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Boundary Layer Trip Size Selection on Streamlined Bodies of Revolution

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Abstract

When testing models in wind tunnels, roughness devices are often used to trip the flow so that the boundary layer transition on the model is "similar to" that on corresponding full-size vehicles. It is not a simple matter to determine the size and type of tripping device to use for a given application. An investigation has been undertaken in the low-speed wind tunnel at DSTO to demonstrate a method that can be used to match the size of a circular wire tripping device with a free-stream velocity to obtain a correctly-stimulated turbulent boundary layer on a body of revolution. The technique used by Erm & Joubert [3] in their flat-plate boundary-layer studies has been adapted and involves measuring skin-friction coefficients with a Preston tube at various axial positions along the model using tripping devices of different sizes for a range of free-stream velocities. The behaviour of the measured skin-friction-coefficient distributions is used to match sizes of devices and velocities to obtain correctly-stimulated flow. Only circular wire tripping devices are considered in the current study.

Introduction

Whenever a model is tested in a wind tunnel, an attempt is made to satisfy similarity requirements so that the tunnel tests are representative of the operation of a full-size vehicle. For low-speed flows, Reynolds-number (*Re*) similarity is by far the most important similarity condition that must be considered. Due to practical difficulties arising from constraints on tunnel size, model size, testing velocity, density and pressure, *Re* similarity is generally not achieved. It is also important to ensure that the boundary layer on the model and full-size vehicle are similar to the extent that laminar, transitional and turbulent flows occur over corresponding regions. On a model the transition location is fixed using a suitable tripping device located at a geometrically similar position to where natural transition is expected on a full-size vehicle. A wide range of tripping devices have been used by researchers, including circular wires/tubes, distributed grit and pins. Such devices, when firmly attached to the surface of a model, are termed passive devices. Tripping devices can also be active, such as suction/blowing arrangements, and vibrating wires or ribbons. Only passive devices are considered in the current study. In the present paper, a method is proposed to determine the "correct size" of a fixed circular wire tripping device to use to achieve suitable transition and streamwise evolution of the turbulent boundary layer on a streamlined body of revolution, representative of a bare hull of a submarine model at a given *Re*. The method used is an extension of that developed by Erm & Joubert [3] for flow over a flat plate in a zero pressure gradient. The work presented in this paper is part of an experimental investigation undertaken at the Defence Science and Technology Organisation (DSTO) by Jones *et al*. [11].

Boundary-Layer Transition

Boundary-layer transition is a complicated physical process dependent on instability mechanisms, including Tollmien-Schlichting waves, crossflow and Gortler instabilities – see Reed & Saric [14]. Over the years, there have been numerous articles published on transition, both from experimental investigations and CFD analyses, in low-speed, transonic and hypersonic flow regimes – see, for example, IUTAM Symposium Proceedings, edited by Schlatter & Henningson [15]. Details of the transition process are still not fully understood. In the present paper, the transition physical processes are not considered, but instead attention is focused on how to stabilize the position of the transition using a tripping device and to ensure that the turbulent boundary layer is not under or over stimulated, irrespective of the flow physics associated with transition.

Expressions to Determine Sizes of Tripping Devices

A diagrammatic representation of a boundary layer being tripped is shown in figure 1. Researchers have proposed different empirical expressions for determining the size of device to use to trip the flow. The relationships incorporate parameters including the height of the tripping device, d, the free-stream velocity, U, the velocity in the boundary layer at the top of the device, u_d, and the wall friction velocity at the device, $u_\tau(x_d) = \sqrt{[\tau(x_d)/\rho]}$, where τ is the wall shear stress in a boundary layer, ρ is the fluid density, and ν is the fluid kinematic viscosity. Recommendations for fully-effective tripping cover quite a wide range. Tani, Hama & Mituisi [17] proposed the criterion $u_\tau(x_d)d/\nu = 15$, Fage & Preston [4] proposed $u_\tau(x_d)d/\nu = 20$, Braslow & Knox [1] proposed $u_d d/\nu = 600$, and Gibbings [5] proposed $Ud/\nu \approx 826$.

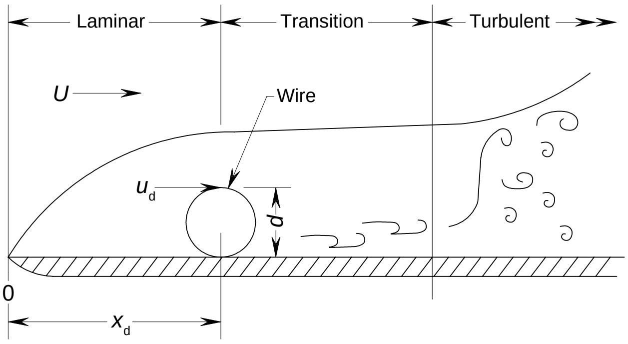

Figure 1. Diagrammatic representation of a boundary layer being tripped.

Such relationships do have their shortcomings and can only be used as a guide. They do not take into account factors that can affect the transition process on a model (effects commonly referred to as the initial disturbance spectrum), including the roughness of a model, tunnel free-stream turbulence level, pressure gradient over a model, noise generated by the tunnel wall boundary layers, vibration of a model, and irregularities in the free-stream, such as slight spatial variations in flow angularity. To use the relationships, it is first necessary to measure the required parameters without a tripping device in place.

Devices used by different researchers on bodies of revolution are given in table 1, together with some details of their experiments - different devices have been used, located at different distances along models, expressed as a percentage of a model length, *L*.

The above formulae can provide a guide on the sizes of devices to use on a given model in a given tunnel, however, for non-flat-plate geometries, the trip size should be determined on a case-by-case basis from dedicated measurements on the model in the test tunnel. The size of device to use on a given model tested in a given tunnel may be different from the size of device to use on the same model in a different tunnel.

Experimental Programme

Low-Speed Wind Tunnel

Tests were carried out in the continuous circuit Low-Speed Wind Tunnel (LSWT) at DSTO. The test section has an octagonal shape with a height of 2.13 m, a width of 2.74 m and a length of 6.553 m, and the turbulence intensity is 0.4% , see Erm [2].

Model and Tripping Devices

The model used in these tests was machined from aluminium and consists of an ellipsoidal nose, a cylindrical centre-body and a streamlined tail section, as shown in figure 2. At the design stage, an N6 surface finish was specified for the model, which corresponds to a roughness of 0.8 μm (distance between peaks and troughs). After manufacture, the surface finish was checked using a Surface Roughness Indicator, and the finish was found to be better than the design specification. The model was anodised, which increased the thickness of the natural oxide layer by about 10 μm. The full model includes a casing, centre fin and control surfaces, but no measurements were taken in the current series of tests with these components fitted. The model has a length of 1348.6 mm and a maximum diameter of 184.6 mm and was supported by a single pylon as shown. All tests were carried out at zero angles of pitch and yaw. The origin of the body coordinate system is located at the nose of the model. The *x* axis corresponds to the axis of symmetry of the model and is positive in the downstream direction, the *y* axis is positive to port and the *z* axis is positive vertically downwards.

Circular wire tripping devices having diameters of 0.1, 0.2 and 0.5 mm were glued to the model around its circumference at an *x* distance of 67.4 mm from the nose, corresponding to 5% of the model length, which is thought to be the approximate position of transition on a full-size vehicle of similar shape to the model. In the current study, the effect of different locations of the tripping device has not been investigated.

Measurement of Skin-Friction Coefficients Using Preston Tube

Skin-friction coefficients, C_f, were measured using a Preston tube having a diameter of 0.6 mm – see Preston [13] and Patel [12] for details of the measurement technique. Preston tubes only give meaningful values of C_f in turbulent boundary layers and cannot be used to measure values of C_f in laminar or transitional flows.

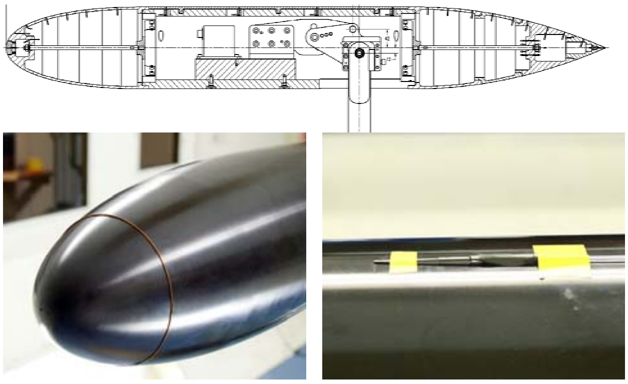

Figure 2. Axisymmetric model (top), tripping wire on model (bottom left), Preston tube on top of model (bottom right).

Details of Tests

The Preston tube was mounted on the uppermost meridian on the model at different *x* locations and skin-friction coefficients were measured – see figure 2. For the 0.2 and 0.5 mm trip wire, measurements were taken at 18 stations between $x = 73$ mm and $x = 1065$ mm. For the 0.1 mm trip wire, measurements were limited to 3 stations between $x = 305$ mm and $x = 442$ mm. Data were acquired for free-stream velocities ranging from 40 to 70 m/s in increments of 5 m/s. For this velocity range, the Reynolds numbers based on the length of the model varied from 3.58×10^6 to 6.27×10^6. Similarly, for the same velocity range, Reynolds numbers based on the diameter of the 0.1 mm wire varied from 266 to 465, those for the 0.2 mm wire varied from 531 to 930, and those for the 0.5 mm wire varied from 1330 to 2320. This range covers the value recommended by Gibbings [5] of 826 for a flat plate boundary layer.

Analysis of Experimental Data

Previous Experiments Using a Flat Plate

As already indicated, the purpose of the current investigation was to determine the best size of circular wire tripping device to use to trip the boundary layer on the model. Erm & Joubert [3] faced a similar question in their studies on low-Reynolds-number flows over a smooth flat surface in a zero pressure gradient. For different types of tripping devices, they measured longitudinal skin-friction coefficients for a range of free-stream velocities. Their data for a 1.2 mm wire tripping device, plotted in the form C_f versus *x*, are given in figure 3. The dashed regions of the curves, corresponding to pre-transitional regions, are quantitatively incorrect since Preston tubes do not give meaningful C_f measurements in laminar or transitional flow. It can be seen that as the velocity is increased from 8 m/s, the laminar-to-turbulent transition region moves upstream. They conjectured that correct stimulation is associated with a particular curve when the peaks of successive curves, corresponding to higher velocities, do not advance significantly upstream. Since the velocity corresponding to the particular curve establishes a turbulent boundary layer

Researchers	Model	Air/Water	Length/Diam of Model (mm)	Tripping Device (mm)	Location of Device from Nose (% *L*)	Free-Stream Velocity (m/s)	Reynolds Number $\times 10^6$
Groves *et al*. [7]	Suboff	Both	4356/508	Wire: $d = 0.635$	5	Not given	Not given
Watt *et al.* [18]	Submarine	Air	6000/?	3 dimensional	3		23
Wetzel & Simpson [19]	Prolate Spheroid	Air	1370/229	Not given	20	45	4.2
Whitfield [20]	Darpa2 Submarine	Air	2236/267	Cylindrical Pins: $h = 0.76$, $d = 1.27$	13.6	30.5, 42.7	4.2, 6.1
Hosder [8]	Darpa2 Suboff	Air	2240/?	Cylindrical Pins: $h = 0.76$, $d = 1.28$, $s = 2.5$	10	42.7	5.5
Gregory [6]	Bodies of rev'n straight, bent	Air	2580/260	Cylindrical Pins: $h = 0.2$, $d = 0.3$, $s = 1.27$	5	15	2.58
Jimenez *et al*. [9]	Suboff	Air	870/101.6	Wire: $d = 0.51$	8.79		1.1 to 67
Jimenez *et al*. [10]	Suboff	Air	870/101.6	Wire: $d = 1.0$	2.92		0.49 and 1.8

Table 1. Summary of tripping devices used by researchers, *d* is wire or pin diameter, *h* is pin height, *s* is pin spacing.

almost to the possible upstream limit of turbulent flow, they indicated that it seemed reasonable to assume that the main effect of higher velocities was to over stimulate the flow. Velocities lower than that corresponding to the particular curve were obviously associated with under-stimulated flows since the peaks of the curves were well downstream of the device and thus the device was therefore not completely effective in tripping the flow. It is apparent from figure 3 that the above condition for correct stimulation was satisfied when the velocity was 10.0 m/s. The method can be used to match device size and testing velocity to obtain correctly-stimulated flows. The above methodology was applied to tests in the LSWT to determine the appropriate size of wire tripping device to use on the model.

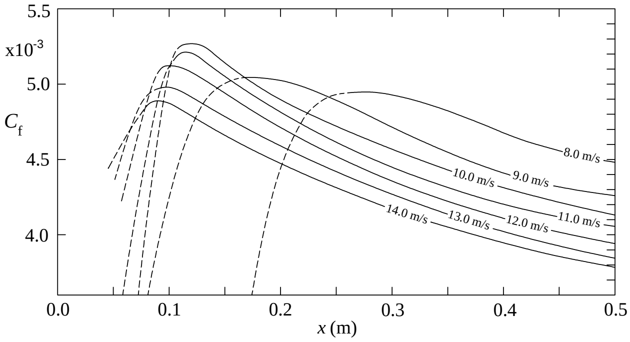

Figure 3. C_f *vs* x for a 1.2 mm diameter wire tripping device for different velocities, as obtained by Erm & Joubert [3].

Skin-Friction Coefficients Measured in the Current Tests

Figure 4 shows plots of C_f versus x for the current experiments for the case of no tripping device. The boundary layer is initially laminar and at some stream-wise coordinate natural transition occurs, corresponding to the sharp rise in the C_f curves. Similarly, figure 5 shows C_f data for the case of a 0.2 mm diameter wire tripping device. Figure 6 shows a limited number of C_f measurements made with a 0.1 mm wire device at stream-wise stations of 305, 360 and 442 mm, as well as data for the cases of no device and the 0.2 and 0.5 mm wires, for the complete velocity range. As for the flat-plate data, dashed parts of curves correspond to pre-turbulent flow and are quantitatively incorrect.

Applying the reasoning for the flat-plate studies to the current tests, it is evident from figures 4 to 6 that a 0.2 mm wire tripping device is effective in tripping the boundary layer at the lowest velocity used, i.e. $U = 40$ m/s, as well as at higher velocities. From figure 6 it can also be seen that a 0.1 mm wire tripping device clearly under stimulates the flow for velocities less than about 60 m/s, so that the start of the turbulent region for such velocities is unacceptably too far downstream from the tripping device to carry out meaningful tests on the model.

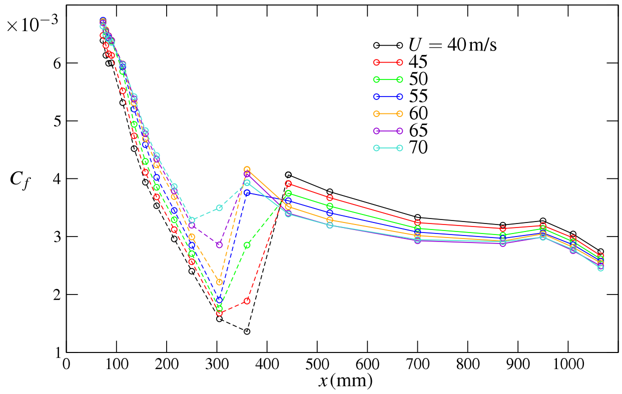

Figure 4. C_f *vs* x for no tripping device for different free-stream velocities for model tests in LSWT.

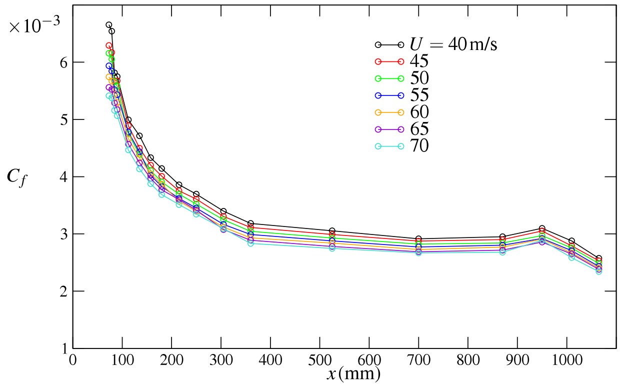

Figure 5. C_f *vs* x for a 0.2 mm wire tripping device for different velocities for model tests in LSWT.

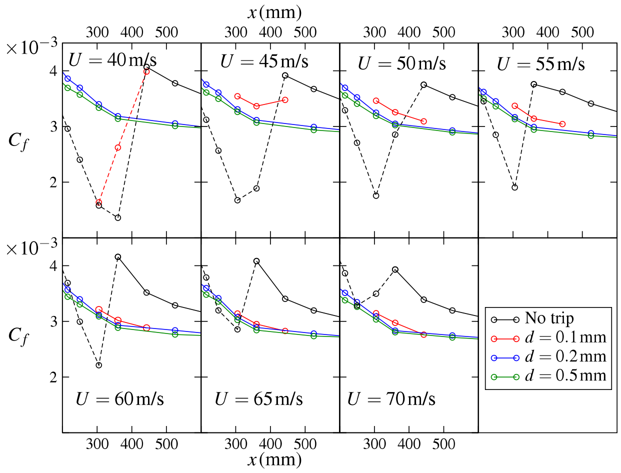

Figure 6. C_f *vs* x for 0.1, 0.2 and 0.5 mm wire tripping devices, plus no tripping device, for different velocities for model tests in LSWT.

From the model tests it can be concluded that the smallest wire tested in the investigation that successfully trips the boundary layer across the velocity range 40 to 70 m/s is 0.2 mm in diameter. Perhaps a wire tripping device having a diameter between 0.1 and 0.2 mm would be a better option, but tests using such wires were not carried out to study their effectiveness. A 0.2 mm trip wire would progressively over stimulate the flow as velocities are increased above 40 m/s, but such a wire would be used over the velocity range since it is impractical to change a tripping device on a model for each velocity used for tests. For the 0.2 mm wire, the minimum Reynolds number is 531, based on wire diameter, to successfully trip a boundary layer. It is important to emphasise that the above findings are only applicable to the current model in the LSWT facility. The size and type of device to use on the model in other facilities may be different, as explained earlier.

For a flat-plate turbulent boundary layer in a zero pressure gradient, C_f approximately scales with $Re_x^{-0.2}$ (Schlichting [16]), where Re_x is the Reynolds number based on the stream-wise coordinate. This scaling can be used to achieve reasonable collapse of the correctly-stimulated or over stimulated C_f data across the velocity range of the experiments, as shown in figure 7, where the product $C_f\, Re_x^{0.2}$ is plotted against x. As can be seen, differences between data for the 0.2 and 0.5 mm wires are most evident directly downstream of the devices, which is consistent with the fact that the 0.5 mm wire is over stimulating the layer, particularly at the higher velocities. For comparison, data for an untripped case for $U = 40$ m/s and an under-stimulated case for a 0.1 mm wire for 40 m/s, are shown in figure 7. It is clear that the 0.1 mm wire fails to correctly stimulate the layer at 40 m/s and the data are close to those for the untripped case. While data for the untripped layer becomes turbulent at about $x = 400$ mm, the subsequent evolution of the turbulent skin friction is very different from that for the tripped data. This highlights the importance of correctly stimulating a boundary layer (trip size) and of placing the trip at the correct x location.

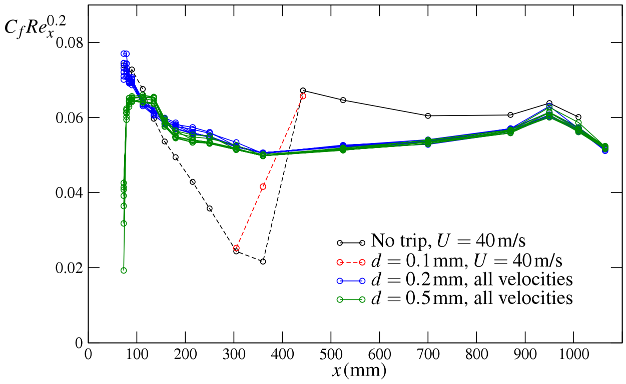

Figure 7. $C_f Re_x^{0.2}$ *vs* x for 0.1, 0.2 and 0.5 mm wire tripping devices, plus no tripping device, for different free-stream velocities for the model tests in the LSWT

Concluding Remarks

When testing a model in a tunnel, it is often necessary to attach a tripping device to the model to stabilise the position of transition from laminar to turbulent flow. A question that researchers must address is "what is the correct size and type of device to use for a proposed test velocity". Published relationships can only be used as a guide since they do not take account of factors affecting transition that are unique to a given tunnel.

An experimental iterative technique has been used in the current wind-tunnel facility to obtain correctly-stimulated turbulent boundary layers. The technique involves measuring skin-friction coefficients along the model using a Preston tube for wire tripping devices of different sizes, each tested at a range of free-stream velocities. Only circular-wire tripping devices were considered in the current study.

Turbulent skin-friction coefficients were measured along the uppermost meridian of an axisymmetric model for free-stream velocities varying from 40 m/s to 70 m/s for the case of no tripping device and for wires of diameter 0.2 and 0.5 mm, with a limited number of measurements taken using a 0.1 mm wire. The tripping devices were located 67.4 mm downstream of the nose of the model, which corresponds to 5% of its length.

As an outcome of the investigation, it was found that a wire of diameter 0.2 mm was the preferred option to trip the boundary layer for subsequent tests in the tunnel. Such a device produced acceptable skin friction distributions on the model for the velocity range tested. A wire of diameter 0.1 mm was found to under stimulate the flow

Further work is required to quantify the boundary-layer profile on the scale model, which would provide an improved means of assessing the effectiveness of the tripping devices used. In addition, the use of small wire tripping devices could introduce errors into the measurements due to the difficulty in locating and attaching them to the surface of the model. Alternative tripping devices, such as cylindrical pins, need to be considered.

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