Study of the Universal Strouhal Number over the Wide Reynolds Number Flow Range* (Effect of Surface Roughness)

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Universality of the Strouhal number in the wake flow of a cylinder over a wide range of Reynolds number, i.e., $5 \times 10^4 < Re < 10^7$, was considered for this paper. Eight cylinders with various surface roughnesses were used for the measurement. The universal Strouhal numbers considered were Roshko's number, Bearman's number, Griffin's number and what took the measured values of the width of wake streets for the reference length. These universal Strouhal numbers were calculated using the measured values of vortex frequencies, surface pressure distributions and drags. Comparisons were then made. It was made clear that Bearman's number was the most uniform of all the universal Strouhal numbers considered. It maintained a uniform value of 0.18 throughout the Reynolds number range. The reason for the nonuniformity of other Strouhal numbers was also considered.

Key Words: Universal Strouhal Number, Wake, Vortex, Cylinder, Surface Roughness, Vortex Street

1. Introduction

Authors have been making experimental investigations on the effect of surface roughness of a cylinder ($4.54 \times 10^{-6} < K_s/d < 2.5 \times 10^{-3}$) in the wide range of Reynolds number including transcritical Reynolds number range, i.e., $5 \times 10^4 < Re < 10^7$. Measurements of pressure distributions on the cylinder and wake passing frequency in the downstream were carried down. According to the test results, the flow behavior around a cylinder placed in the test section is classified into 4 regions irrespective of relative surface roughness. They are subcritical, transitional, supercritical and transcritical Reynolds number ranges. These ranges

are classified by the variation of drag coefficient and Strouhal number with Reynolds number. The minimum value of drag coefficient C_{dmin} decreases with a decrease in (K_s/d) , but it becomes constant for the smaller value than $(K_s/d) = 5 \times 10^{-4}$ and there is a limiting value of surface roughness (K_s/d) , which influences the value of Reynolds number at the critical point. If the relative surface roughness is smaller than this limiting value, the variation of C_d and St with Reynolds number shows the same procedure, in the Reynolds number range smaller than that of the critical point^{(1),(2)}. If the relative roughness is larger than this limiting value, the Reynolds number that corresponds to the critical point, i.e., $Re(C_{dmin})$, becomes smaller and the minimum value of the drag coefficient becomes larger as reported by Fage⁽³⁾, Achenbach⁽⁴⁾, and Okajima and Nakamura⁽⁵⁾. Adachi et. al. showed that if the surface roughness is larger in the axial direction than in the circumferential direction, i.e., as if grooves are engraved along the circumferential direction, there can be seen a retardation in the separation point along the cylindrical surface in the super and transcritical Reynolds number range in some cases, and in the other cases, the laminar boundary

* Received 9th August, 1995. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 61, No. 583, B (1995), pp. 793-799. (Received 25th April, 1994)

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layer can be kept longer along the surface in the neighborhood of $\theta=90^\circ$. A decrease in drag coefficient could be seen in these cases. Roshko⁽⁷⁾ and Bearman⁽⁸⁾ studied the similarity of vortex streets which arise in the downstream of the body. The Universality of the vortex street was also considered.

In this paper, the universal Strouhal number of vortex frequency was investigated. Strouhal number depends on the surface roughness value in the transcritical Reynolds number range. Many studies have been made concerning the universal nondimensional number which includes vortex shedding frequency. The dimension of a body d which is included in the Strouhal number $St=(f \cdot d/U_\infty)$ is not related to the vortex street. In order to have a uniform Strouhal number, some other length value relating to the vortex street and other than the diameter must be taken as a representative length. In this paper a nondimensional universal Strouhal number which includes vortex frequency and independent of the surface roughness throughout the wide Reynolds number range from subcritical to the transcritical range was considered.

Nomenclatures

C_p : pressure coefficient $= (p_\theta - p_\infty)/(\rho U_\infty^2/2)$

C_{pb} : base pressure coefficient (mean value of pressure coefficients of 5 points in steps of 5° taking $\theta=180^\circ$ as center)

d : representative length of a body (diameter of a cylinder) m

f : vortex shedding frequency 1/s

K_s : surface roughness

St : Strouhal number

U_∞ : undisturbed flow velocity m/s

Re : Reynolds number

ρ : density

Subscripts

b : back surface

crit : critical point

θ : angle measured from the forward stagnation point along surface

∞ : undisturbed stream

2. Effects of Surface Roughness on the Vortex Shedding Frequency in the Wake of a Cylinder in a Uniform Flow

It is well known that the vortex street is formed in the downstream of a body, of which shedding frequency is related by the Strouhal number $St=(f \cdot d/U_\infty)$, where f is vortex shedding frequency, d representative length of a body and U_∞ velocity of flow. But there are various relations between representative length of a body and shape of vortex street

depending on the shape of a body. In this paper, vortex shedding frequency of a cylinder with the same diameter and with various surface roughness is considered.

Authors have investigated effects of surface roughness on the drag and Strouhal number of a cylinder by measuring pressure distributions and vortex shedding frequency in the wide Reynolds number range ($5 \times 10^5 \leq Re \leq 10^7$), placing a cylinder with various surface roughness in the test section of the cryogenic windtunnel (500 mm $\times$ 500 mm). In this windtunnel various Reynolds number flows can be obtained by circulating low temperature and high pressure nitrogen gas which was got by injecting and making vapourize liquid nitrogen into the windtunnel body^{(1),(2)}. Table 1 shows specifications of the cryogenic wind tunnel. The detail of experimental apparatus and method of measurements were written in the references^{(2),(9)}. A cylinder is supported vertically in the measuring section of the cryogenic windtunnel penetrating its upper and lower wall. Pressure holes with a diameter of 0.3 mm ϕ are drilled perpendicular to the cylinder surface and temperature measurements are also made by thermocouples (copper-constantan) attached to the surface. Table 2 shows the surface conditions of the cylinders used in this research. They are measured by traversing a stylus along the surface using a roughness meter. The

Table 1 Specifications and main dimensions of cryogenic wind tunnel

Type of Wind tunnel	Gottingen Type Inner Insulated
Pressure	0.8 MPa
Temperature	112 K
Maximum Velocity	65 m/s
Maximum Reynolds number	10^7
Maximum Mach Number	0.3
Velocity Distribution	Lower than $\pm 1\%$
Turbulence	0.26 % (Atmospheric temp, 0.1 MPa, 34 m/s) 0.37 % (110 K, 0.2 MPa, 38 m/s)

Table 2 Relative surface roughness of cylinder

Cylinder	A	B	C	D	E	F	G	H
K_{θ} (m)	(0.08 ~ 0.5) $\times 10^{-6}$	(0.3 ~ 0.5) $\times 10^{-6}$	(10~17) $\times 10^{-6}$	(20~30) $\times 10^{-6}$	(50~68) $\times 10^{-6}$	(70~90) $\times 10^{-6}$	(50~110) $\times 10^{-6}$	(130~ 150) $\times 10^{-6}$
K_{ω} (m)	(0.03 ~ 0.5) $\times 10^{-6}$	(0.9 ~ 1.4) $\times 10^{-6}$	(9~15) $\times 10^{-6}$	(28~36) $\times 10^{-6}$	(60~75) $\times 10^{-6}$	(78~94) $\times 10^{-6}$	(62~110) $\times 10^{-6}$	(119~ 126) $\times 10^{-6}$
K_{θ}/K_{ω}	0.85	0.38	1.08	0.75	0.84	0.89	0.98	1.03
K_{θ}/d	4.54 $\times 10^{-6}$	8.57 $\times 10^{-6}$	254 $\times 10^{-6}$	500 $\times 10^{-6}$	1160 $\times 10^{-6}$	1600 $\times 10^{-6}$	1810 $\times 10^{-6}$	2540 $\times 10^{-6}$

K_{θ} , roughness in the tangential direction, K_{ω} , roughness in the axial direction

values of relative roughness were calculated by dividing the measured values of roughness based on JIS (Japanese Industrial Standard) B 0601 (Definition and Designation of Surface Roughness) by diameter d . The values of relative roughness are nearly uniform in the circumferential and axial direction with exception to that of cylinder B. Figure 1 shows variations of Strouhal number St with Reynolds number of vortex shedding frequency for cylinders with various relative roughness. Figure 2 shows those of drag coefficient. In the subcritical Reynolds number range, Strouhal number takes a constant value irrespective of the relative roughness. For $(K_s/d)_{crit} \leq 5 \times 10^{-4}$, Strouhal number increases suddenly with Reynolds number at the critical point. In the supercritical Reynolds number range, Strouhal numbers maintain a nearly constant value with an increase in Reynolds number. However, their values become larger for smaller relative roughness.

Fig. 1 Variations of Strouhal number St of shedding vortex in the wake of cylinder with Reynolds number Re for various values of relative surface roughnesses (K_s/d)

Fig. 2 Variations of drag coefficient C_d with Reynolds number Re for various values of relative surface roughnesses (K_s/d)

For cylinders with the relative roughness mentioned above, the relation of drag coefficient with Reynolds number shows the same procedure under the critical point. For cylinders with larger relative roughness than this critical value, transitional range and the critical point shift to the lower Reynolds number range. The drag coefficient at the critical point also take the larger values. On the other hand, the drag coefficients take the larger value in the super and transcritical Reynolds number ranges with exception to that of cylinder B. The fact that the drag coefficient of cylinder B is the smallest of all cylinders is cited in the reference⁽⁶⁾. The universal Strouhal numbers which are independent of the body shape and include dimensions of vortex streets of bluff bodies with various shapes are discussed by Roshko⁽⁷⁾, Bearman⁽⁸⁾, Simmons⁽¹⁰⁾ and Griffin⁽¹¹⁾. The idea lying behind the assumption of universal Strouhal numbers comes from those ideas that same size vortex street may originate from bodies of different bluff bodies (which may be considered to be characterized by the ratio of the width of wakes and the body width), and that this fact may be taken into account by means of the beforementioned connections between the body and the reference velocity and length.

In this paper, by comparing universal Strouhal numbers with those calculated using the measured values of width of vortex street and those using surface pressure distributions and vortex shedding frequencies, discussions on the universal Strouhal number of cylinders with various relative roughness were considered.

3. Universal Strouhal Numbers by Various Researchers

(1) Roshko's number S_R

Roshko considered that the universal Strouhal number must have relation with the irrotational velocity at the point of the separation $U_s = U_\infty(1 - C_{pb})^{1/2}$ and is independent of the body size. He defined Roshko's number $S_R = (f \cdot d' / U_s)$ by using width of wake d' decided by the Roshko's notched hodograph theory. He got Roshko's number $S_R = 0.16$ for subcritical flow from the experimental values of Strouhal number St , base pressure coefficient C_{pb} of wedge and plates⁽⁷⁾. Roshko's number is defined as

$$S_R = \frac{f \cdot d'}{U_s} = \frac{f \cdot d}{U_\infty} \cdot \frac{d'}{d} \cdot \frac{U_\infty}{U_s} \quad (1)$$

$$U_s = U_\infty(1 - C_{pb})^{1/2} = k \cdot U_\infty \quad (2)$$

where relation of U_s and base pressure coefficient C_{pb} can be acquired by using Bernoulli eq.. Roshko assumed for the relation of drag coefficient and base pressure coefficient

$$\frac{d'}{d} = -\frac{C_d}{C_{pb}} \quad (3)$$

Then Roshko's number becomes

$$S_R = -\frac{St}{k} \cdot \frac{C_d}{C_{pb}} \quad (4)$$

(2) Bearman's number

Bearman⁽⁸⁾ considered that wake vortex street in the wake of two dimensional body with a splitter plate or with a base bleed is arranged to minimize drag coefficient according to the Kronauer's criterion. Simmons investigated the two dimensional bluff bodies with various shapes and showed that a constant value of Bearman's number is acquired for the vortex street with various separation angle from 0 to 90°. Using wake Strouhal number with the lateral vortex spacing, Bearman's number was defined. It takes a constant value of 0.181 throughout wide range of k .

Bearman's number S_B can be written in the form

$$S_B = \frac{f \cdot h}{U_s} \quad (5)$$

There is a relation between drag coefficient C_d and vortex street drag coefficient C_{ds}

$$C_d \cdot d = C_{ds} \cdot l \quad (6)$$

Where, vortex drag coefficient related to the longitudinal spacing of vortices $C_{ds} = D_s / (\rho U_\infty^2 / 2)$. h and l are lateral and longitudinal spacing of the vortices of the opposite sign. Remembering that the velocity of the centers relative to the body U_N is related

$$U_N = f \cdot l = (U_\infty - u) \quad (7)$$

where u denotes velocity of vortex centers relative to the stream, and f frequency of vortex shedding from one side of the body. Then the relation is

$$C_d \cdot St = C_{ds} \frac{U_N}{U_\infty} \quad (8)$$

Using this relation Bearman's number is

$$S_B = \frac{f \cdot h}{U_s} = \frac{f \cdot l}{k} \cdot \frac{h}{l \cdot U_\infty} = \frac{1}{k} \cdot \frac{h}{l} \cdot \frac{U_N}{U_\infty} \quad (9)$$

Calculating $C_d \cdot St (= C_{ds} \cdot U_N / U_\infty)$ by using experimental values of C_d and St , referring to the Kronauer's stability criterion (Fig. 1 of reference(10)), and also using the corresponding values of $(U_N \cdot h / U_\infty \cdot l)$, Bearman's number S_B is calculated by Eq.(9).

(3) Griffin's number $G^{(11)}$

Griffin considered relation between universal wake Strouhal number $St^* = f \cdot l_w / U_s$ and wake drag coefficient $C_d^* = (C_d \cdot d / l_w \cdot k^2)$ and showed that product $(St^* \cdot C_d^*)$ is a constant 0.0073 ± 0.005 for wake Reynolds number $Re^* = 100 \sim 10^7$. Using the wake width at the end of vortex formation region

$$St^* = \frac{f \cdot l_w}{U_s} = St \frac{U_\infty}{U_s} \cdot \frac{l_w}{d} = \frac{St}{k} \cdot \frac{l_w}{d} \quad (10)$$

$$Re^* = \frac{U_s \cdot l_w}{\nu} = Re \cdot k \cdot \frac{l_w}{d} \quad (11)$$

$$St^* \cdot C_d^* = \frac{St}{k^3} \cdot C_d = G \quad (12)$$

(4) Universal Strouhal number S' which uses measured wake width as reference length

In the modified Strouhal numbers as written above the reference length of Eq.(1), (5) and (10) are width of wake decided by the Roshko's hodograph theory d' , lateral vortex spacing h and wake width at the end of vortex formation region l_w . These have all dimensions of wake width. We can also consider another reference length using measured wake width as the reference length.

$$S' = \frac{f \cdot h_e}{U_s} \quad (13)$$

4. Modified Strouhal Number Taking the Measured Value of Width of Vortex Street as Reference Length

4.1 Measurement of width of vortex street

Figure 3 shows hot wire probe and its supporting apparatus to measure wake vortex street. Strouhal number shown in Fig.1 was calculated using the vortex shedding frequency measured at 6 points designated by $\bullet$ markers^{(1),(2)}. Method of measurement of width of vortex street is explained in this section. Hot wire probe of 10 μ m thickness was used for this purpose from the consideration of strength. Two of these probes were attached to the traversing apparatus 50 mm apart each other and were traversed. Shear layers grow along the cylinder surface and separate from it. With the support of energy from thus created shear layers develop the vortex gradually, but its growth stops when the shear layer on the other side are sucked in across the wake centerline. Its fluctuating components decrease when it passed the creating zone. It takes a constant value in the zone of a stable pair of vortex. In the real flow only several pairs of vortices can be observed. Then the width of vortex street becomes larger with the effect of viscosity and vortices diminish gradually. Authors measured strength of vortices, i.e., expressed as fluid velocity of RMS output signal of hot wire probe with vortex shedding frequency, at various distances in the downstream from the cylinder as shown in Fig.3. Then it was made clear that varying distances from the cylinder at the fixed Reynolds number fluctuating

Fig. 3 Cylinder and hot wire probe and its support for measurement of vortex street in the wake

component of shear layer decreases gradually and it takes a constant value at the stable zone of vortex street. Authors measured the variation of its distance leading to the fixed value for various Reynolds numbers. Indeed vortex formation length varies with Reynolds number. There are some differences in these measured value with surface roughnesses, but the distances are 30 - 40 mm in the subcritical Reynolds number range, 80 mm in the neighborhood of the critical point and 40 mm in the super critical range. It somewhat increases with an increase in Reynolds number. From these considerations the distance of 80 mm as shown in Fig. 3 was decided as the distance from the cylinder throughout our experiments ($5 \times 10^4 < Re < 10^7$).

For measurement for the width of the vortex street, we made traverse hot wire probes at $x=80$ mm as shown in Fig. 3, and analyzed its vortex shedding frequency component of RMS output. Figure 4 shows its method of analysis. In these figures $\circ$ markers show those with larger than 70% of the maximum value in the downstream at $x=80$ mm. Taking weighted average values from these values of markers, with exception to those at most outside, stations of vortex were decided. Using those stations of both sides, the width of vortex street was decided.

4.2 Comparisons of wake width with those measured by the other methods

Figure 5 shows variations of the measured wake width with Reynolds number. In this figure $\circ$ markers show the ratio of the measured wake width h_e and diameter of cylinder d and $\triangle$ markers show those calculated from drag coefficient C_d and base pressure coefficient C_{pb} using Eq. (3). If the values of (h_e/d) and (d'/d) by Eq. (3) coincide, it shows that Roshko's assumption (3) is justified. The $+$ markers are calculated with drag coefficient and Strouhal number St using Eq. (9) by the above mentioned method $(h/d) = (S_B \cdot k/St)$. This can be said to have been calculated by Bearman's method. Figure 5 contains only some representatives of the cylinders. Figure

Fig. 4 Measurement of spacing of vortex street

5(a) that was for cylinder C, i.e., with relative roughness smaller than the critical value, wake widths h_e are larger or equal than the cylinder diameter, however they take nearly constant values in the subcritical range. They take smaller values at once and increase again with an increase in the Reynolds number range, however they take nearly the same values as cylinder diameter in the super and transcritical Reynolds number ranges. Figure 5(b) shows that have larger relative roughness than the critical roughness, the critical point shifts to the lower Reynolds number range, and not much difference can be seen in the variation with Reynolds number. On the other hand, $\circ$ markers are much different than $+$ markers, but they are very near to $\triangle$ markers. Roshko's assumption, i.e., Eq. (3), can be said to be justified in the wide Reynolds number range excepting those in the neighborhood of the critical point.

4.3 Modified Strouhal number taking the measured values of width of vortex street as reference length

Figure 6 shows variations of modified Strouhal number S' with Reynolds number Re . The values in the ordinate take almost the constant values throughout the subcritical, supercritical and transcritical Reynolds number ranges. They can also be seen to be independent of the surface roughness. As can be seen

(a) Cylinder (C)

(b) Cylinder (H)

Fig. 5 Comparison of vortex spacing of the measured and the calculated values of Strouhal number with Reynolds number.

in Fig. 5, there is a large scattering in the values of the width of vortex street, also the scattering can be seen in the values of modified Strouhal number. Measurements were made as many times as those for S_R , S_B and G , but values of the width of the vortex street could not sometimes be determined especially for relative roughness smaller than the critical relative roughness. Many times values of the ordinate could not be determined.

4.4 Roshko's number S_R

Figure 7 shows variations of Roshko's number S_R with Reynolds number Re . The values of the ordinate were calculated according to Eq.(4), in which the assumption of Eq.(3) is also made. About this point we have discussed in 4.2. It can be said that the coincidence of the values are fairly well if we consider the difficulty in determining the width of vortex street and the scattering of the data. By the way, the variation of S_R have some tendency to increase with an increase in Reynolds number, but it takes 0.16 irrespective of relative roughness, and it coincides with the values in the reference (7). But in the supercritical Reynolds number range, Roshko's number S_R takes somewhat larger values for small relative roughness.

4.5 Bearman's number S_B

Figure 8 shows variations of Bearman's number with Reynolds number Re . It was calculated accord-

Fig. 6 Variations of Strouhal number S' using lateral values of vortex street h_e with Reynolds number Re

Fig. 7 Variations of Roshko's number S_R with Reynolds number Re

ing to Eq.(9) by using the corresponding values of $(C_{ds} \cdot U_N / U_\infty)$ calculated by Eq.(8) using Fig. 1 of reference (10). For the calculation of the value $(C_{ds} \cdot U_N / U_\infty)$ measured values of drag coefficient C_d and Strouhal number St were used. The values are nearly constant in the subcritical and supercritical Reynolds number range. Comparing with other universal Strouhal numbers, Bearman's number have almost constant value of 0.181, as was written by Bearman, and have the smallest deviations. It can be said that Bearman's number is almost constant over the wide Reynolds number range irrespective of the relative roughness.

4.6 Griffin's number G

Figure 9 shows variations of Griffin's number G with Reynolds number Re . Indeed they can be seen to reduce to the nearly constant value irrespective of relative roughness in the subcritical and supercritical Reynolds number range, but the scattering are somewhat larger in the transitional and supercritical range. Authors discussed the variations of the product $St \cdot C_d$ with k in the reference (2). The transitional and supercritical ranges correspond to the range $k < 1.3$, the values can be reduced to a curve in the subcritical and supercritical ranges. According to the author's research, as the value of $k = 1.25 - 1.5$ were attained, G becomes $G = 0.074 - 0.08$.

According to Griffin, the relation becomes $St \cdot C_d$

Fig. 8 Variations of Bearman's number S_B with Reynolds number Re

Fig. 9 Variations of Griffin's number G with Reynolds number Re

Fig. 10 Variations of Griffin's number G with Reynolds number Re (Excepting values in the range of separation bubble)

$= a + b \cdot k$, where $a = -0.48 \pm 0.03$, and $b = 0.50 \pm 0.02$, and G becomes $G = 0.073 \pm 0.0058$ (in the range $k = 1.2 - 2$, G is $0.067 - 0.078$), and it takes nearly constant values in the range $10^3 < Re < 10^5$. Buresti showed somewhat larger values of $G = 0.075 - 0.0855$ in the range $Re = 200 - 9 \times 10^{12}$.

5. Discussions

In this paper calculations of universal Strouhal number including vortex shedding frequency f in the down stream of a cylinder with various relative roughness were carried down using measured values. The Reynolds number ranges cover wide range of Reynolds number from the subcritical to the transcritical Reynolds number range of $5 \times 10^4 < Re < 10^7$. At first, the universal Strouhal number which uses the measured wake width of h_e as reference length scatter in the fairly wide Reynolds number range and only small numbers of data are obtained because of the difficulty in determining the wake width, especially in the supercritical range. The scatter in the variation of Roshko's number is fairly large. It takes the value of 0.16 and increases with an increase in Reynolds number and takes ~ 0.18 . It comes from the assumption of Eq. (3) which was made from Roshko's method holds besides the transitional range and critical point and supercritical range⁽¹¹⁾. Bearman's number is the most uniform and does not deviate in wide Reynolds number range. It contains the condition that the vortex street which have the minimum drag coefficient exists in the down stream. For the Bearman's number Buresti got the value of 0.18 - 0.19 in the Reynolds number range $10^2 < Re < 10^3$. In our research, the value of 0.18 was obtained in the Reynolds number range $5 \times 10^4 < Re < 10^7$. As shown in Fig. 9, Griffin's number G takes a somewhat smaller value in the Reynolds number range $Re \cong 10^5 - 10^7$. Authors had investigated the variations of $St \cdot C_d$ with k , and found out that the domain $k < 1.3$ corresponds to the transitional and supercritical range, and that separation

bubble may be created in these ranges and, if we avoid the data in these ranges, we have one curve of Griffin's number from subcritical to the transcritical Reynolds number ranges. Using the same procedure as written above, the variation of Griffin's number $G (= St^* \cdot C_d^*)$ with Reynolds number shows the uniform value as shown in Fig. 10, and we can get the uniform value of Griffin's number from subcritical to the transcritical range.

6. Conclusions

In this paper, experiments were done on the cylinders with various surface roughnesses in wide Reynolds number ranges ($5 \times 10^4 \leq Re \leq 10^7$) and discussions on the 4 sorts of universal Strouhal number calculated using measured values of frequencies, lateral distances of vortex street, drag coefficients and back pressure coefficients were made. From these considerations, the following conclusions have been obtained.

(1) Bearman's number was the most uniform universal Strouhal number among Roshko's number S_R , Bearman's number S_B , Griffin's number G and what took measured values of lateral vortex distance as the reference length.

(2) Uniform Griffin's number can be obtained, if we avoid the data in the range which have separation bubbles.

(3) Roshko's number somewhat deviates. It is because that its assumption of $(d'/d) = -(C_d/C_{pb})$ does not hold in some ranges.

(4) Universal Strouhal number S' which have the measured values of wake width as its reference length was considered. According to the difficulty in the determination of wake width, the values of S' have considerable scatter.

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