AERODYNAMICS OF A SPINNING SPHERE
AN INVESTIGATION INTO THE VARIATION OF LIFT AND DRAG WITH VELOCITY RATIO AND ORIENTATION OF SPIN AXIS

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Russel E. Lewis

on this 23 day of October 1991

ACKNOWLEDGEMENTS

I would like to thank the Master Of The Universe for giving me this opportunity to learn, not only that which was required for this dissertation, but all the extra that was required to complete this project, the biggest lesson being perseverance.

To my wife Lynne, parents and parents-in-law for their unending support and motivation.

To my supervisor for always having his door open and being willing to give advice.

To my fellow students and the staff of the Mechanical Engineering Faculty and Laboratory for their help and support and constructive advice and criticism.

SUMMARY

This experimentation was carried out to investigate the forces on a spinning sphere. The tests were carried out in the Reynolds number range from Re = 70 000 to Re = 250 000. The angle between the spin axis and the flow direction was varied from 0^{o} to 90^{o}. To validate the sting balance a set of tests was carried out on a stationary sphere, giving drag values comparable to those quoted by Schlichting (1979), Mc Cormick (1967) and Massey (1979). A very conservative estimate of the turbulence level was 0.65%.

When the axis of spin was perpendicular to the wind axis, the variation of lift and drag were measured with relation to the velocity ratio. The results showed that there were three ranges. The first range was for Re $\leq$ 70 000, during which positive lift was generated with spin. The lift tended to increase with spin to a maximum value and then level off. The second range was for 95 000 $\leq$ Re $\leq$ 165 000, during which negative lift was generated before a fluctuation set in. The oscillation occasionally damped out and resulted in a steady positive lift. The third range was 188 000 $\leq$ Re $\leq$ 250 000, during which a steady trend could be found. The sphere would develop a negative lift increasing in magnitude to its maximum at a velocity ratio of 0.2, then decreasing and crossing the zero lift point at a velocity ratio of approximately 0.6 and then developing positive lift. It appears that the maximum magnitude of negative lift increases with an increased Reynolds number. For a Reynolds number of 240 000 the maximum negative lift was C_L = -0.6

The experimental data for the tests where the angle between the axis of spin and wind direction were changed did not validate the assumption the spin could be broken down into components and predict the Lift and Drag based on the component spin vectors.

It was found that spin could induce transition when testing in the critical Reynolds number range, independent of whether the spin axis was perpendicular or parallel to the wind axis.

The current results agree with both Davies (1949) and Maccoll (1928) for comparative Reynolds numbers. Davies tested at a Reynolds number of 90 000 and Maccoll tested up to a maximum Reynolds Number of 110 000. The present work extends this maximum limit to a Reynolds number of 250 000

Davies considered average loading conditions over the complete test period which would not have picked up unsteady phenomena. Maccoll used a lever system to measure his forces and visually noted the loads measured which inherently could only give long duration average values and accuracy limited by human observation, this too would have eliminated the possibility of documenting unsteady phenomena. The present work averaged the loads over a test period of 100 milliseconds. This resulted in the recording of certain unsteady phenomena.

NOMENCLATURE

A	Non-dimensional spin parameter	$\frac{\omega r}{V}$
C_L	Coefficient of lift	$\frac{Lift}{\frac{1}{2}\rho V^2 S}$
C_D	Coefficient of drag	$\frac{Drag}{\frac{1}{2}\rho V^2 S}$
L	Moment about x axis	
M	Moment about y axis	
N	Moment about z axis	
Re	Reynolds number	$\frac{\rho V D}{\mu}$
X	Force along x axis	
Y	*Force along y axis*	
Z	Force along z axis	
Γ	Circulation	
γ	Angle between wind axis and Spin axis	
ω	Rotational velocity	
V_t	Tangential velocity	ωr
r	Radius of sphere	
l	Length of cylinder	
D	*Diameter of sphere*	
V	Free stream velocity	
ρ	Density	
S	Frontal area	$\frac{\pi D^2}{4}$
$o(x)$	Error estimation implying that $o(x) \to 0$ as $x \to 0$	
$O(f(x))$	Estimation implying that $O(f(x)) \to f(x)$ as $x \to 0$	

SUBSCRIPTS

b	at the cg in body axis
s	at the virtual centre of the sting in body axis
w	at the centre of gravity *in wind axis*

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1 INTRODUCTION

Aerodynamics is the study of fluid mechanics as it relates to air flow over solid bodies, usually aircraft. A fluid by its very nature is a collection of loosely bonded molecules and therefore the best way to predict the flow over a solid body would be to base the prediction on molecular flow. The computation required for this task would be too intensive for most computers if the complexity of the solid body is anything more than trivial. For this reason most aerodynamics is based on average flow phenomena. If one were to analyse the flow over a spinning sphere mathematically one would have to consider the following four flow domains, the boundary layer, the attached vortex, the trailing vortex system and the mean flow. For a stationary sphere many researchers have spent years trying to understand and be able to predict the flow in any one of these domains. The effects of turbulence and Reynolds number have to be considered in each case. To predict the forces on the sphere one would have to integrate the pressure on the surface over the entire surface. This would require a knowledge of the characteristics and inter-relations of all four domains. If one was then to incorporate the complexity of spin to this problem the result would be very complex. For this reason an experimental approach was adopted to help give an understanding of this complex problem.

1.1 HISTORICAL

The aerodynamic effects of rotating spheres was probably the first study of aerodynamics carried out (cf. Barkla 1971). The first reference found on the subject dates back to 1671/2, when Newton noted that the flight path of a tennis ball was affected by spin. He explained that "the motions conspiring to excite a greater reluctance and reaction implied a greater pressure on the side of the ball moving forward faster."

Robbins in 1742 using the ballistic pendulum, measured the loss of 'celerity' of musket balls at transonic speeds up to Mach 1.5 (cf. Barkla 1971). He recognized the disproportionate rise in drag at sonic velocities. He used a spinning pendulum to measure the transverse force on a spinning sphere. By measuring the change in period, he determined the increase in lift due to spin.

Magnus in 1853 carried out experiments on rotating cylinders and spheres (cf. Barkla 1971). The work he carried out on cylinders led to the transverse force being called the Magnus effect by Rayleigh in 1877.

Euler in 1777 rejected the existence of a transverse force and claimed that the force measured was not due to the spin but due to the 'want of perfect roundness' (cf. Barkla 1971).

No direct experimental data is known to exist on the lift of rotating spheres at velocities of the order of those charateristic of a musket ball (cf. Barkla 1971).

Maccoll in 1928 (Maccoll 1928) took measurements on spheres up to a free-stream velocity of 34 ft/s (10.36 m/s) with a peripheral to free stream velocity ratio of up to 7. Davies in 1949 (Davies 1949) verified these results with his tests at a velocity of 105 ft/s (32 m/s). He only achieved a maximum velocity ratio of approximately 0.6.

The more modern research into spinning spheres has been mainly numerical modeling of the Navier-Stokes equations. There has also been a fair amount of work into the vortex shedding and flow visualization on spheres, generally non rotating.

The research that is being done is either for chemical plant optimisation, lubrication, sport or fundamental understanding of fluid flow.

1.2 <u>PRESENT WORK</u>

This work has been carried out to obtain a basic understanding of the forces experienced by a spinning sphere in an air stream. The model is a simple three dimensional body but has the added complexity of spin.

The existing results for the forces on a spinning sphere with the axis of spin perpendicular to the wind axis, are limited to Re = 90 000 carried out by Davies (Davies 1949) and a range of Re = 32 000 to Re = 109 000 carried out by Maccoll (Maccoll 1928). The present tests have covered a range from Re = 70 000 to Re = 250 000

In reality most rotating spheres moving through the air are neither spinning purely about the direction of flight, nor are they rotating exactly perpendicular to the direction of motion. They are generally rotating about an axis that is neither parallel nor perpendicular to the direction of motion. However, all the experimental data that the author obtained from a comprehensive literature search has the axis of spin either parallel or perpendicular to the direction of motion. From this point on, the direction of motion will be called the wind axis. This implies that there is an inherent assumption made by those making use of this data for practical purposes. They are assuming that the velocity and spin can be broken down into components. By taking components of the spin vector, a spin parameter can be determined using the component perpendicular to the wind axis. The Magnus force such a spin parameter would generate is then used as an approximation for the sphere spinning at an angle to the flow. In the numerical work of Rubinow (1961), this assumption is made without even stating that it has not yet been experimentally validated.

The present work has attempted to validate this assumption and find the limits within which it is valid. The method used for this validation was to firstly determine experimentally what the forces experienced by a sphere are when the angle between the spin axis and wind axis are changed. The second step was to take three particular cases and predict the lift for all angles between the spin and wind axes from 0^{o} to 90^{o}. The three cases chosen were those where data was available for both the spin axis perpendicular to the wind axis, and for varying angles between spin and wind axes at comparable Reynolds numbers. A pair of tests was taken at low, medium and high Reynolds numbers.

The present work has also attempted to determine the effect of spin on the drag experienced by a sphere, for the case of wind axis parallel to the axis of spin.

2 OBJECTIVES

1) The first requirement in this set of tests was to validate the new sting balance, parallelogram support and data acquisition system on the University Of The Witwatersrand's 1.5m wind tunnel.

2) To measure the variation in lift on a rotating sphere when the axis of spin is perpendicular to the wind.

3) To measure the variation in drag on a rotating sphere when the axis of spin is perpendicular to the wind.

4) To determine the effect of changing the angle between the spin axis and the wind axis on both lift and drag.

5) To validate the assumption that spin can be regarded as a vector and therefore be broken into components.

3 LITERATURE SURVEY

The first reports of research on the aerodynamics of spinning spheres were those by Robbins and Magnus. Both these works were experimental studies of the lift force generated by a spinning sphere. The main objective of these experimenters was to convince the scientific community that a spinning sphere did generate a force, if the axis of spin was perpendicular to the direction of motion. The force is perpendicular to both these axes. This meant that the results were not documented rigorously, preventing the data from being re-processed. Comparisons can therefore not be made with more recent work. The experimentation was continued by Maccoll and Davies, while other researchers concentrated on the vortices being shed behind cylinders and spheres. When computer power reached a stage where numerical modelling became possible, attempts were made to model the flow over spheres and cylinders as well.

The literary survey has been split in to five sections.

1) Text books

2) Experimental work on spinning spheres

3) Theoretical and experimental work on cylinders

4) Theoretical and Numerical studies of spheres

5) Experimental work on stationary spheres

3.1 TEXT BOOKS

Schlichting (1979), Massey (1979) and Mc Cormick (1967) show graphically the effect of increasing the Reynolds number on the drag of a sphere.

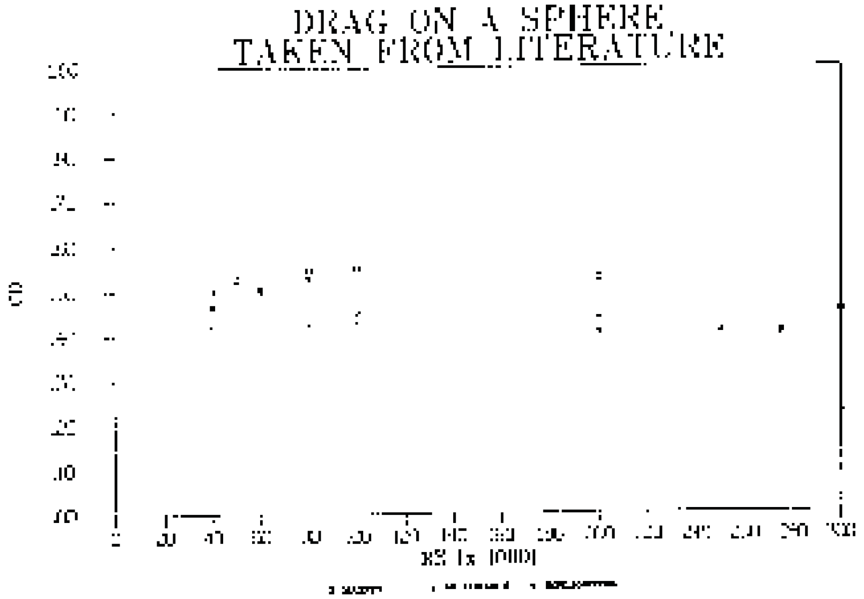

Fig. 3.1 Drag on a stationary sphere taken from the literature.

Massey shows that if the sphere is not round but ellipsoid then the critical Reynolds number changes. If the diameter parallel to the flow is smaller than the diameter perpendicular to the flow, the drag coefficient increases as does the critical Reynolds number. If the diameter parallel to the flow is larger than the diameter perpendicular to the flow, the critical Reynolds number decreases, while the curve of coefficient of drag with respect to Reynolds number follows the same trend as for a sphere until transition.

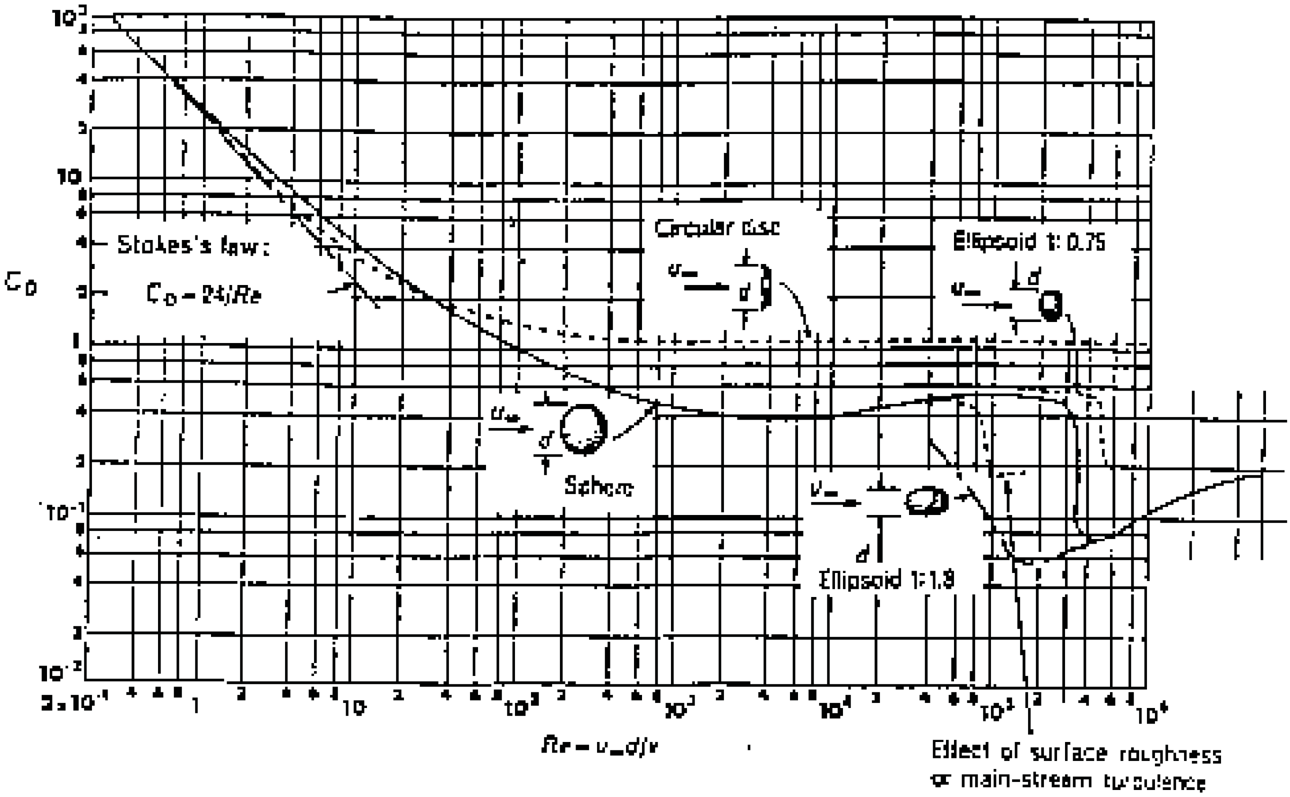

Fig. 3.2. Drag on stationary axially-symmetric bodies taken from Massey (1979).

Schlichting has graphical data of the relationship between drag and Reynolds number for a sphere spinning with the wind parallel to the axis of spin.

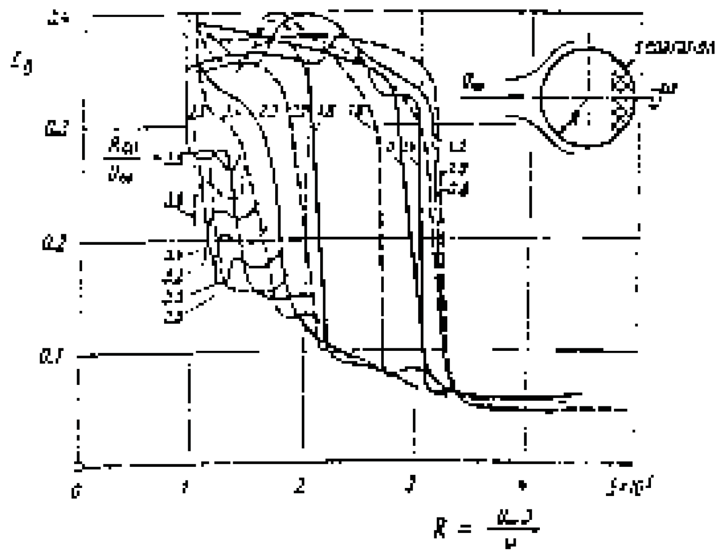

Fig 3.3 Drag on a rotating sphere with wind axis parallel to the axis of spin taken from Schlichting (1979)

Both Rae and Pope (1984) and Schlichting (1979) quote the method developed by Dryden (in N.A.C.A. Technical Report 581 and 342) of scaling the Reynolds number and measuring the turbulence by means of the experimentally obtained critical Reynolds number.

The wind tunnel has to be able to achieve a Reynolds number of 400 000 based on the sphere diameter to use the method quoted in Rae and Pope (1984) as stated. However if the relationships stated are used without following their method exactly, an indication of the turbulence level can still be obtained.

When using the method described in Rae and Pope, one first finds a turbulence factor and then using the following graph (Fig. 3.4) one can obtain the turbulence level.

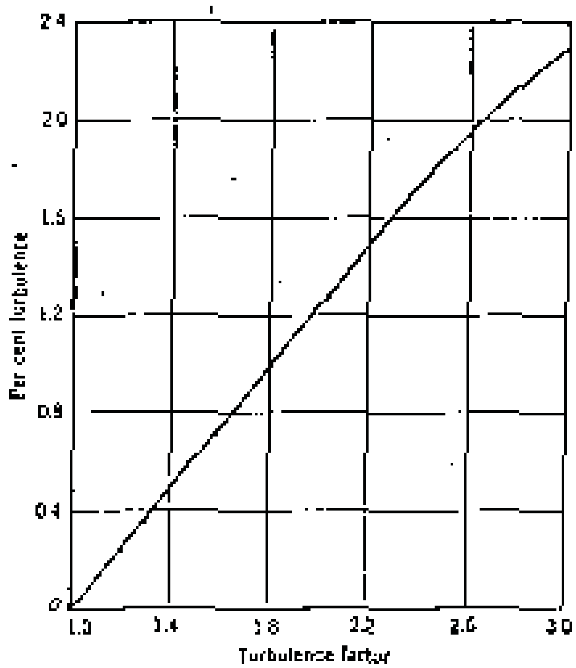

Fig. 3.4. Relationship between Turbulence Intensity and Turbulence Factor for a sphere from Rae and Pope (1984).

Schlichting's method on the other hand uses the critical Reynolds number to determine the turbulence level.

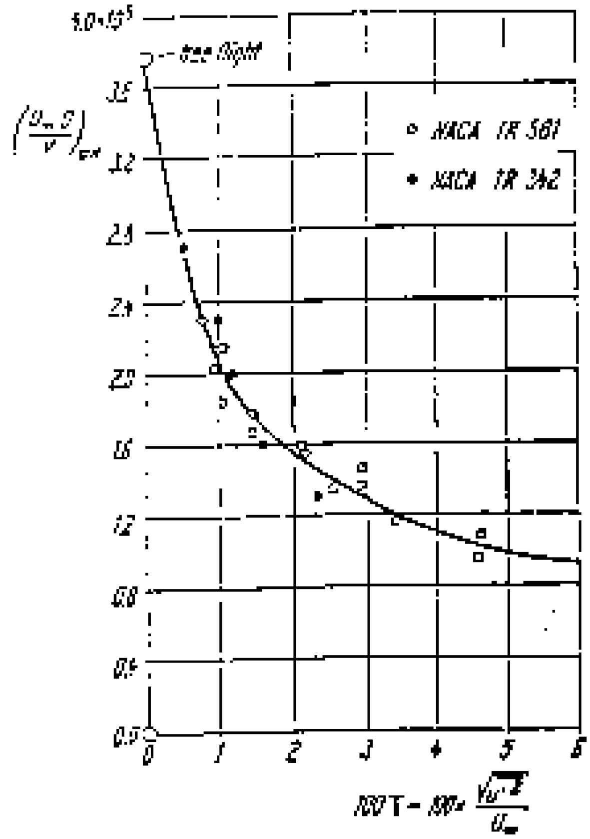

Fig. 3.5. Relationship between turbulence intensity and Reynolds number for a sphere from Schlichting (1979).

Rouse (1946) and Tritton (1979) consider the aerodynamic effect of spinning a sphere with the axis of spin perpendicular to the flow. Rouse shows the relationship of both lift and drag to spin parameter at a Reynolds number of 100 000, but does not quote a source. Tritton shows the variation of lift with spin parameter and quotes Davies and Maccoll. The two books differ in the range from A = 0.8 to A = 3.

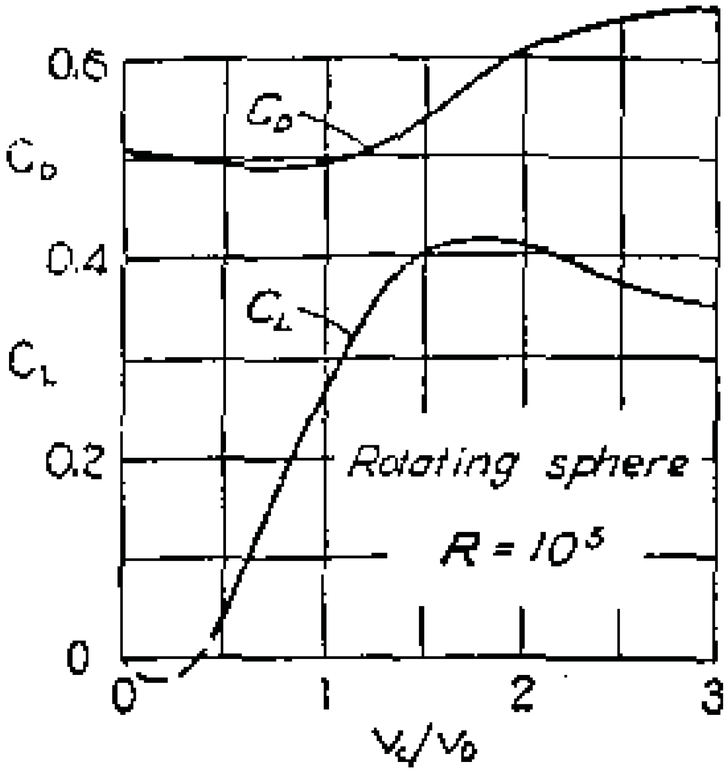

Fig. 3.6. Lift and Drag on a spinning sphere with the axis of spin perpendicular to the wind axis from Rouse (1946).

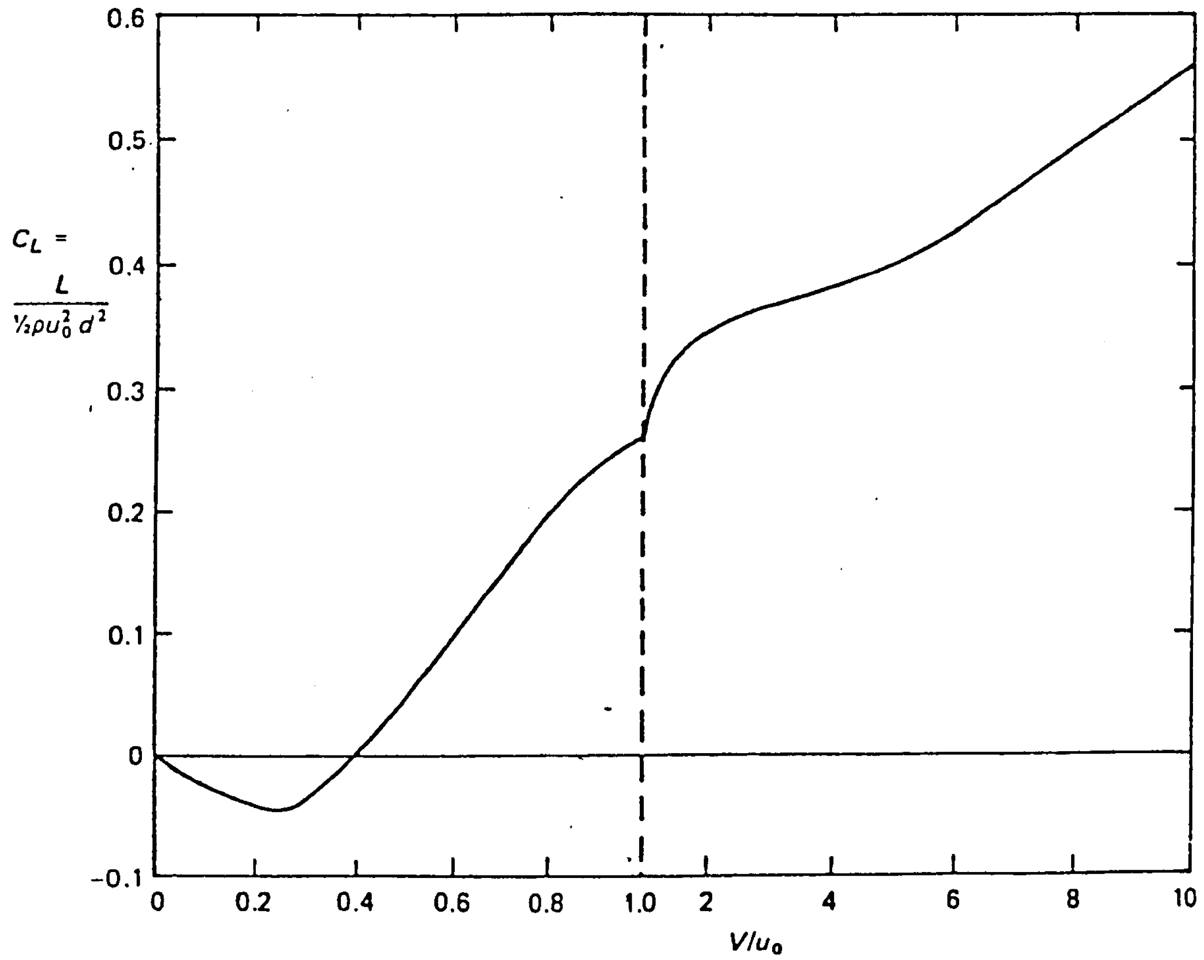

Fig. 3.7. Lift on a spinning sphere with the axis of spin perpendicular to the wind axis from Tritton (1979).

3.2 EXPERIMENTAL RESEARCH ON SPINNING SPHERES

Barkla and Auchterlonie (1971) gives a historical background to the research on spinning spheres in a flow. The first experiments mentioned were those making use of a musket, where the last few inches of barrel were bent through 3^o to 4^o. The trajectories were noted by means of paper walls through which the projectiles passed. The data was not noted sufficiently rigorously to allow it to be re-analysed. The second set of tests were carried out using a spinning sphere on the end of a pendulum. When these tests were processed, the effect of density was ignored and a least squares approximation was applied to all the points.

Davies (1949) and Maccoll (1928) are the only two experimenters known to the author to have published results of their tests on the forces experienced by a sphere that has its axis of spin perpendicular to the wind axis. The other sources presenting results of this effect are quoting these two papers if a source is quoted.

Maccoll placed a 6 inch sphere in a wind tunnel. The sphere was sting mounted and powered throughout the test. He carried out tests at 10.0 ft/s, 14.6 ft/s, 19.6 ft/s, 24.6 ft/s and 34.0 ft/s which correspond to Re = 32 000, Re = 47 000, Re = 63 000, Re = 79 000, and Re = 109 000 respectively, assuming International Standard Atmosphere (ISA) conditions for sea level since the work was carried out in Glasgow. Maccoll only detected negative lift at the two highest Reynolds numbers.

Maccoll did not use the standard form of nondimensionalization for forces on aerodynamic models, but defined new coefficients $K_D = \frac{DRAG}{\rho V^2 D^2}$ and $K_L = \frac{LIFT}{\rho V^2 D^2}$. These are a factor of $\frac{8}{\pi}$ smaller than the accepted standard coefficients C_D and C_L. This can lead to misinterpretation when comparing data. The results quoted in this work have been converted to standard format.

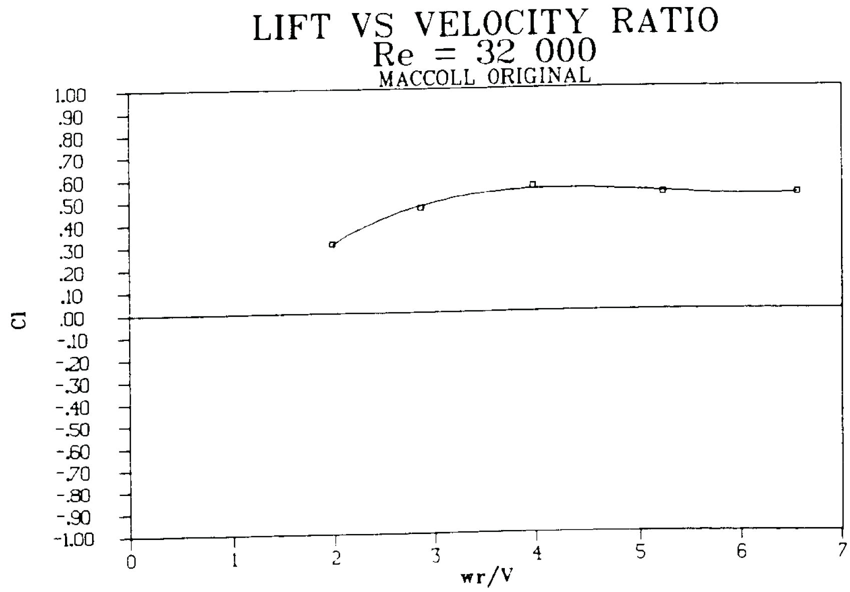

Fig. 3.8. Lift vs Velocity Ratio for Re = 32 000 according to Maccoll.

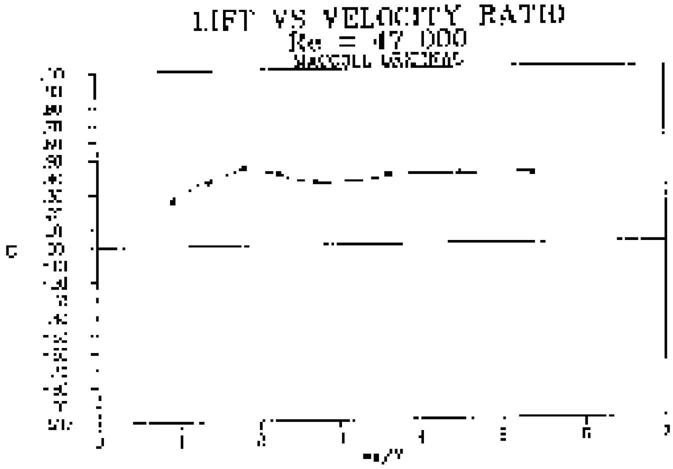

Fig. 3.9 Lift vs Velocity Ratio for Re = 47 000 according to Maccoll.

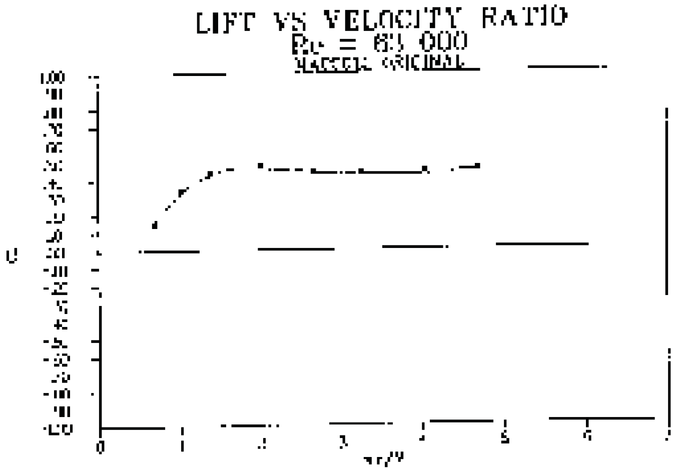

Fig. 3.10. Lift vs Velocity Ratio for Re = 63 000 according to Maccoll.

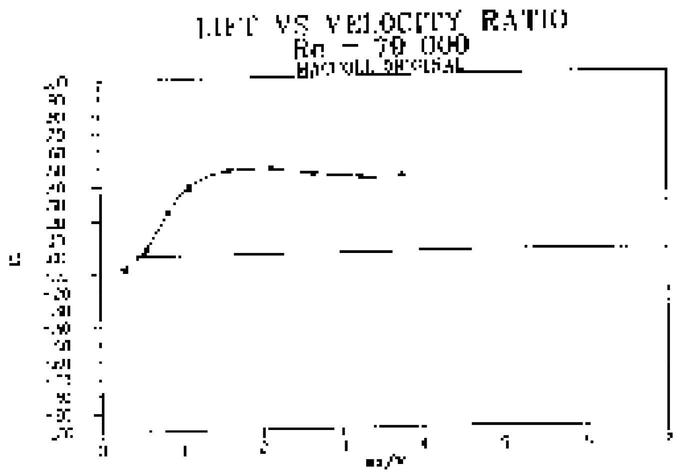

Fig. 3.11. Lift vs Velocity Ratio for Re = 79 000 according to Maccoll.

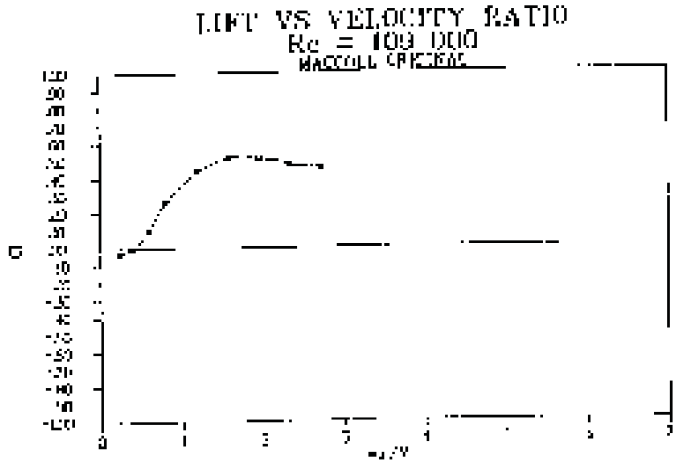

Fig. 3.12. Lift vs Velocity Ratio for Re = 109 000 according to Maccoll.

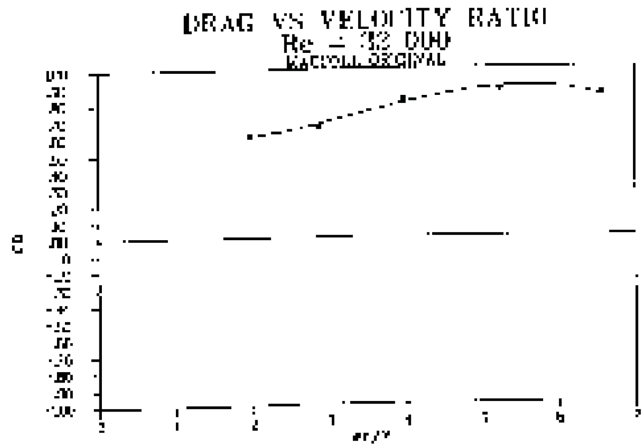

Fig. 3.13. Drag vs Velocity Ratio for Re = 32 000 according to Maccoll.

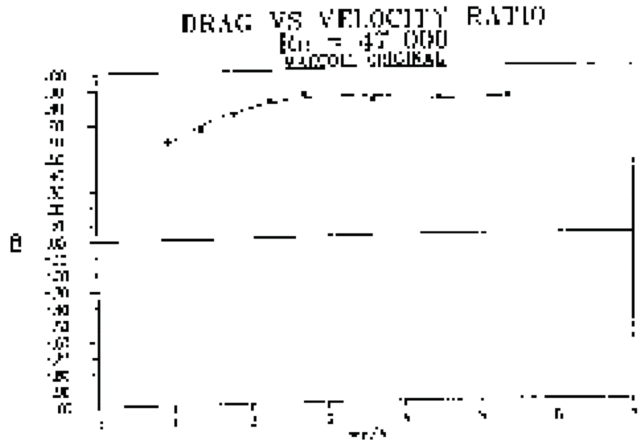

Fig. 3.14 Drag vs Velocity Ratio for Re = 47 000 according to Maccoll

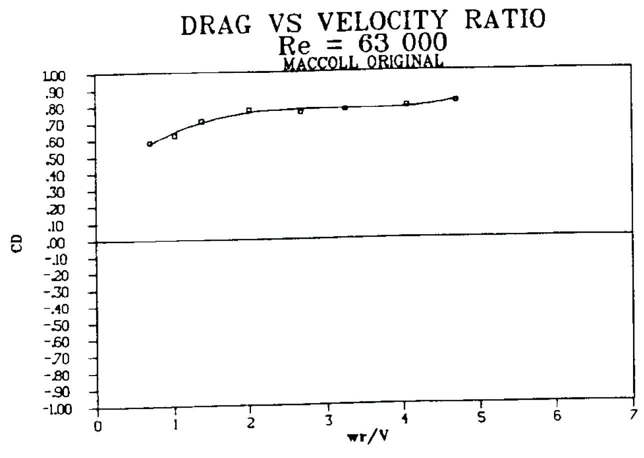

Fig. 3.15. Drag vs Velocity Ratio for Re = 63 000 according to Maccoll.

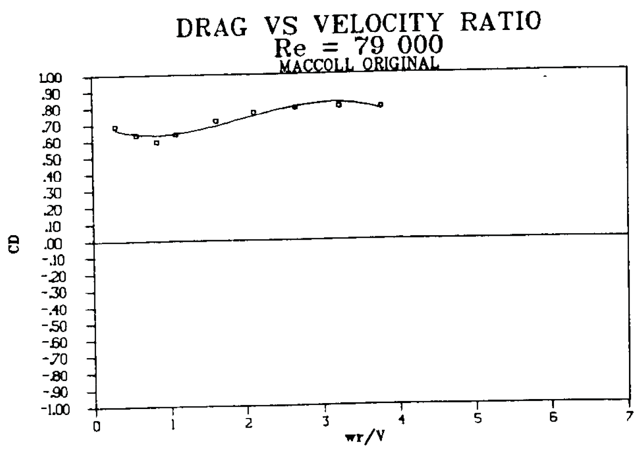

Fig. 3.16. Drag vs Velocity Ratio for Re = 79 000 according to Maccoll.

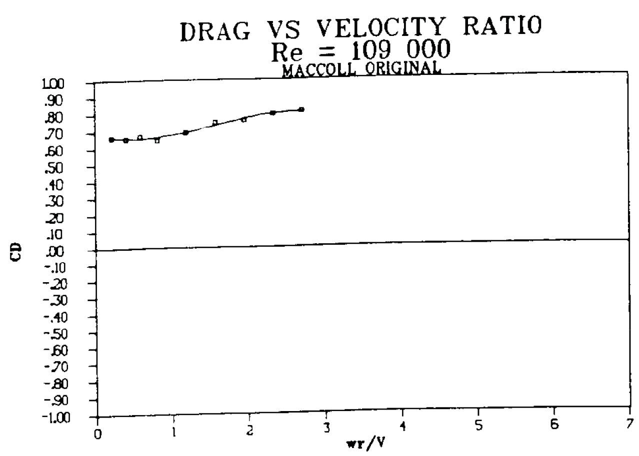

Fig. 3.17. Drag vs Velocity Ratio for Re = 109 000 according to Maccoll.

Davies used a different technique to conduct his testing. He spun the ball by placing it between two cups and then dropped it into the airstream. The wind velocity was reported to be constant. The displacement in the wind direction was measured from the time of release to the time of the first bounce. The procedure was repeated for the ball being spun both clockwise and anti-clockwise. From these two values the average lift and drag could be determined for the complete test.

He quotes his results in pounds and RPM, but reduces his values for the drag on a non-rotating sphere to a C_D value. Working backwards from this value it was possible to find values for density, and thereby reduce all his test results to nondimensional forces.

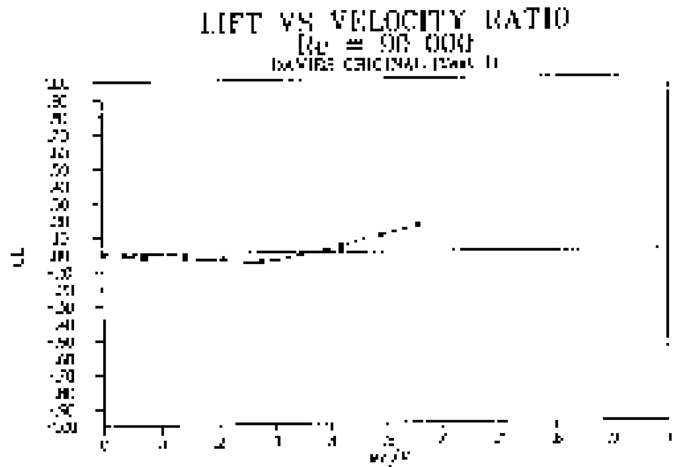

Fig. 3.18 Lift vs Velocity Ratio for Re = 90 000 according to Davies' first test.

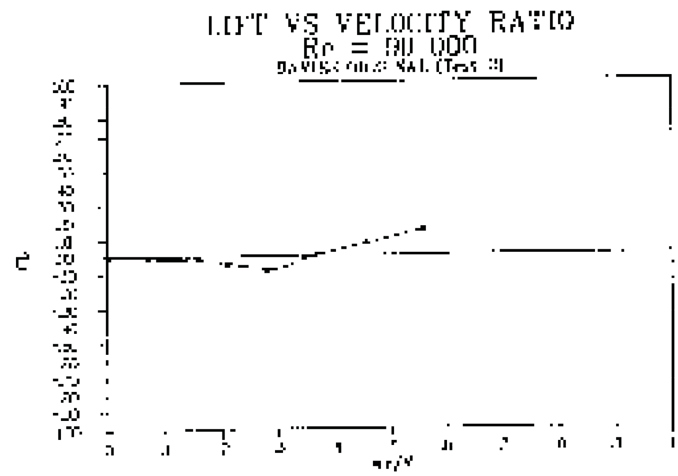

Fig. 3.19 Lift vs Velocity Ratio for Re = 90 000 according to Davies' second test

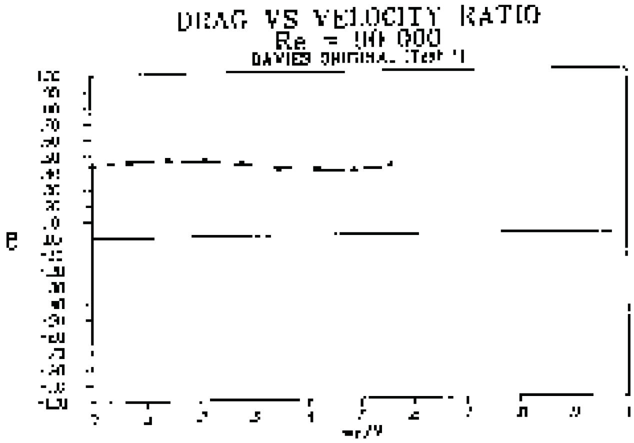

Fig. 3.20. Drag vs Velocity Ratio for Re = 90 000 according to Davies' first test.

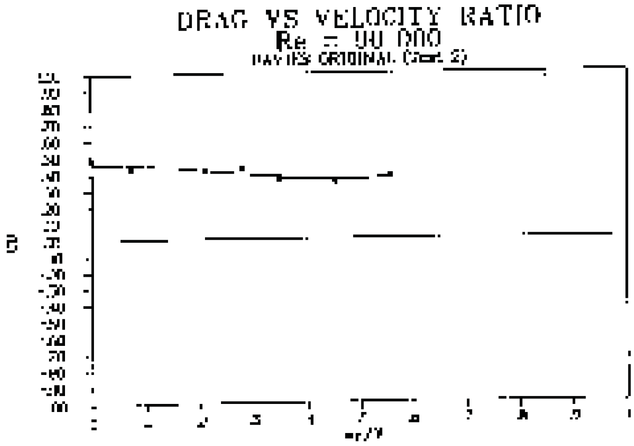

Fig. 3.21. Drag vs Velocity Ratio for Re = 90 000 according to Davies' second test.

Horlock whose main interest was in cricket balls, researched the effect of the seam on a cricket ball's performance. He also did tests on cylinders using trip wires.

Bearman and Harvey (1976) worked on the aerodynamics of golf balls. They used model balls with both conventional dimples and hexagonal dimples. They compare their results to Davies and Maccoll. Bearman and Harvey question the accuracy of Maccoll's results because the size of his sting support was 15% of the diameter of his sphere. They also only quote one of his curves and do not state that they have neglected the others.

Mehta (1985) gives a summary of the experimental work carried out on sports balls. The types of sports covered are cricket, golf and baseball. The report gives results of static as well as spinning balls where results were obtainable.

3.3 THEORETICAL AND EXPERIMENTAL RESEARCH ON CYLINDERS

Gerrard (1961) measured the oscillating lift and drag on a cylinder shedding vortices. The measurements were made by taking pressure traces.

Sarpkaya and Schoaff (1979) developed a discrete vortex model based on the interaction of boundary layer and potential flow theory. The primary objective was to model impulsively started flow over a circular cylinder. Kimura (1986) used the same method to model the flow over a rotating cylinder. This method could even model the negative lift at low spin rates.

Aldoss and Mansour (1988) used superposition and then Thwaites' method to calculate the stagnation position and both separation points on a rotating cylinder. A linear pressure distribution in the wake region was assumed to calculate the lift and drag coefficients.

Swanson (1961) published a paper summarising the work carried out on the Magnus Effect up to that time, concentrating on spinning cylinders. The figure below shows the comparative results published in the paper. It is clear from these results that the flows are highly complex, even for the case of a cylinder, particularly in the low velocity ratio range.