


D I S C U S S I O N

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Dr. Chen presents in his paper a number of new insights into the geometry and properties of the vortex wake behind bluff cylinders. Several curves depicting pertinent wake parameters as a function of the characteristic Reynolds number have been drawn together from a diversity of sources. The dependence between the cylinder base underpressure and the length of the vortex street is illustrated by a comparison of Figs. 10 and 12, for Reynolds numbers between 60 and 2 x 10^6. This correspondence has been suggested in a different context by Roshko [25] and Gerrard [44] for flow over a streamlined model with a blunt trailing edge and fitted with splitter plates.

Any mathematical model for the Karman vortex street must take account of viscous effects at low Reynolds numbers, as evidenced by the previous work of Berger [14] and Schaefer and Eskinazi [5] for Reynolds numbers below 150-300. The Kro- nauer stability criterion as applied in the subject paper seems independent of the fluid viscosity and its applicability at these low Reynolds numbers is not without question. Equation (2) applies only to a street of potential vortices.

A number of measurements for the longitudinal vortex spacing are shown together in Figs. 6 and 12(a), and the shape of the longitudinal spacing as a function of Reynolds number is quite similar to those for the base underpressure and the formation length. A universal dependence between the longitudinal spacing and the formation length of the vortex street seems less likely in view of some recent experiments on the effects of syn-
chronized, or locked-in, vibrations of cylinders. It has been reported [46] that the length of the vortex formation region is controlled by both the amplitude and frequency of the synchronized vibrations. The effect of increasing cylinder amplitude is to decrease substantially the formation region length. Also, vibration frequency greater than the Strouhal frequency contracts the formation region in length while vibration frequency less than the Strouhal frequency expands it. Cylinder vibrations of half a diameter reduce the formation region to 1.7 dia in length from a value of 3.4 dia for the stationary cylinder at a Reynolds number of 120. More recent experiments at Reynolds number 144 show that the vortex longitudinal spacing is independent of cylinder vibration amplitude so long as the locked-in street frequency remains fixed [47]. Changes in frequency respectively expand and contract the longitudinal spacing when the frequency of vibration is less and greater than the natural wake frequency. The longitudinal spacing is thus not directly controlled by the formation region length for the synchronized vortex wake.

A new universal wake parameter is introduced by Dr. Chen in his paper where

$$C = \frac{f h^3}{v}$$

and is based upon the transverse vortex spacing $h$, the Strouhal frequency $f$, and the vortex strength $V$. This parameter is closely related to the fundamental properties of the vortex street, but poses many difficulties for the measurement of these properties over the entire range of Reynolds numbers from 60 to 2(10$^6$). The difficulties encountered in measuring vortex strength and spacing at low Reynolds numbers have been described by Berger [14] and Schaefer and Eskinazi [5], while the measurement of turbulent vortex parameters at higher Reynolds numbers presents further difficulties that are described by Bloor and Gerrard [48].

An examination of Fig. 11(b) of the subject paper shows that the wake number $C$ is not constant for Reynolds numbers less than 200. It would seem from this result that $C$ is a universal wake parameter only in the Reynolds number range where viscosity does not play an important role in the determination of the vortex street parameters.

Dr. Chen is to be congratulated for introducing several new ideas and presenting a wealth of experimental results in clear and concise terms. This paper not only provides new insights, but also suggests that many questions pertaining to the vortex wakes of bluff bodies yet remain to be answered.

Additional References


$^3$ The notation used here is that of the subject paper.

Author's Closure

The comments made by O. M. Griffin are to be appreciated. The first point raised by him is the question of the applicability of the Kronauer stability criterion for the low Reynolds number range which is connected with large effect of fluid viscosity. The writer's answer would be in the affirmative, because this criterion of the minimum resistance will apply both to the total drag ($C_t$) and to each of its components, i.e., to the pressure drag ($C_p$) and the skin friction drag ($C_f$) as well. This can be examined by comparison of the theoretical results with the experimental values for the longitudinal spacing $l/d$ which can be measured with great accuracy. The agreement between both is excellent in the whole Reynolds number range extending from the low region (i.e., from $R = 40$) to the high region (i.e., to $R = 2 \times 10^6$, see Fig. 6), although the fluid viscosity is quite different in these two regions. It plays a very important role in the low Reynolds number range ($e.g., C_f = 0.75$ compared with $C_p = 0.95$ for $R = 40$), whereas it has a disappearing influence in the high Reynolds number range ($e.g., C_f = 0.01$ according to Achenbach 1971 compared with $C_p = 1.2$ for $R = 10^6$). This strong contrast gives us confidence that the Kronauer criterion, and thus the present theory derived from it, are really independent of the effect of the fluid viscosity. At the same time, the use of the mathematical equations derived from the ideal Karman model, such as equation (2) etc., is also justified to give a right result concerning the geometry of the vortex street.

The further argument given by Griffin for supporting his criticism lies in the increase of the wake number $C = f h^3/\Gamma$ from a value of 0.108 at $R = 100$ to a value of 0.180 at $R = 40$. He also ascribed this variation to the effect of the fluid viscosity in the low Reynolds number range. However, this assertion can be refuted as well. Let us first consider the Reynolds number range from $R = 10^6$ to $10^9$, at the lower region of which the skin friction drag coefficient is still large with a value of about 0.47 for $R = 10^9$, but decreasing to a negligible value of 0.01 as the Reynolds number reaches a value of $10^9$. The ratio of these two drag coefficients is as great as 47:1. Nevertheless, the universal wake number remains practically constant about a value of 0.105 in the whole range for an ideal flow condition (see Fig. 11(b)). In addition, there is no unified tendency of the wake number to vary correspondingly with the variation of the skin friction drag. Thus any direct effect of the fluid viscosity on the wake number and thus on the applicability of the Kronauer criterion for the Reynolds number range of $R = 10^4$ does not exist at all. Then, there cannot be any such effect arising for $R < 10^4$, since no principal change of the curve for the skin friction coefficient does appear in the region of the Reynolds number of $R = 10^3$ (see Fig. 3).

As a matter of fact the variation of the wake number $C$ in the low Reynolds number range below $R = 100$ has a quite different reason as pointed out in the paper already. The cause lies in the change of the property of the vortex street when the Reynolds number decreases below about $R = 80$. For the Reynolds numbers above 80 each vortex will be formed directly from the detached boundary layer from the corresponding side of the cylinder, so each vortex has a very strong independent character with regard to its neighboring one. However, at $40 < R < 80$ the formation of the vortex takes an entirely different way. The detached boundary layer will not directly roll up into a vortex. The two detached boundary layers from the two sides of the cylinder will first join each other downstream into a thin free shear layer along the center line of the cylinder. A wave-like motion due to instability will first arise in this free shear layer and finally dissolves into regular, asymmetrical vortices downstream, when the Reynolds number just reaches a value of about 40. These vortices are entirely interconnected by the free shear layer and therefore dependent on each other. This formation zone of the vortex will shift upstream with increase of the Reynolds number. It will reach the cylinder at about $R = 80$. This special behavior of the vortex street in the low Reynolds number range is reflected in the very large longitudinal spacing $l/d$ of the vortices (see Fig. 6).

As will be shown in a further paper, the wake number $C$ is a characterizing quantity for the swing movement of the near wake. It incorporates the constant factor relating to the force exerted by the cylinder on the vortex street and the reaction of the near wake in the form of a rotational movement. The value of the wake number depends therefore on the formation mechanism

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of the vortex street. As the property of the vortex street for $40 < R < 80$ deviates from that for $R > 80$, the wake number $C$ must be different accordingly. Since the behavior of the vortex street changes continually from $R = 40$ to 80 due to the shift of the vortex formation zone, the variation of the wake number in the corresponding Reynolds number range is thus intelligible. As the formation mechanism of the vortex remains unchanged for the Reynolds number extending from 80 to as high as $10^7$ (i.e., directly rolling up of the detached boundary layer from the cylinder shoulder to form a vortex), the wake number will remain unchanged in the whole range, in spite of the vortex being laminar at $R = 80$ and highly turbulent at $R = 10^7$.

The third point raised by Griffin lies in the doubt of any relationship between the vortex formation zone length $s$ and the vortex longitudinal spacing $l$, as proposed in the writer's paper. His argument was based on several experimental results obtained with vibrating cylinders. It is a well-known fact that the vibration of the cylinder will modify the geometry of the vortex street a great deal.

It seems to be a misunderstanding of Griffin in the interpretation of the context of the writer's paper, in which only the fundamental vortex street of a circular, stationary cylinder is considered. Any additional effect arising from the vibration of the cylinder is beyond the scope of the writer's paper. Therefore, the statement of Griffin can only apply to this additional effect. He has brought no evidence for the dissimilarity of the vortex formation zone length to the vortex longitudinal spacing for a fundamental vortex street of a circular, stationary cylinder.

The writer succeeded in the meantime in deriving a relationship between these two quantities theoretically by means of the ideal model introduced by Karman, namely

$$s = \frac{\alpha}{2\pi} \frac{l}{U_a - u} \frac{U_a - u}{u}$$

where $\alpha$ is a constant slightly depending on the spacing ratio $l/h$. The value of $\alpha$ is 0.538 for $l/h = 3$, increasing to 0.568 at $l/h = 5$. The similarity between the two quantities $s$ and $l$ is thus confirmed both experimentally and theoretically. By using the data resulting from the theory in the present paper, the dimensionless formation zone length $s/d$ can be computed. The theoretical values obtained this way agree excellently with the available experimental results such as those given by Schaeffer/Eskinazi [5], Bloor [37], and Bloor/Gerrard [48].

In conclusion, the writer wishes to express his gratitude to Mr. O. M. Griffin for his exhaustive discussions and kind acknowledgment of the writer's paper.