Appraisal of Universal Wake Numbers
From Data for Roughened Circular
Cylinders

P. W. Bearman. I am pleased to see Professor Buresti returning us to the problem of universal Strouhal numbers. The derivation of the three numbers he has chosen to study all imply a unique relation between $SC_D$ (the product of Strouhal number and drag coefficient) and the base pressure parameter $K$. The accompanying figure indicates that available experimental data confirms this dependence. In addition I have plotted the functional relationships given by constancy of the three wake Strouhal numbers. Using free streamline theory to link $C_D$ and $C_{pb}$ ($C_Dd = -C_{pb}d'$) and assuming $S_r = 0.164$, the Roshko number gives rise to the relation $S.C_D = 0.164 K (K^2 - 1)$. This can be seen to overestimate the data at high $K$. My formulation (given in Bearman [2]) is invalid for large values of $K$. It is based on an interesting idea by Kronauer that vortex streets composed of point vortices arrange themselves into a configuration giving minimum drag. This appears now to have been a too simplistic approach to the real vortex street stability problem. Use of the number suggested by Griffin gives the best overall fit to the data although it overestimates $S.C_D$ for bodies of low bluffness.

The correlation between $S.C_D$ and $K$ suggests that regular vortex shedding is a result of an instability mechanism which is primarily inviscid. The success of the discrete vortex method in predicting Strouhal numbers of bluff bodies is a further indication of the unimportance of viscosity. Results presented in this paper, however, show the interesting result that wake Strouhal numbers depend on a roughness Reynolds number. An alternative parameter is the ratio of roughness height to cylinder diameter, does this also collapse the data?

When referring to different Reynolds number regimes for flow around a circular cylinder I would urge that the nomenclature used by Roshko [10] be followed. However I would endorse the author’s use of the term postcritical rather than transcritical to describe the highest Reynolds number range. The regimes then become subcritical, supercritical and postcritical. Roshko describes how each is separated by a transition regime. Regular vortex shedding can be detected through the sub and supercritical regimes but disappears in the upper transition range. Separation bubbles form on the cylinder in the supercritical regime and they break down at the commencement of the upper transition region. Professor Buresti calls the lower transition region the critical regime and states that it is typified by the absence of vortex shedding. Other authors, including most recently Schewe [11], have measured a distinct shedding frequency and hence the author’s statement is puzzling.

Additional References

Author’s Closure
I am grateful to Dr. Bearman for his discussion and particularly for his additional data which substantiate the results given in the paper about the possibility of describing the experimentally observed relation between $SC_D$ and $K$ by means of the three universal numbers considered. As regards the points raised by Dr. Bearman, I would like to start from the problem of the definition of the flow regimes. Indeed, it is certainly true that time has come for researchers to find an agreement on the nomenclature to be used for the flow regimes around circular cylinders. Therefore, I will accept and support Dr. Bearman’s proposal of calling the regimes, in order of increasing Reynolds number, subcritical, lower transition, supercritical, upper transition and postcritical. However, it is also important that we all agree on the phenomenological description of the transitional regimes. On this respect, I would like to remark...
that the curves of $C_D$ and $S$ as a function of $Re$ given by Roshko [10], Bearman [12] and Schewe [11], all refer to very smooth cylinders. The variations induced on these curves by even small quantities of surface roughness are dramatic and well documented (see [5] and [13]). Now, the definition of the flow regimes given in my paper applies to rough cylinders and its correspondence with the nomenclature proposed by Dr. Bearman is as follows: my critical regime corresponds to his lower transition, my supercritical to his upper transition, while the subcritical and postcritical regimes coincide. Dr. Bearman's supercritical regime, which corresponds to a low-$C_D$, high-$S$ plateau, is practically absent for rough cylinders.

The puzzle of the “missing vortex shedding” in the lower transition is easily explained if we recall that, as reported by Schewe [11], vortex shedding in this regime corresponds to a single bubble appearing on one side of the cylinder, a situation which is hardly possible unless the cylinder is smooth and the turbulence level of the wind tunnel low. I would also like to stress the fact that the peaks in the spectra of the lift force reported in [11] and [12] for this regime and for the supercritical one, are normally two orders of magnitude lower than those for the subcritical and postcritical regimes, and thus in the tests described in [5] they could have been masked by turbulence-induced fluctuations. In conclusion, I think that, as suggested by Berger and Wille [14], regular vortex shedding may take place only provided the separation of the boundary layer occurs along a straight line; now, in the transitional regimes of a very smooth cylinder in a low turbulence flow the separation bubbles are extremely unstable, and thus a long range of weak vortex shedding is observed. On the contrary, for a rough cylinder the transition range is much shorter and the bubbles, when they exist, are smaller and have a reduced range of existence. A quicker return to regular vortex shedding, corresponding to a stable separation of the turbulent boundary layer, is then possible, and this explains the absence of the instability phenomena in the upper transition regime which were found in [10] and [11].

I perfectly agree with Dr. Bearman on the observation that all evidence now available suggests that regular vortex shedding can appropriately be described with reference to fundamentally inviscid mechanisms, and I do not think that a moderate dependence of the wake numbers on the roughness Reynolds number contradicts this point. In fact, when we say that the phenomenon is mainly inviscid we mean that the vorticity is concentrated in thin sheets emanating from the separation points of the body. However, the resulting flow and pressure fields are very sensitive to the actual distribution of this vorticity, and therefore it is not unreasonable that slightly different parameters be found for different conditions (and in particular different momentum thicknesses) of the separating boundary layers. The accompanying figure shows that the ratio of the roughness height to the cylinder diameter $e/D$ does not give as good a collapse of the data as was given by $R_e$. This is not unexpected because $e/D$ is not sufficient to describe the effect of roughness on the transition between the flow regimes; in other words, the regime can be subcritical even for high values of the surface roughness if the Reynolds number is sufficiently low. Conversely, as shown in Fig. 4 of my paper, two distinct values of Griffin’s number seem to apply to the subcritical and to the roughness-induced post-critical regimes; it might be interesting to check if a further increase in Reynolds number for a rough cylinder does not give rise to a decrease of $G$ back to its subcritical value.

Additional References


I. P. Castro. The basic conclusion of this paper is that the flow around a two-dimensional rectangular section surface mounted obstacle is strongly dependent on the axial length/height ratio. This is not a startling conclusion and, despite the authors’ statement that to their knowledge “the flow field past a surface mounted obstacle for various width-to-height ratios has not been previously investigated” there is, in fact, an increasing body of literature covering this whole field. Hosker [12] has recently given a very extensive review and cites a number of papers which discuss precisely this point (e.g., Arle et al. [9]). Incidentally, most authors use “width” to mean the spanwise dimension of the body, so the present authors’ use of the term to mean the axial length could be confusing.

While it is becoming increasingly apparent that the body geometry is often the dominant factor governing the behavior of the surrounding flow field, particularly of course in the near wake, there is no doubt that the characteristics of the upstream boundary layer and, in wind tunnel experiments, the blockage ratio, can have important effects. The authors’ data certainly show again the importance of body geometry and they do specify the blockage ratio and state that the boundary layer velocity profile, in the absence of the body, obeys a 1/6.9 power law and is 0.49H in thickness. However, they do not discuss the likely influences of the upstream flow characteristics and it must be emphasized that their results are specific to their particular flow. Presumably, as other authors have shown, increasing $\delta/H$ (i.e., increasing the turbulent energy at, say, the body height) would lead to a reduction in the reattachment length, $L_R$, and a reduction in the value of $W/H$ at which the separated shear layer permanently reattaches onto the top surface of the body. The authors’ technique of “defining” the reattachment point as the location where the mean output from a linearized (near-wall) single hot wire is a minimum has little to justify it and could possibly not be good enough to determine even the trends in $L_R$ as $\delta/H$ varied.

Considerable use of flow visualization was made in the work, but the authors do not state how they defined the “trajectory of the shear layer” (Fig. 2). Perhaps it was a certain looseness in this concept (admittedly often inevitable in trying to use flow visualization to obtain quantitative data) which led to their statement “that the angle of separation is much smaller” (for $W/H = 5$) “compared to that of a square section obstacle.” This must surely be incorrect? If the Reynolds number is high enough separation at the leading

---

2 University of Surrey, Guildford, United Kingdom.