern at high lift.

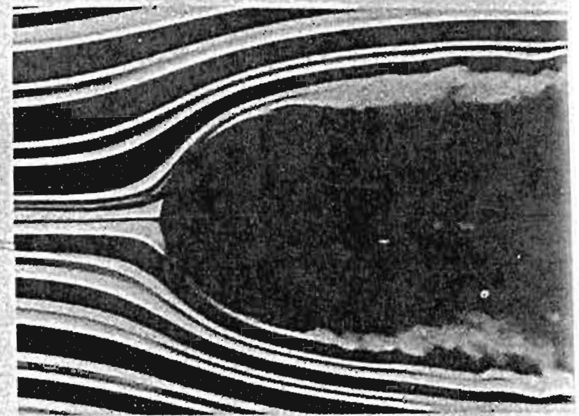

FIG. 15. Flow pattern at zero-spin, zero-lift (see Fig. 13).

FIG. 16. Flow pattern at positive lift, (see Fig. 13).

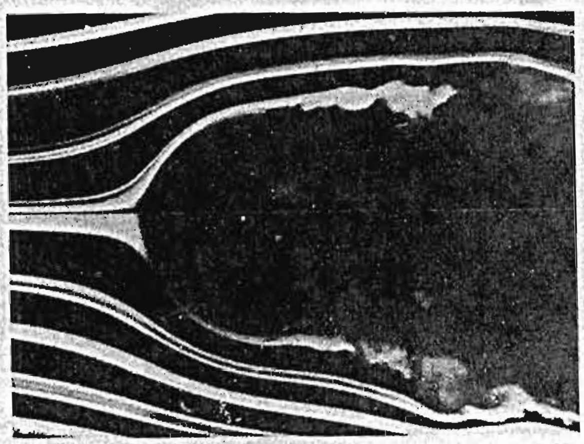

FIG. 17. Flow pattern at negative lift, (see Fig. 13).

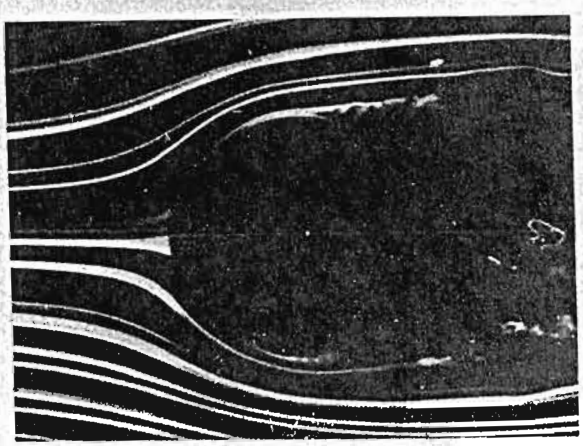

FIG. 18. Flow pattern at zero lift with spin, (see Fig. 13).

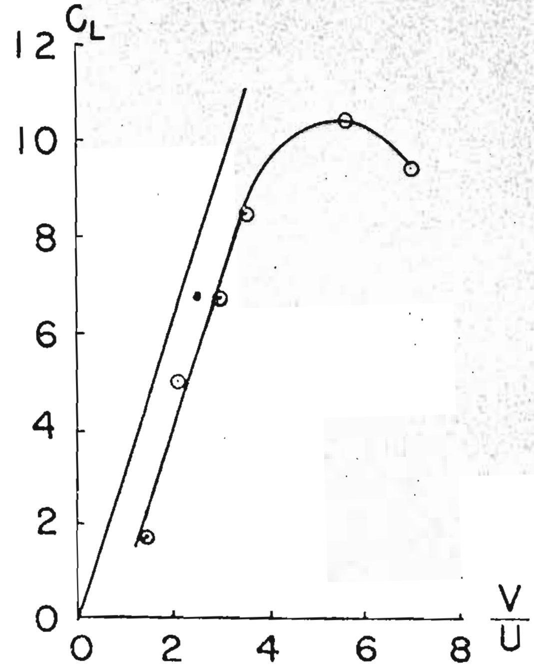

FIG. 19. Maximum measured lift coefficient.

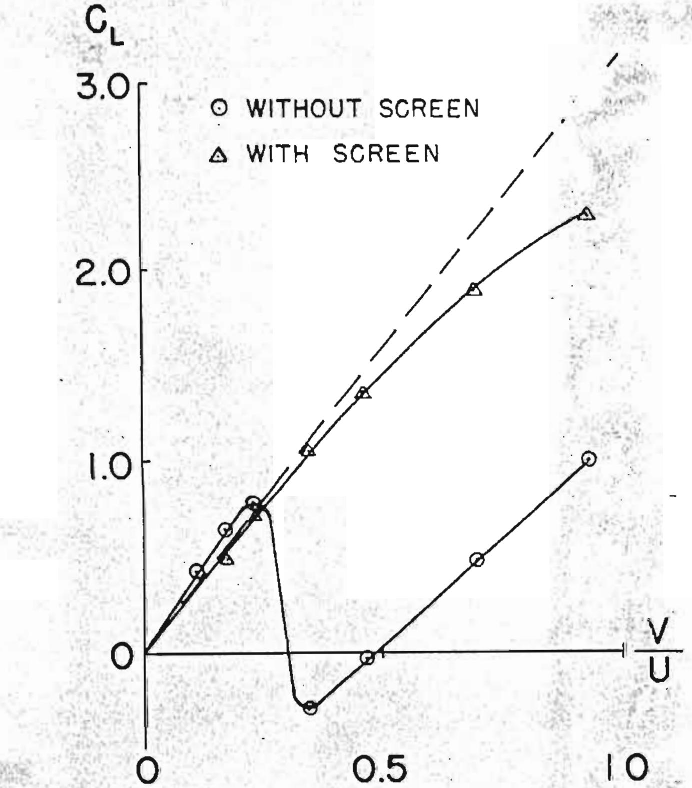

FIG. 20. Effect of turbulence screen on lift coeffic

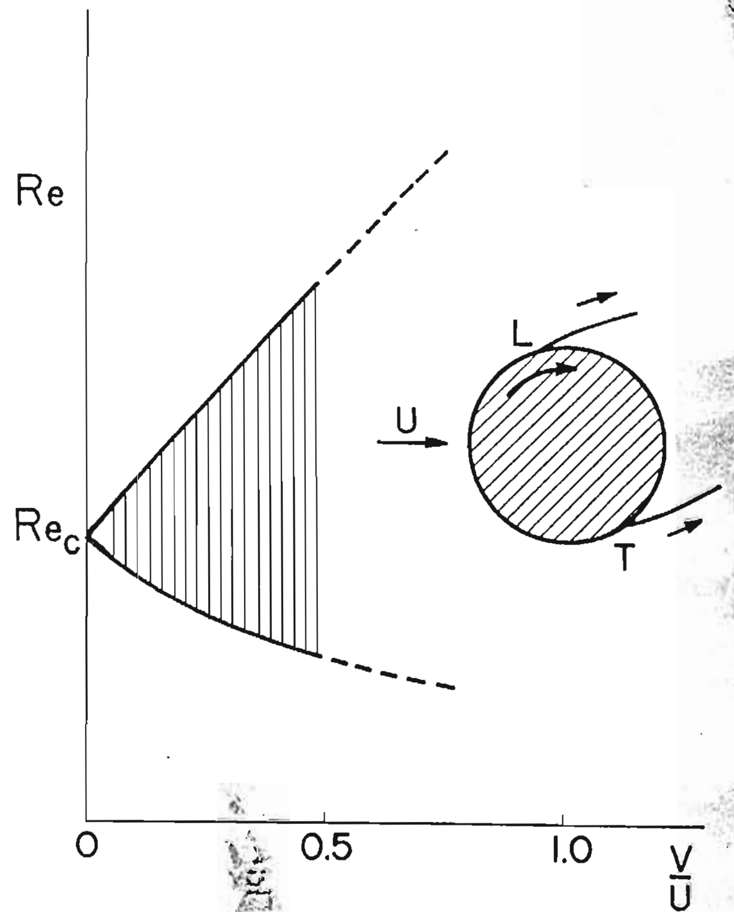

FIG. 21. Krahn's theory.

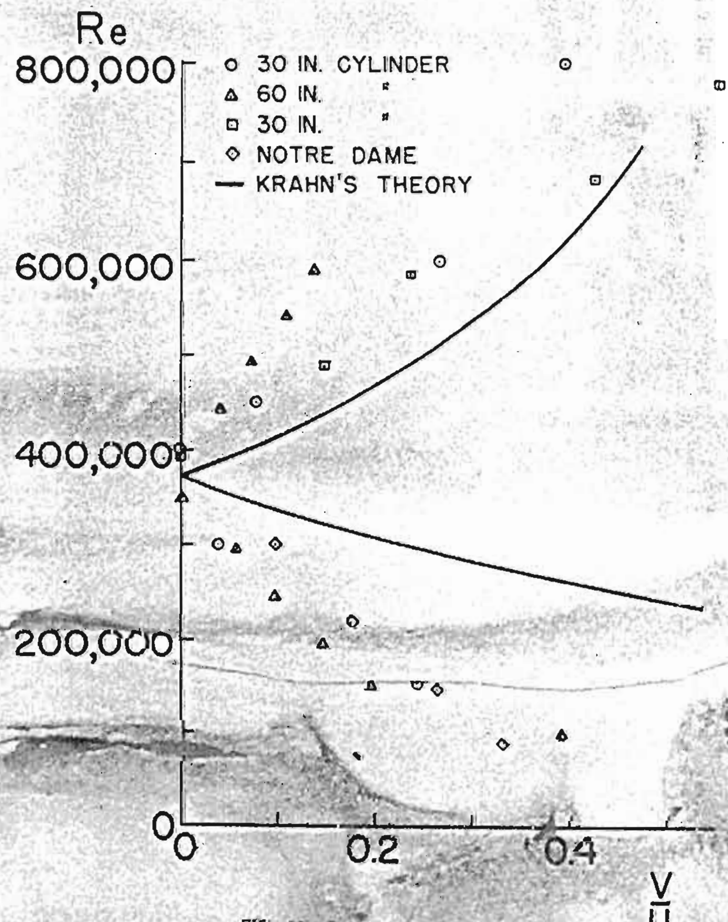

FIG. 22. Comparison of Krahn's theory

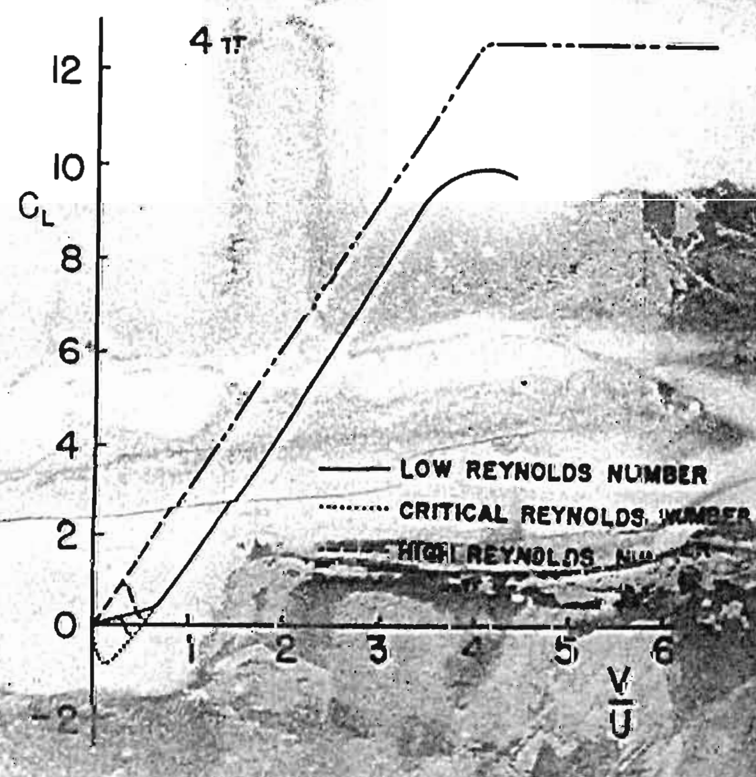

FIG. 23. General behavior of Magnus

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