A Technique for the Investigation of Boundary Layer Development on Rough Surfaces

D. K. Das*

Abstract :

A very simple but unique method of replicating rough surfaces and hence making an experimental pipe-line has been described.

A method of determining the error in the origin of velocity profile on rough surfaces and hence calculating some important TBL characteristics has also been described.

NOTATION

B = Law of the wall co-eff.

H = Shape factor = $\frac{\delta_1}{\theta}$

u_∞ = Free-stream velocity

c_f = Skin friction co-eff.

k = von Karman constant

u = Local mean velocity

u_o = Wall shear velocity

u', v' = Fluctuating velocity constants

y = Velocity profile ordinate from the datum

$\in$ = Virtual error in origin

ν = Kinematic viscosity

δ = Boundary layer thickness

δ_1 = Displacement thickness

θ = Momentum thickness

$\frac{\triangle u}{u_o}$ = Velocity shift or Roughness function

$W\left(\frac{y}{\delta}\right)$ = Wake function.

Π = Coles' Wake parameter

TBL = Turbulent Boundary Layer.

Introduction :

For most practical applications, the solid surfaces (e.g ship-hulls, lifting surfaces of an air-craft, etc.) can not be considered hydraulically smooth, and the resistance to flow offered by rough surfaces is naturally larger than that by the smooth ones. H. Lackenby in 1962 in a review of ship reistance, has underlined the importance of the role played by skin friction on the resistance of ships. He reported differences of as high as 20% in power requirements between sister ships and these differences are attributed to be the result of differences in the surface textures of different ships. So the study of the development of turbulent boundary layers (TBL) on rough surfaces has become very important. Its imporance is accentuated by the ever rising cost of fuel, and since in as little as two years the resistance of the ship can increase by as much as 30%

*Associate Professor

Department of Mechanical Engineering, BUET, Dacca.

(because of the deterioration of surface-finish which is partly due to corrosion and partly due to marine growth) the problem of combating this has become urgent. It is felt that useful practical knowledge regarding this can be obtained by having some laboratory tests where actual ship-hull roughness replicas could be subjected to flow conditions identical to those in reatily with the provision of measuring the respective wall friction directly. A fully developed turbulent pipe flow in which the pressure drop cover a given length of pipe can be linked directly to the wall friction, seems to be the easiest method of securing the flow. Of course, such a pipe must be lined over its entire test section with the roughness in question. In the following section a technique of roughness-replication will be described first and then a method of obtaining some important chanacteristics of TBL on rough surfaces will be dealt with.

Roughness Replication :

The preparation of the mould (also called the negative of the rough surface) for an easily accessible surface i.e. a flat or slightly curved surface on the ground (but not a ship-hull) is very simple. This is done by using a chemical, trade-named "Vinamould" a hot pour compound which is liquid when heated to approximately 150°—170°C, but which solidifies rapidly on cooling. The moulding process consists of the selection of a suitable area on the rough surface concerned. The "Vinamould" is then heated (in a pan) and when a sufficient quantity of liquid is formed, the vinamould is slowly poured over the rough surface concerned, particular care being taken to provide a full and thick cover of the substrate. On cooling (about 5 mins.) the rubber patch is peeled from the surface very carefully and this gives the negative replica of the surface concerned.

But the Ship-hull surface or any other surface where pouring of liquid rubber is not as easy as described above, the negative replica is prepared in a completely different way as follows—

A sample area of required size is chosen on the shiphull in the dry dock. A thixotropic silicon rubber paste is applied to the surface using a fine quality paint brust to a depth sufficient to cover the surface roughness. A layer of fine glass fibre tissue matting, soaked with silicon rubber paste is then applied directly over the brushed area and rolled gently to avoid air bubbles. The cure time of the catalysed rubber depends on the amount and type of catalyst added and also on the ambient temperature, cold weather prolonging the cure time. When the patch is fully cured it is peeled off and taken to the workshop. The next stage is to lay the patch flat in a simple horizontal wooden frame work so that the rough surface is facing downwords and plaster-of-paris is poured over the back of the patch. When the plaster is set the whole rig could be turned over and the frame removed to yield the negative coppy of the rough surface. The plaster acted as a firm base for the rubber negative. At this stage it has to be decided whether the investigation of the development of TBL will be done by a wind tunnel (on a flat plate) or by a pipe flow technique. If a wind tunnel technique is to be used, a positive copy of the rubber negative is made on a suitable frame using an epoxy resin reinforced with a medium grade glass fibre matting; trim it to the required size to use it directly in the wind tunnel working seection. If a pipe flow techique is to be used, after trimming it to the required size (which is goverfned by the internal dimensions of the pipe-line), the positive epoxy resin roughness is again copied by pouring a free flowing silican rubber over its surface and allowed to cure. The final rubber negative is then wrapped around a wooden mandrill whose diameter is mechnied so that the combined effective diameter of the mandrill with the rubber negative is equal to the desired internal diameter of the pipe-lines. The rubber negative, of course has now been "circularised" around the mandrill in such a way that the desired negative roughness is on the outer surface. Alternate layers of epoxy resin and glass fibre matting are then applied to the rubber negative and allowed to cure. After rumoval of the mandrill and rubbeer negative a cylindrical plastic shell is left, the inside surface of which contains the original roughness. After trimming, the ends of the shell are machined to form the complete rough liner which can be used subsequently in the pipe-line.

Determination of some TBL characteristics :

Probably it is not an exageration if it is said that the ultimate aim of the investigation of TBL is to ascertain or predict the total drag force in the form of friction co-efficient as accurately as possible and to locate the separation under different physical conditions of the surface. To determine the local co-efficient of friction experimentally, one of the methods is to use the momentum integral equation—

$$\frac{d\theta}{dx}+(H+2)\frac{\theta}{u\infty}\cdot\frac{dU\infty}{dx}=\frac{c_f}{2}+\int_0^{\infty}\frac{u'^2-v'^2}{u\infty^2}\dots\quad\dots\quad(1)$$

The accuracy in determiming the displacement thickness and the momentum thickness as required by the equation (1) depends on the accurate plotting of the velocity profile. But plotting-velocity profile for a rough surface is not as

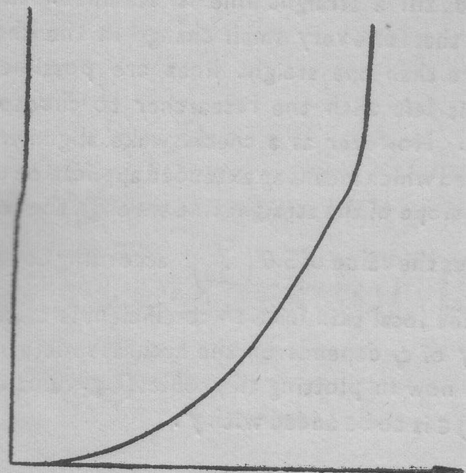

Fig 1 Velocity Profile on a Smooth Surface.

straight forward as it is for smooth one. Referring to fig. 1 and 2, it is seen that the origin of 'y' for the velocity profile on the rough surface is not known. Of course, the measurement can be started from an artifical datum which

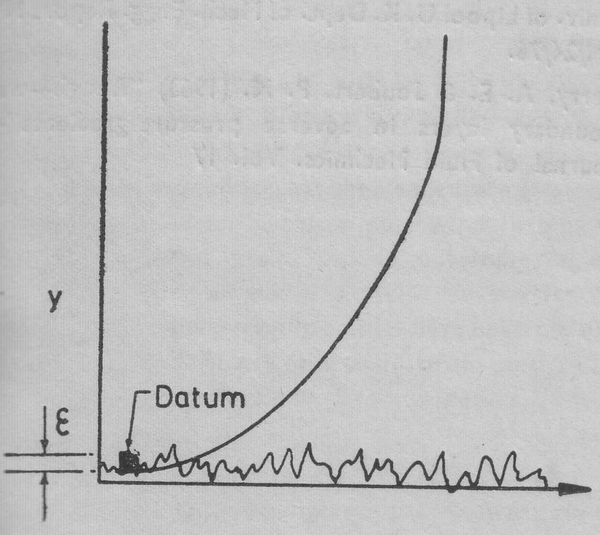

Fig. 2 Velocity Profile on a Rough Surface.

may be the crest of the local roughness element. The origin of the profile (i.e. y) is at some distance, $\in$ below the crest. The location of $\in$ (popularly known as virtual error in origin) is essential. A unique but very simple method of determining $\in$ is the one that uses equation of the TBL velocity profile. The velocity profile for a smooth surface is given as

$$\frac{u}{u_o} = \frac{1}{k} \ln \frac{y u_o}{\nu} + B + \frac{\Pi}{k} W(y/\delta) \quad \ldots \quad \ldots \quad (2)$$

Without the third term on the R. H. S. of equation (2) is known as the universal logarithmic law of the wall and on semilog plot of $\frac{u}{u_o}$ vs $\log \frac{y u_o}{\nu}$, this represtnts a straight line. But the experimental velocity profile of TBL on a rough surface shows that the logarithmic profile becomes distorted into a curve, and this distorsion is due to the error in origin of y. Now if the virtual error in origin (i.e. $\in$) can be located accurately and the profile is replotted with the corrected origin the logarithmic profile will appear as a straight line. While the correction in the origin is performed the local co-efficient of friction is also estimated. The accuracy of c_f depends on the accuracy of $\in$. This is done by rearranging equation (2).

For the rough surface equation (2) is modified as follows—

$$\frac{u}{u_o} = \frac{1}{k} \ln \frac{(y' + \in) u_o}{\nu} + B - \frac{\triangle u}{u_o} + \frac{\Pi}{k} W(y/\delta) \quad \ldots \quad \ldots \quad (3)$$

Multiplying both sides of the equation (3) by $\frac{u_o}{u_\infty} = \left(\frac{c_f}{2}\right)^{\frac{1}{2}}$, the following is obtained—

$$\frac{u}{u_\infty} = \frac{1}{k}\left(\frac{c_f}{2}\right)^{\frac{1}{2}} \ln \frac{(y' + \in) u_\infty}{\nu} + \left(\frac{c_f}{2}\right)^{\frac{1}{2}} \left\{ \frac{1}{k} \ln \sqrt{\frac{c_f}{2}} + B - \frac{\triangle u}{u_o} \right\} + \sqrt{\frac{c_f}{2}} \frac{\Pi}{k} W(y/\delta) \quad \ldots \quad \ldots \quad (4)$$

In equation (3) and (4) y is replaced by $y' + \in$ where y' is the measured distance from the top of the artificial datum. $\frac{\triangle u}{u_o}$ is known as the velocity shift (also known as roughness function). When plotted on the basis of $\frac{u}{u_o}$ vs $\log \frac{(y' + \in) u_o}{\nu}$ equation (3) (without the 4th term on R.H.S.) is represented by a family of straight parallel lines each being displaced downwards from the smooth wall profile (i.e. equaion (2) without 3rd term on R.H.S.) by an amount $\frac{\triangle u}{u_o}$. Equation (4) can also be written in a more experimentally convenient form such as

$$\frac{u}{u_\infty}=5{\cdot}6\left(\frac{e_f}{2}\right)^{\frac{1}{2}}\log(y'+\epsilon)+P+\frac{\Pi_\circ}{2}W(y/\delta) \quad \dots \quad \dots (5)$$

Where $P=\left(\frac{c_f}{2}\right)^{\frac{1}{2}}\left\{5{\cdot}6\log\frac{u_\infty}{\nu}\left(\frac{c_f}{2}\right)^{\frac{1}{2}}+B-\frac{\Delta u}{u_\circ}\right\}$

and $\Pi=\frac{k\Pi_\circ}{2}\left(\frac{2}{c_f}\right)^{\frac{1}{2}}$

Equation (5) is shown plotted on fig. 3. The circles represent

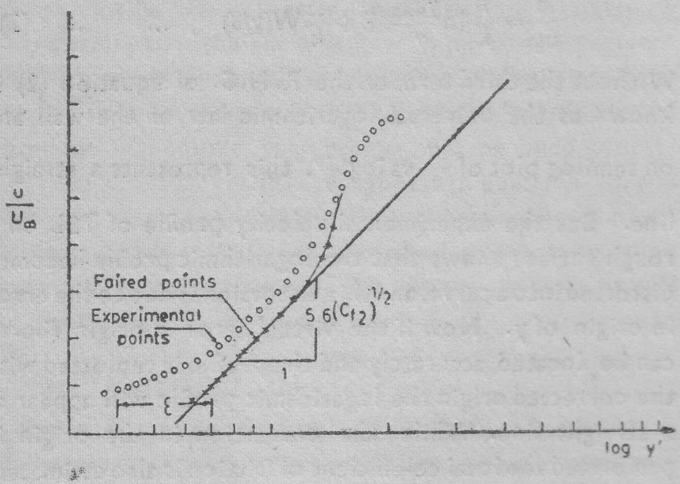

Fig. 3 Graphical Method of Determing Error in Profile Origin and Skin Friction.

the experimental points that would be actually plotted during a traverse, it being a plot of $\frac{u}{u_\circ}$ vs $\log y'$, Once the error ϵ is known, an addition of it to y' value would give the curve shown in full (through x's). The procedure of determining ϵ is somewhat a trial and error process. However, a good guess work always yields a very good result. To start with, a very small vlue of ϵ (it is advisable to choose a value, one third of the average roughness height) is chosen and added with the experimental ordinate (y') and an "eye-fit" is applied to see if considerable amount of the profile (10—15%) lies on a straight line. If still a curvature is existing the chosen value is increased and the process is continued till a straight line is obtained. It is always probable that for a very small change in the chosen-value of ϵ more than one sraight lines are possible. In this case, it is left with the researcher to choose the best fit curve. However as a check, wake alignment method can be used which means an extended application of equation (5). The slope of the straight line through the faired points (x's) gives the value of $5.6\left(\frac{c_f}{2}\right)^{\frac{1}{2}}$ according to equation (5).

Hence the local skin friction co-efficient is calculated. The accuracy of c_f depends on the accurate determination of ϵ. From now in plotting all profiles (e.g. velocity, logarithmic law) ϵ is to be added with y'.

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