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WIND TUNNEL TESTING OF LOW REYNOLDS NUMBER AEROFOILS FOR WIND TURBINE BLADES

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ABSTRACT

The paper describes a series of wind tunnel tests performed on small scale aerofoil sections to document their aerodynamic properties at low Reynolds numbers. The range of flow regimes investigated is relevant to the behaviour of small power wind turbines, which are often operated with laminar flow over part of the blade surfaces.

The aerodynamics of aerofoil sections has been studied in detail for high Reynolds numbers, but when used in the above mentioned conditions the force coefficients may exhibit significant changes particularly if large angles of incidence are employed, and the global performance of a wind turbine will reflect such effects.

The experiments concentrated on the measurement of lift and drag forces. The tested profiles were the well known NACA 4412 and 4415 and also two thinner geometries, Eppler 387 and NACA Br-63-44-12. The tunnel was operated through a range of velocities that produced chord Reynolds numbers between 35000 and 105000 and the angle of incidence covered the whole interval of 0° to 360°.

The results quantify the differences in behaviour that have been detected and show that the extent of Reynolds number dependence varies noticeably from one profile to another. Particular care has been exerted to estimate the influence of the tunnel lateral boundaries on the measured force coefficients and the associated corrections are also discussed.

1. INTRODUCTION

The aerodynamics of aerofoil sections has been extensively studied for high Reynolds numbers, and the application to flight may at present be predicted with satisfactory accuracy by using experimental data that was acumulated over several decades. The general trend in more recent experimental studies has been to extend the range of Reynolds numbers upwards, to approach real flight conditions, leaving behind the low Reynolds number range where laminar effects are likely to occur but are of little interest for pratical aeronautical purposes.

One exception is model flight, where Reynolds numbers are one or more orders of magnitude smaller. Several new profile shapes have been developed and tested for that purpose, most of them using thin sections that appear to achieve better lift/drag characteristics in laminar flow than conventional profiles. Quantitative information may be found in reference [1], among others.

Another application where low Reynolds numbers are relevant is the design of small power wind turbines. Chord Reynolds numbers under 100000 occur in propeller-type turbines with diameters below 10 m at starting conditions, if operated in moderate wind. But often such conditions are associated with large angles of incidence that have little in common with the use of aerofoil sections in flight. The same is true of vertical axis wind turbines, where adequate knowledge of the aerodynamic forces for any incidence angle is essential. Quantitative information is however in short supply and small variations of the force coefficients may produce important changes of rotor performance (see, for example, reference [2]).

Although substantial progress has been made in the development of prediction methods applicable to the calculation of the flow around aerofoils, the behaviour in stalled conditions poses particularly severe computational problems. When added to the difficulties in modelling transition from laminar to tubulent flow, one is still left with the experimental approach as the main source of information for the prediction of lift and drag in aerofoils at low Reynolds numbers and large angles of incidence. The collection of such data in wind tunnels is relatively easy, but careful attention must be paid to the evaluation of the interaction between the models being tested and the tunnel boundaries. At low Reynolds numbers the flow around aerofoils exhibits thick boundary layers and wakes that spread laterally and interact with the tunnel walls, so that measured forces may be strongly dependent on tunnel geometry and adequate corrections mut be devised and applied.

The present paper aims to contribute to a more clear understanding of the particular features of such flows and of the experimental techniques used to assess them. Apart from providing laboratory data on the lift and drag characteristics of four aerofoil sections, it brings in additional details of the comparative behaviour of classic and "laminar" profiles at low Reynolds numbers. The results quantify the differences that have been detected and also demonstrate that the extent of Reynolds number dependence varies from one profile to another.

Careful precautions were adopted to evaluate the influence of the tunnel lateral boundaries on the measured force coefficients, so that the reported results may be used as representative of two-dimensional flow in a wind tunnel for models of infinite aspect ratio.

The following section describes the test rig and associated instrumentation and the results of measurements are presented and discussed in section 3. Summary conclusions are contained in the last section of the report.

2. TEST RIG AND INSTRUMENTATION

The experiments comprised the measurement of lift and drag forces on two-dimensional sections of 65 mm chord and 365 mm span, corresponding to an aspect ratio of approximately 5.6:1. The tested profiles were the well known NACA 4412 and 4415 and also two thinner geometries, Eppler 387 and NACA Br-63-44-12 described in reference [1] and [3] , respectively.

The model sections were made out of epoxy resin, using a technique described in reference [4] . Briefly, each model was obtained by pouring liquid resin into an outter case of paraphin wax in which the appropriate profile contour had been produced using a high precision steel cutter. The various cutters were machined directly from the coordinates of the profiles and were accurate to 0. 01 mm. The resulting model sections present good dimensional accuracy and adequate mechanical strength.

The wind tunnel had a test section with lateral dimensions of 400 x 400 mm and was of the open circuit type, with a variable speed fan at the inlet end, capable of producing a range of air speeds between 8 m/s and 24 m/s in the test section. A smooth contraction with an area ratio of 6.25 and various screens were employed to ensure uniformity of air velocity and turbulence intensity of approximately 0.5% in the measuring section.

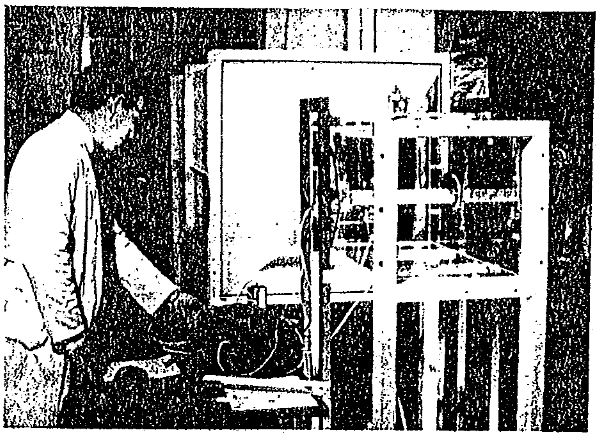


Fig. 1: General view of test rig

The models were suspended from their tips, through rods that crossed the side walls of the tunnel and were connected outside to the arms of a balance mounted above the measuring section. The balance was a three component system, with three strain gauge bridges used to measure drag, lift and pitching moment. The outputs of the bridges were amplified, low-pass filtered and immediately digitized by a multiplexer - A/D converter module connected to a microcomputer.

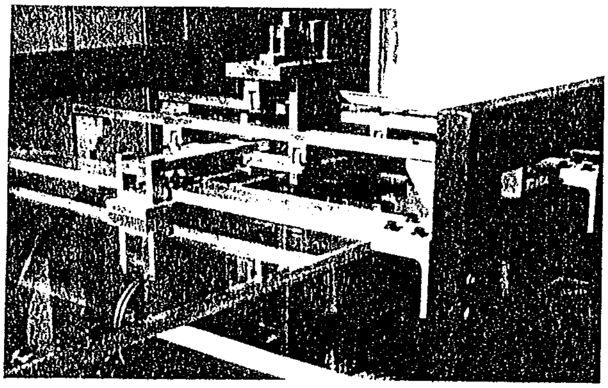


Fig. 2: Detail of force measuring system

Attached to one the side arms of the balance, a DC motor with reduction gear was employed to rotate the models about their suspension axis, allowing the angle of incidence to be varied continuously, at the rate of approximately one turn every 30 minutes. The computer-controlled data acquisition system also kept a record of the incidense angle, derived from a potentiometric transducer connected to the motor shaft, and of the air velocity in the tunnel, measured by means of a Pitot tube and a pressure transducer. An overall view of the experimental settup and a detail of the balance and test section are shown in figures 1 and 2, respectively.

Typically one test comprised a sequence of measurements, at regular time intervals, of the three bridge outputs, incidence angle and air velocity, while the model was being continuously rotated by the driving motor.

Each sequence covered one complete turn in 0.5° increments or a narrower interval of incidence angles in more detail. Each test was preceded by static calibration of the balance to remove uncertainties associated with long term drift of the force measuring elements.

Files of measured data were then transferred through a serial link to a computer for data processing, which included additional filtering by software to smoothen out random sources of error acuumulated in the measuring chain.

3. EXPERIMENTS AND MEASURED RESULTS

Each model section has been tested over a range of air velocities that correspond to Reynolds numbers between 35000 and 105000 based on profile chord. The measured results are presented below, preceded by a sub-section where the method adopted to evaluate finite span efects is explained.

3.1 Estimation of finite span effects

The use of a large span/chord ratio suggests that three-dimensional effects have been limited, in the reported experiments, to a small fraction of the model span, close to its tips. previous observations of oil patterns on the model surfaces, described in [4] , confirmed it for geometries that extended accross the tunnel full width.

In the present measurements the model tips were fitted with thin circular plates, parallel to the side walls of the tunnel and displaced about 17 mm from them. These disks were 140 mm in diameter and had sharp edges machined to a 30° bevel. They were employed to inhibit the induced tip vortices that appear in models with free tips, and thus minimize distorsion of two-dimensional flow.

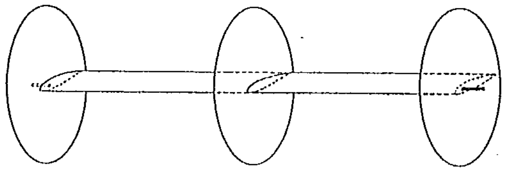
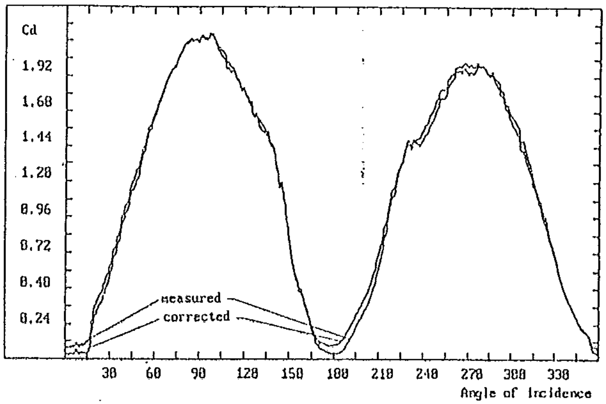
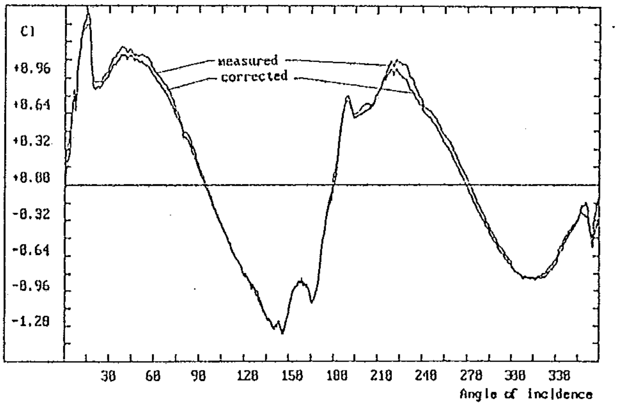


Fig. 3: Model with lateral and central disks

In addition to the above, the residual contributions of tip effects to the measured drag and lift have been evaluated. For this purpose, tests were also performed with a third disk mounted at the plane of symmetry of the models, as seen in figure 3, and it has been assumed that this third disk introduced, at each of its sides, the same distorsion to the flow as one of the tip disks. By comparing the results of measurements with and without the central disk, it has been possible to isolate the magnitude of the corrections that must be applied to the gross lift and drag coefficients, and so obtain corrected coefficients. These represent the lift and drag characteristics that would have been measured in a tunnel with models of infinite aspect ratio, uncorrected for other sources of error such as effects of tunnel blockage.



DRAG COEFFICIENT



LIFT COEFFICIENT

Fig. 4: Comparison of corrected and uncorrected drag and lift coeficients

Sample comparisons of corrected and uncorrected coefficient are shown in figure 4 for the NACA 4415 profile at Re of about 37000.

3.2 Measured results - NACA 4415 profile

This profile was chosen for a more detailed study of the influence of Reynolds number on the force coefficients. Measurements were performed for various Reynolds numbers and sample results are shown in figures 5 to 9 for Re of 37099, 46785, and 57810.

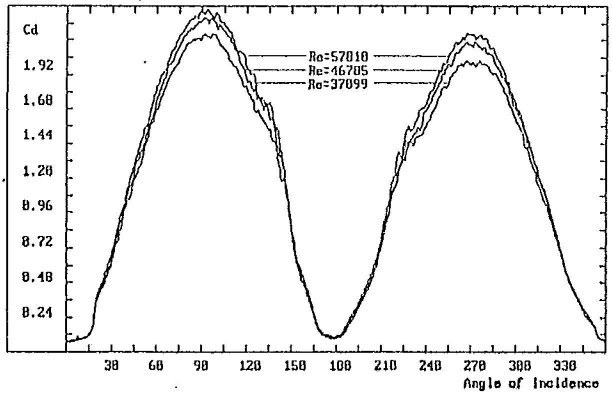


Fig. 5: Drag coefficient for NACA 4415

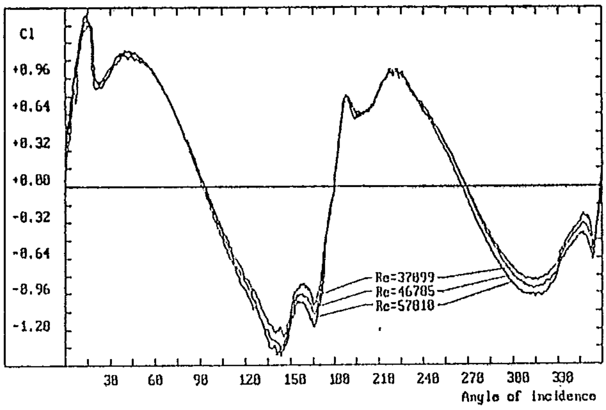


Fig. 6: Lift coefficient for NACA 4415

The plotted coefficients were corrected as described in the previous sub-section. Other corrections have not been generally implemented, as it appears that most studies of tunnel blockage and related effects have been carried out for higher Reynolds numbers and small angles of incidence, and should not in principle be extrapolated to the flow conditions.

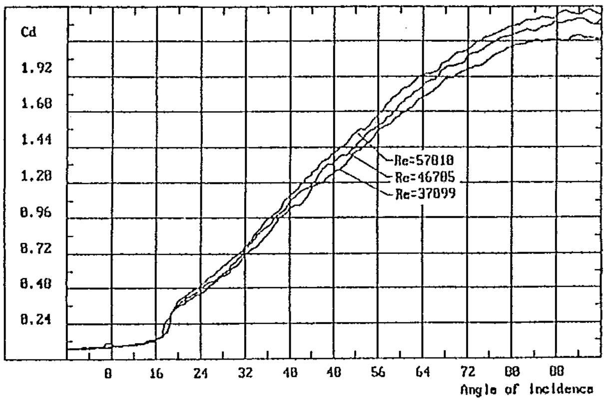


Fig. 7: Detail of drag coefficient for NACA 4415

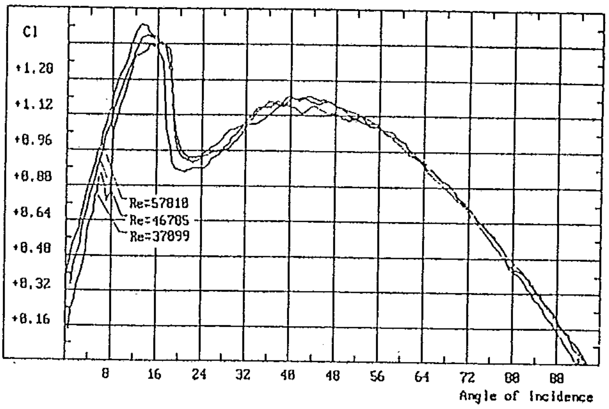


Fig. 8: Detail of lift coefficient for NACA 4415

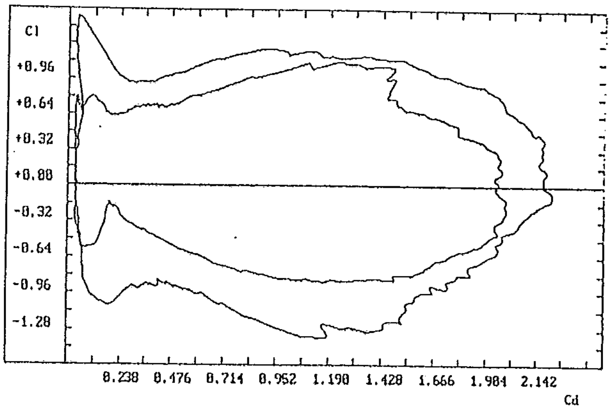


Fig. 9: Eiffel Polar for NACA 4415 at Re of 37099

A comparison with other available laboratory data for the NACA 4415 profile is not presented at this stage, mainly because of the difficulties already metioned in applying suitable corrections to the measured data. An attempt to approach the flow conditions corresponding to the published data of reference [5], namely Re of around 105000 and incidence up to 28°, produced some obvious discrepancies. The maximum lift coefficient observed here was 1.42 comparing with 1.26 for the quoted source of data, and stall always was accompanied by a sharp decrease in lift instead of the smooth reduction that had been reported before. For the purpose of these comparisons, the present measurements were corrected according to the reccommendations of reference [6] for two-dimensional test sections.

It is not clear whether the observed differences may as well be atributed to other details of the test rigs employed, such as the levels of turbulence intensity in the tunnels and the surface finish of the models. Additional work is necessary and is now proceeding in order to obtain apropriate corrections for these low Reynolds number, high incidence angle flows, and so contribute to a better quantitative description or of their properties.

The limitations just mentioned do not impair a comparative analysis of the measured data for different flow conditions, and the influence of Reynolds number on the NACA 4415 profile is an interesting example, particularly obvious at Re below 40000. Laminar separation first affects lift at small angles of incidence when the angle is being decreased and produces hysteresis of the lift curves, documented in figures 10 to 13.

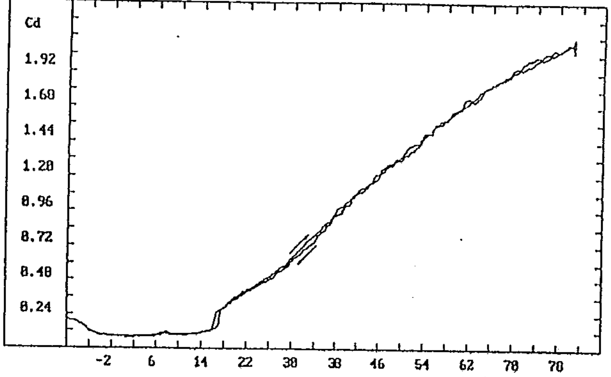


Fig. 10: Detail of drag coefficient for NACA 4415 at Re=37891

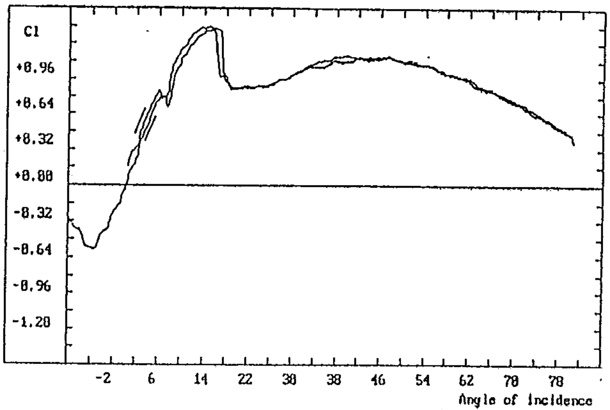


Fig. 11: Detail of lift coefficient for NACA 4415 at Re=37891

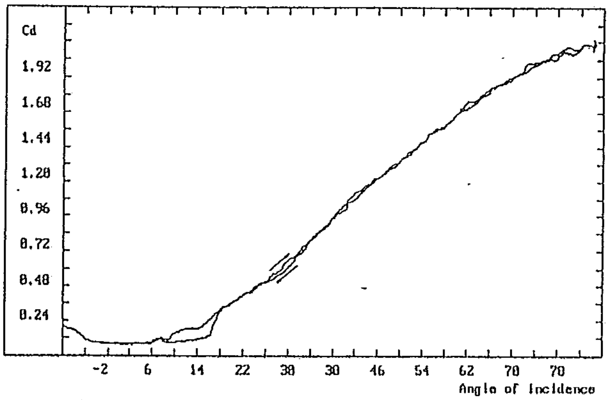


Fig. 12: Detail of drag coefficient for NACA 4415 at Re=37388

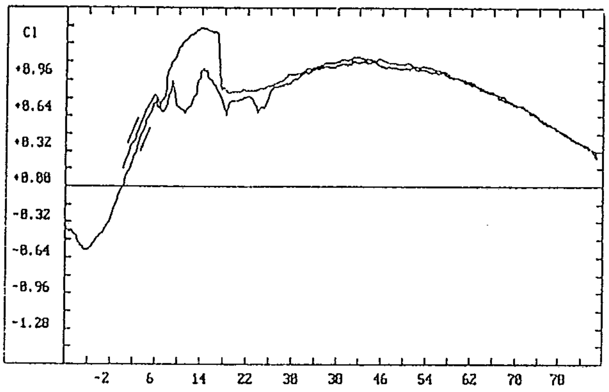


Fig. 13: Detail of lift coefficient for NACA 4415 at Re=37388

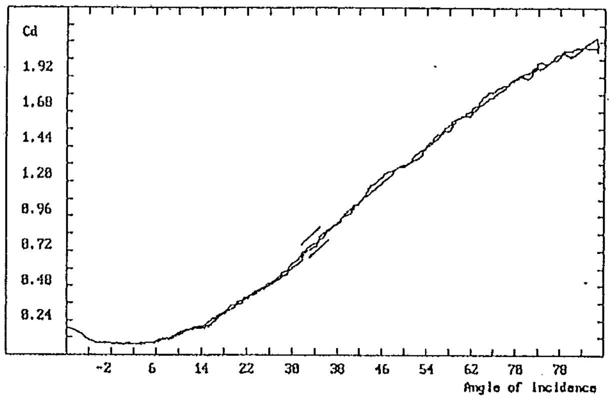


Fig. 14: Detail of drag coefficient for NACA 4415 at Re= 36827

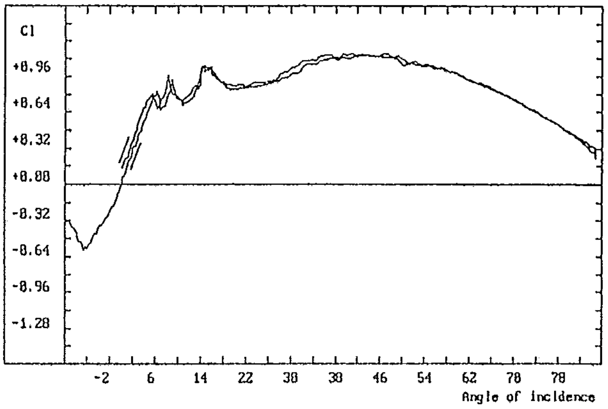


Fig. 15: Detail of lift coefficient for NACA 4415 at Re=36827

The observed changes in aerodynamic behaviour evolve rapidly with a reduction in Reynolds number and at Re below 37000 lift has deteriorated for both increasing and decreasing angles. The profile has then completely lost the lift properties that have made it popular in wind turbines.

3.2 Measured results - other profiles

The remaining tests were performed with the profiles NACA Br-63-44-12, NACA 4412 and Eppler 387 and were oriented towards the collection of C_l and C_d data at various Reynolds numbers.

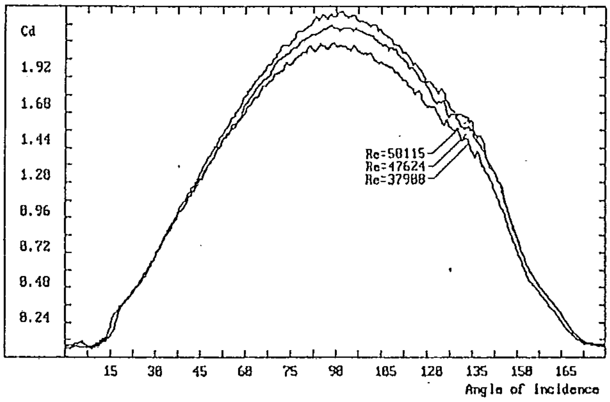


Fig. 16: Drag coefficient for NACA Br-63-44-12

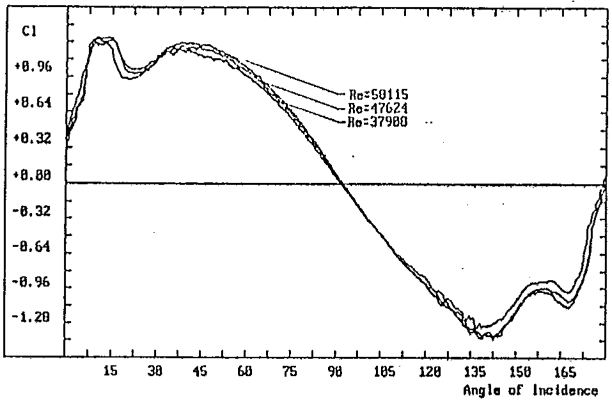


Fig. 17: Lift coefficient for NACA Br-63-44-12

Figures 16 and 17 reproduce results for the NACA Br-63-44-12 profile, corrected as indicated in sub-section 3.1. It is clear that this profile exhibits a less pronounced loss of lift at angles that correspond to stalled flow in the NACA 4415 profile.

Figures 18 to 21 show results derived from the NACA 4412 and Eppler 387 profiles, and were obtained with a preliminary version of the aerodynamic balance, described in reference[7] , that did not allow the use of incidence angles above 30° due to excessive deformation of the force measuring elements.The results do not contain any correction, but from the small magnitude of the corrections shcw in figure 4 one may expect that the main features of the behaviours displayed in figures 18 to 21 would still be present in the corrected data.

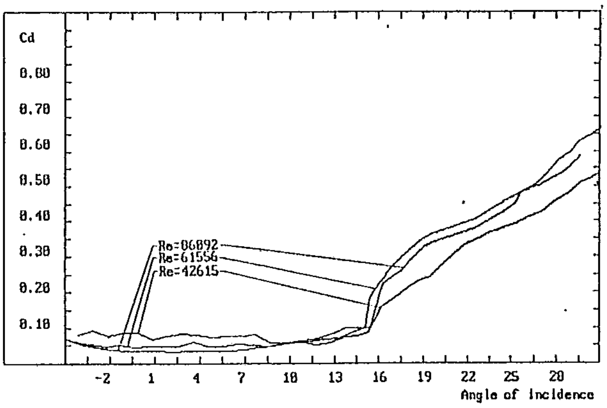


Fig. 18: Drag coefficient for NACA 4412

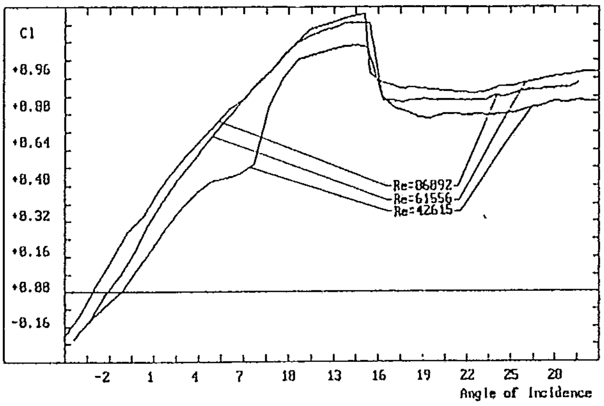


Fig. 19: Lift coefficient for NACA 4412

It is obvious that the Eppler 387 profile exhibts low Reynolds number properties that resemble those of the NACA Br-63-44-12 in what concerns the ability to withstand relatively large angles of incidence retaining useful lift characteristics, although the maxima of C_l are in both cases somewhat lower than those of the NACA 4412 profile. Additional tests with the latter profile not shown here, also indicated a less pronounced loss of lift at the lowest Reynolds numbers tested than for the NACA 4415 profile.

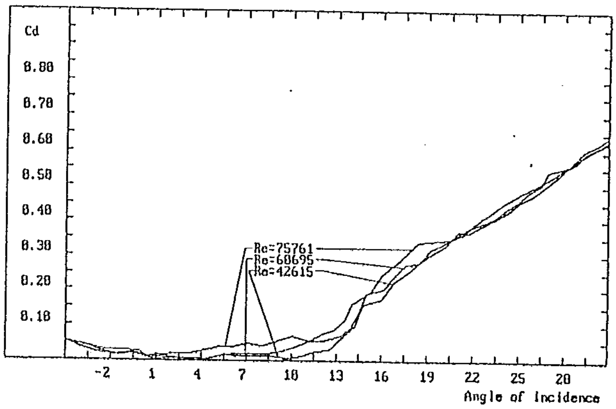


Fig. 20: Drag coefficient for Eppler 387

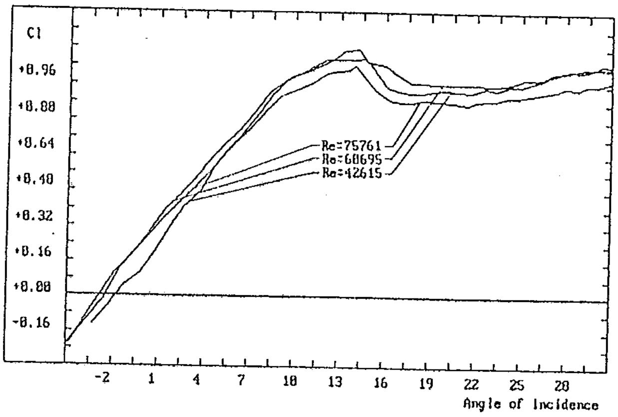


Fig. 21: Lift coefficient for Eppler 387

4. CONCLUSIONS

It has been demonstrated that the lift and drag characteristics of aerofoils may be adequately studied in small scale sections for the range of Reynolds numbers below 100000, where laminar effects become noticeable and affect most obviously thick profiles like the NACA 4415.

The results include the direct measurement of the correction necessary to produce really two-dimensional force coefficients, although other corrections, namely those associated with tunnel blockage, still require careful quantification.

The measured data spans the entire 360° interval of incidence angles, specially useful for vertical axis wind turbines.

It has been shown that the "laminar" profiles tested, Eppler 387and NACA Br-63-44-12 exhibit good low Reynolds number properties in what concerns the ability to withstand large angles of incidence with adequate lift characteristics, although the maxima of C_l are in both cases semewhat lower than those of the NACA 4412 profile, even at the smallest values of Re. The latter appears to be less sensitive to Re than the NACA 4415 and may provide a suitable choice for application in small turbines where the reduced thickness of the "laminar" profiles is perhaps a drawback in what concerns the structural strenght of the blades.

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REFERENCES

[1] - MTB - Modell-Technik-Berater, Eppler Profile--Verlag fur Technik und Handwerk, A und B. Ledertheill-Sweingniederlasung der Ehapaverlag GmbH, 1978.

[2] - G. R. Frederick and J. M. Savino, The Effect of Airfoil Section Properties on the Rated Power of a Horizontal Axis Wind Turbine Rotor, Proc. Delphi Workshop on Wind Energy Appl., pp. 147-161, 1985.

[3] - F.L. Galvão, Moderniser des Profils Classiques, Aero Revue Suisse 8/1965.

[4] - F.T. Pinho, Estudo Experimental do Comportamento Aerodinâmicc de Perfis Alares a Baixos Números de Reynolds. M. Sc. Thesis, University of Porto Portugal, 1986.

[5] - Eastman N. Jacobs and Albert Sherman, Airfoil Section Characteristics as Affected by Variations of the Reynolds Number, NACA Report nº 586.

[6] - E. A. Brun, A. Martinot-Lagarde, J. Mathieu, Mécanique des Fluides, Dunod, 1970.

[7] - F. T. Pinho and A. Restivo, Estudo Experimental do Comportamento Aerodinâmico de Perfis Alares para Turbinas Eólicas, Proc. III Congr. Ibérico de Energia Solar, pp. 615-621, Madrid, 1987.