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EXPERIMENTAL STUDY OF THE INFLUENCE OF AN EXCRESCENCE ON THE DRAG OF A FLAT PLATE TURBULENT BOUNDARY LAYER

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Abstract. *The drag generated by a three-dimensional cylindrical excrescence placed in a flat plate turbulent boundary layer was investigated experimentally. A number of turbulent boundary layer features were measured to validate the experimental setup. Velocity profiles across the wake were measured with a Pitot-tube traverse system and the momentum method was used to evaluate the drag. The results were compared with those found in the literature and the influence of the measuring station is discussed.*

keywords: *excrescence, parasite drag, flat plate, turbulent boundary layer*

1. Introduction

The drag coefficient is an extremely important parameter for the aeronautical project. This is due to the fact that the performance of the aircraft is related to this coefficient. An example of these aspects is the fuel consumption. It is according to the consumption of the aircraft that the range and the useful take off loading are defined, items that are indicative of the performance of the aircraft. In view of the strong competition observed in this sector, the knowledge of the influence of excrescences in the drag of an aerodynamic surface is a factor that can be decisive for the success of the project of an aircraft. Therefore such a study is of industrial interest.

The aerodynamic drag can be subdivided into different types, deriving of the viscous forces and pressure forces. The drag focused in this work is the parasite drag, produced by a cylinder mounted on a flat plate on which a turbulent boundary layer developed. This was intended to simulate in a simplified form the effect of the excrescences located on the surface of an aircraft.

According to Young and Paterson, 1981 the additional drag generated by an excrescence results from the interaction among various factors such as Mach number, Reynolds number and excrescence geometry.

Following Kundu et al., 2000 the excrescence drag corresponds to about 8 to 12 percent of the total cruise drag of an aircraft, but can reach values up to 20 percent.

In the current work a methodology was tested to measure the drag generated by a cylindrical excrescence placed in a flat plate turbulent boundary layer. The Pitot-tube traverse method was used to measure the velocity profiles across the wake.

2. Literature Review

The demand for high performance aircraft with low fuel comsumption has stimulated the research on the reduction of all types of drag. Increasing attention was given both in trying to eliminate unnecessary excrescences and in reducing the drag of those excrescences that cannot be removed. Wieghardt, 1946 presents results of tests for a number of forms of excrescences totally immersed in the boundary layer, in low speeds and low Reynolds number flows. Gaudet, 1987 carried out a program of tests covering a large range of Reynolds number for some common forms of excrescences. A comprehensive compilation of results for a number of forms of excrescence totally or partially immersed in the boundary layer for various flow conditions can be seen in Young and Paterson, 1981. In ESDU90029, 1993 some excrescences are analyzed taking into account other factors such as pressure gradients and cross flow. This was done with the aim of reproduce real conditions of flow in the aircraft flight. Special attention to cylindrical excrescences is given in ESDU83025, 1983. In all the cited

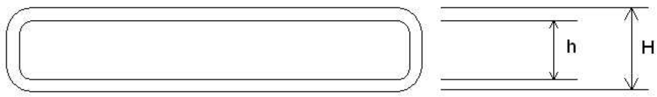

Figure 1: Pitot tube frontal section

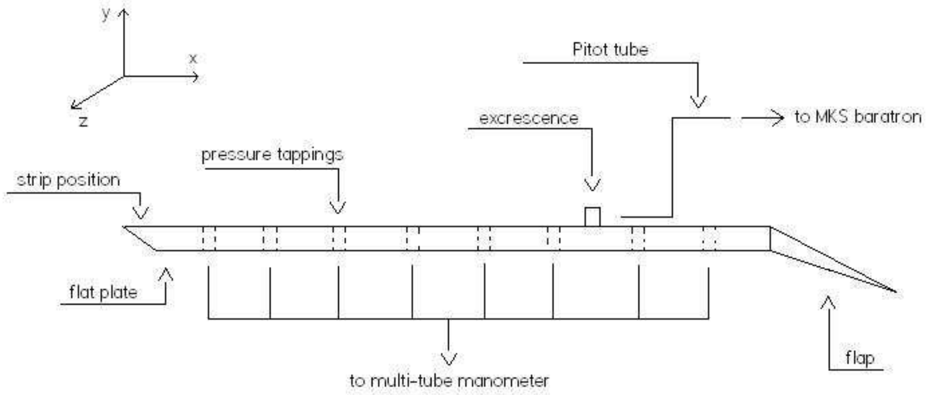

Figure 2: Experimental setup

works strain gauged balances mounted on wind tunnels were used. The drag attributed to the excrescence was the difference between the drag generated for the flat plate with the excrescence and without it.

The results obtained in the currrent work were compared with those extracted from the references cited above in order to evaluate the tests and the developed methodology.

3. Experimental set up and procedures

The tests were carried out in an open circuit wind tunnel whose test section measured 0,40mx0,35m. The free stream turbulence level was of the order of 0.15 percent. The 0.5mx0.35m flat plate was mounted horizontally along the center line of the tunnel. The sandpapered and polished cylindrical excrescence, with 0.01m in diameter(d) and 0.013m in height was mounted on the center line of the flat plate, 0.356m from the leading edge. The boundary layer was tripped to turbulent with a roughness strip placed at 0.01m from the leading edge. The free stream velocity was 8.3m/s. The total pressure probe was flattened to $H/h = 0.6$, fig.(1), as suggested by Ismail, 1998; Chue, 1975.

The measurements were taken at 0.1m from the excrescence. This was equivalent to ten times the cylinder diameter. The probe was positioned by a home made traverse system of two degrees of freedom with vertical resolution of 0.01mm and spanwise resolution of 0.4mm. The total pressure from the Pitot-tube was measured by the MKS Baratron with a resolution of 0.001mm of Hg column. For the measurement of the static pressure there were along the plate 22 pressure tapings that were connected to a multi-tube manometer. A flap mounted at the trailing edge of the plate was used to control the pressure gradient.

A flat plate turbulent boundary layer has well established characteristics, Schlichting, 1969. In order to test the experimental set up prior to the experiment, velocity profiles were measured without the excrescence. It was assumed that transition to turbulence took place at the roughness strip. The velocity profiles were compared with the universal velocity distribution law. The displacement thickness was measured and compared with the theoretical results given in Schlichting, 1969.

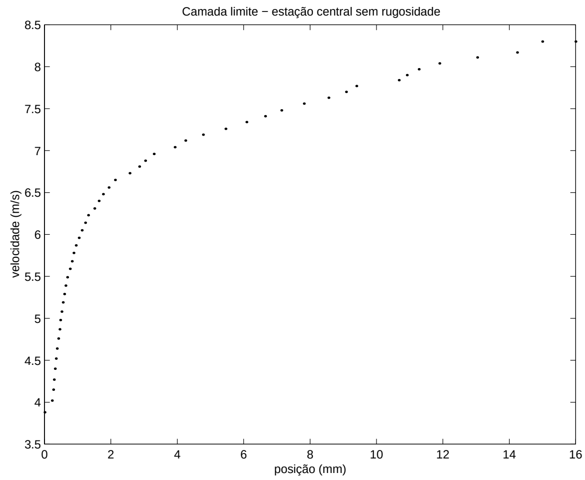

Figure 3: The flat plate turbulent boundary layer, central station

The momentum method was developed to the measurement of the profile drag, see Schlichting, 1969; Goett, 1938. The momentum difference between two planes, one upstream and one downstream of the excrescence represents the drag due to the excrescence plus the drag of the plate between the measuring planes. In the present work, to obtain the drag from an excrescence it was enough to compare the momentum between a flow with the excrescence and the flow without it, measured at the same posotion downstream of the excrescence. The difference between the measured momentum with the excrescence and that without it furnishes the parasite drag directly:

$$D_{excrescence} = (\int\int \rho\vec{U}(\vec{U}\cdot\vec{ds}))_{without\ excrescence} - (\int\int \rho\vec{U}(\vec{U}\cdot\vec{ds}))_{with\ excrescence} \quad (1)$$

The planes where the velocity profiles were integrated, measured 16mm in y by 30mm in z. The position where profiles were taken were separated by 5mm in the spanwise direction. Corrections were applied in the velocity profiles measured in all the stations to compensate for the effect of velocity gradients and wall proximity. The last measurement station was that where the velocity profile were sufficiently close to that measured without the excrescence for the same z position.

4. Results and Discussion

4.1. Characterization of the turbulent boundary layer

Figure(3) shows the velocity profile measured at the center of the flat plate at distance of 454mm from the leading edge.

The displacement thickness (δ^*) of the turbulent boundary layer is given by:

$$U\delta^* = \int (U_\infty - u)dy$$

Using the equation above, the profile in fig.(3) yields $\delta^* = 1,783mm$.

The value above was found using the trapezoidal integration method.

The value quoted by Schlichting, 1969 for a turbulent boundary layer with a transition point at the leading edge is $\delta^* = 1,813mm$. This is in agreement with the current experiment.

Figure(4) shows the measured velocity profile in a logarithmic scale. The values of the wall shear stress and of the friction velocity were evaluated from the points closer to the wall in fig. (3). These values agreed very well with those found in the literature. The measured logarithmic profile does not agree completely with that found in literature. However, this was expected in view of the fact that the Reynolds number in the current experiment was very low. In fact, in the current experiment the Reynolds number was out of the range of the logarithmic law. The Reynolds number was chosen to enable a comparison between the excrescence drag of the current work and the better established results found in the literature.

5. Momentum method for determining parasite drag

Figure(5) shows the measured profiles at various spanwise stations in the boundary layer with the roughness. It shows that the maximum momentum loss is not just behind the excrescence. The maximum momentum loss

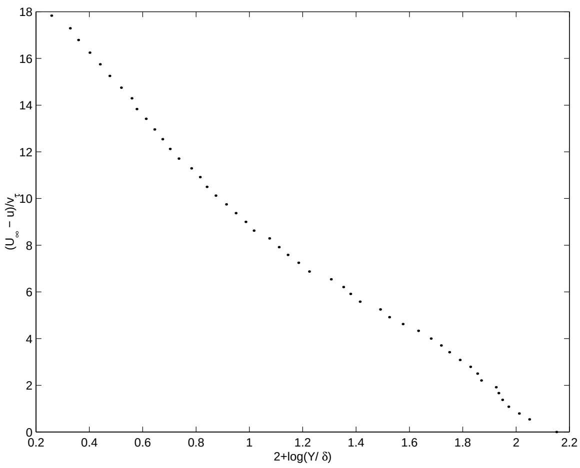

Figure 4: Turbulent boundary layer without excrescence, logarithmic velocity-distribution law

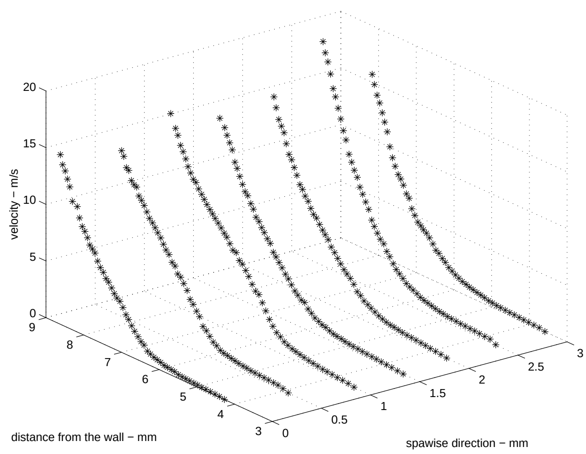

Figure 5: The flat plate turbulent boundary layer with roughness at various spanwise stations

is at the third spanwise station measured. This is probably due to the complex vortex formation, see Park and Lee, 2000.

Figures(6) to (12) show the velocity profiles measured at various spanwise stations in the boundary layer with the excrescence and without it.

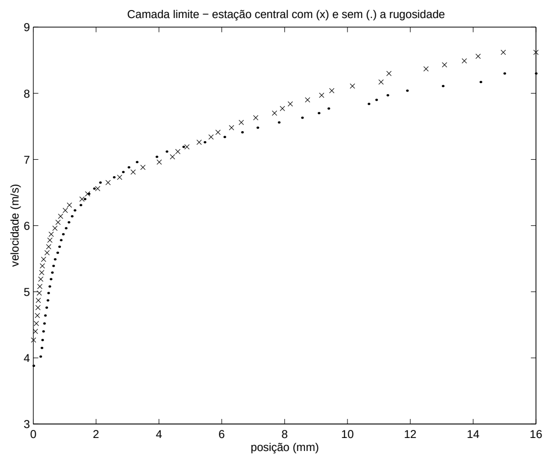

Figure 6: Turbulent boundary layer - central station - (x) with the excrescence (.) without it

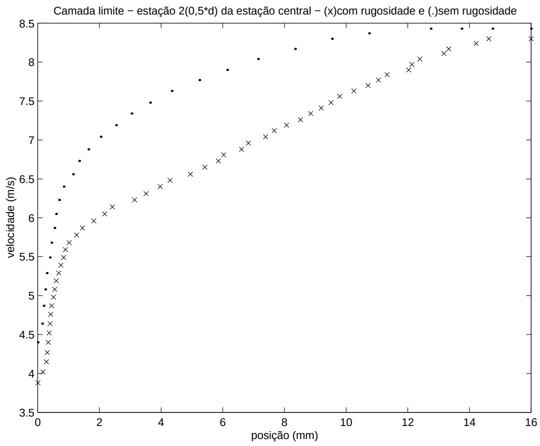

Figure 7: Turbulent boundary layer at 0.5*d from the central station - (x) with excrescence (.) without it

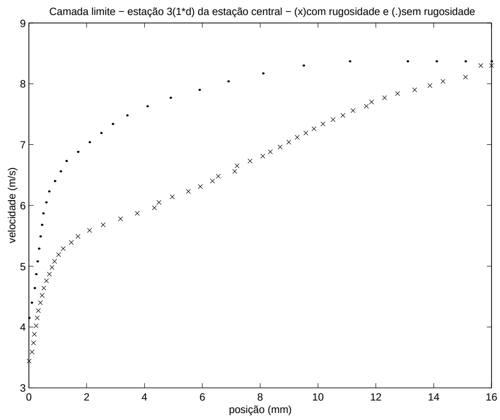

Figure 8: Turbulent boundary layer at 1.0*d from the central station - (x) with the excrescence (.) without it

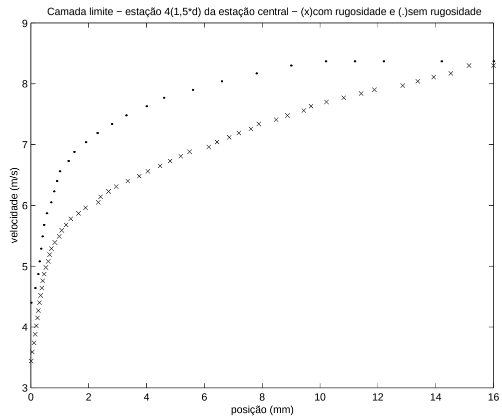

Figure 9: Turbulent boundary layer at 1.5*d from the central station - (x) with excrescence (.) without it

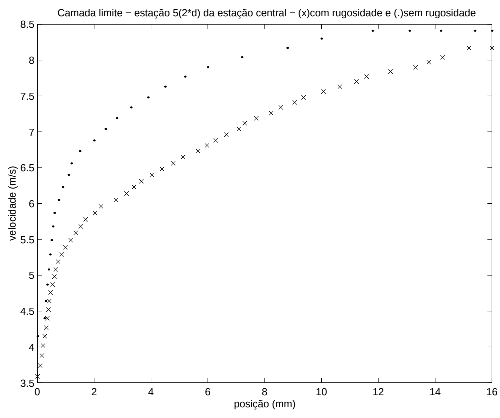

Figure 10: Turbulent boundary layer at 2.0*d from the central station - (x) with the excrescence (.) without it

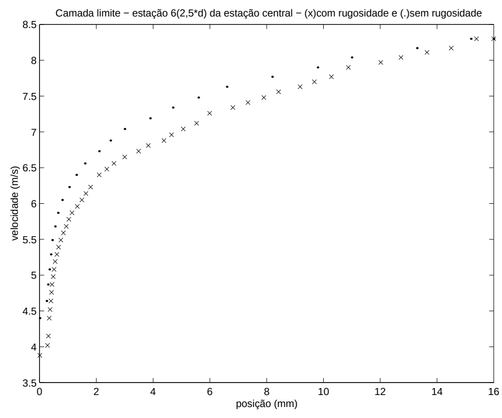

Figure 11: Turbulent boundary layer at 2.5*d from the central station - (x) with excrescence (.) without it

The measurements were taken only at the right hand side of the excrescence. At the other side only two profiles were taken. As they compared favorably with those at the right hand side, fig.(13) and fig.(14), was considered unnecessary to measure the profiles at both sides of the excrescence.

Using these velocity profiles and eq.(1) the drag was evaluated. For a cylindrical excrescence at the same

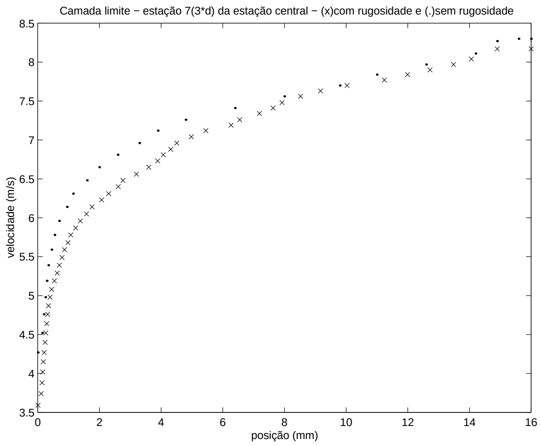

Figure 12: Turbulent boundary layer at 3.0*d from the central station - (x) with the excrescence (.) without it

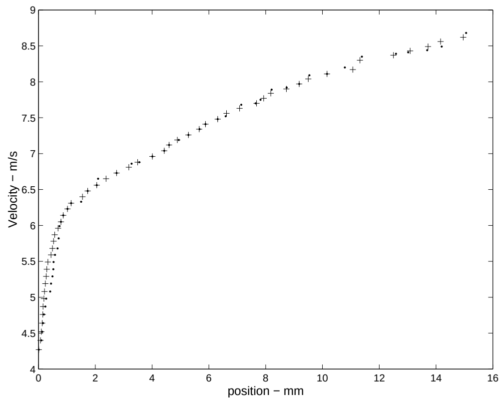

Figure 13: Turbulent boundary layer with the excrescence at 0.5*d from the central station - (+)left hand side (.)right hand side

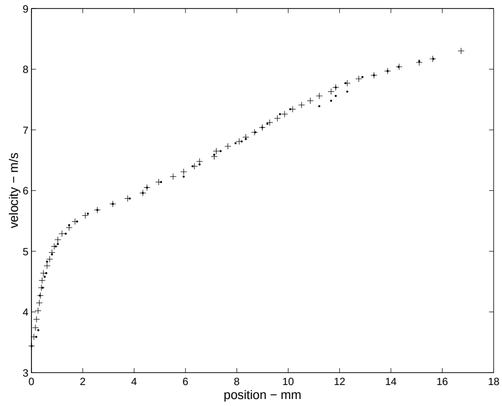

Figure 14: Turbulent boundary layer with the excrescence at 1*d from the central station - (+)left hand side (.) right hand side

conditions, the literature (ESDU83025, 1983; Gaudet, 1987; Young and Paterson, 1981; Winter and Gaudet, 1967) gives values in the range of:

$$D_{literatura} = 0,0039N \sim 0,0048N$$

The experimental value found here was:

$$D = 0,0088N$$

Note that in the current experiment it was not possible to obtain a zero pressure gradient flow. The values given in the literature for the case with zero pressure gradient should be corrected to be compared with the current result.

As showed in Nash and Bradshaw, 1967; ESDU90029, 1993, magnification factors can be used for the correction of the parasite drag in the presence of pressure gradients. However, the method due to Nash and Bradshaw, 1967 is limited to two-dimensional excrescence. The literature does not give corrections for the drag from three-dimensional excrescence as treated in the current work. The magnification of the drag (from literature) leads to the following drag range:

$$D_{literatura} = 0,0057N \sim 0,0068N$$

The effect of an excrescence on the drag of a body can be divided into two parts: there is the drag of the excrescence itself and the effect of the excrescence on the profile drag of the body. The second is related to the fact that the boundary layer downstream of the excrescence differs from that which developed on a similar body, but without the excrescence. Most studies consider only the first part, namely, the drag on the excrescence. That is because they restrict the measurements to a region close behind the excrescence. In the current work the drag was measured further downstream, and includes a larger portion of the second part of the drag. It is as yet unclear how far downstream of the excrescence the drag should be measured. In principal, it is unclear if the boundary layer will ever recover the characteristics of the case without an excrescence. If that was so, the effect of the excrescence would disappear, and there would be no drag associated with it. What happens is that, since the excrescence is three-dimensional and localized, its wake is diffused in the spanwise direction and the effect of the excrescence eventually contaminate the regions that are quite far from it.

It is also unclear whether the effect of the excrescence on the profile drag is to increase or decrease in comparison to the case without the excrescence. That is because the boundary layer behind the excrescence has various regions of downwash and upwash. The upwash regions displays a reduction is friction drag, whereas the downwash regions shows an increase. But the total balance is not easily determined. The current result tends to suggest that the overall effect is to increase the friction drag. The situation would be even more complicated if an airfoil were considered. In that case the profile drag includes a pressure drag. The pressure drag is associated with the boundary layer thickness. The pressure drag is increase in the upwash reagion, where the boundary layer is thicker. Therefore, the effect is reversed as compared to that of the friction drag.

The problem with the drag related with the boundary layer downstream of the excrescence has not been systematically dressed in the literature. There is a possibility that the roughness will have a permanent effect on the boundary layer downstream, producing some kind of scar in the flow. If that is so, the measured drag will depend on the distance from the roughness. This might be linked to the difference found. This may also raise an important issue, with apparently has not been analyzed previously, namely, how to define the drag from an excrescence, or whether or not its definition should invoke a distance from the roughness.

6. Acknowledgements

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