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Flow measurement by a new type vortex flowmeter of dual triangulate bluff body

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Abstract

Experimental studies were carried out on the performance of a new dual triangulate bluff body vortex shedders used for vortex flowmeter in a Φ50 mm circular pipe. Nine dual combinations on the basis of different sized triangulate bluff body geometries for a range of separations between 35 and 65 mm were used in this work. The vortex shedding frequency was obtained on the basis of measured fluctuating pressure on the lateral side of the vortex shedder by piezoelectric press sensor. The performances of a number of dual triangulate combinations were described as follows. First, the pressures loss of these dual triangulate combinations are increased compared to that of single triangulate shedder. Second, the best linearity conditions of the new type vortex flowmeter were advanced. Third, the sensitivity of the detection of vortex shedding frequency of the new type vortex flowmeter was studied. A good linearity, regularity, sensitivity and range ability prototype of two triangulate shedders vortex flowmeter was developed.
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Keywords: Vortex flowmeter; Dual bluff body; Strouhal number; Fluctuating pressure

1. Introduction and background

The phenomenon of vortex shedding from bluff bodies has been studied since the pioneering work of Strouhal (1878) and Von Karman (1912). When a bluff body is placed in a flow stream, vortices shed alternately from each side surfaces of the body. The non-dimensional shedding frequency, the Strouhal number, is defined as:

$$S = \frac{fD}{U_m} \quad (1)$$

Where f is the vortex shedding frequency. D is the bluff body diameter, and U_m is the mean free-stream velocity.

The idea of building a flowmeter base on the assumption of a constant Strouhal number was first proposed by Roshko [18], who studies vortex shedding from a circular cylinder in a Reynolds number range of $40 < Re < 10^4$. For $Re >$ 300 (the "irregular" range), the Strouhal number remains at an almost constant value of 0.2, independent of Reynolds number. Roshko [19] also showed that as Re is increased beyond a critical value of 2×10^5 for a circular cylinder, the Strouhal number increases rapidly.

The vortex flowmeter based on vortex shedding emerged in the early 1970s. Since there is no moving part in this flowmeter, little is concerned for wear or physical damage caused by foreign matter. The low-pressure drop across the meter also results in low energy cost. In addition, it has a number of attractive advantages, i.e. high reliability, low maintenance, and insensitivity to fluid properties and temperature. Karman vortex flowmeter is widely used in the measurement of flow rate in a pipe flow. In this method, the flow rate is measured by the vortex shedding frequencies from a two-dimensional cylinder [7,3,8].

However, the vortex flowmeter has its own disadvantage i.e. poor noise immunity and low-flowrate sensitivity. Thinh and Evangelisti [20] proved that the ambient noise as well as the inherent pressure fluctuation from the measured system could considerably reduce the measurement accuracy through experiments. On the other hand, the sufficiently high signal-to-noise ratio cannot be achieved by piezoelectric press sensor in lower Reynolds number, which results in a limited measuring range for the vortex flowrate.

In order to improve the noise immunity and low-flowrate sensitivity of the vortex flowmeter, great efforts have been

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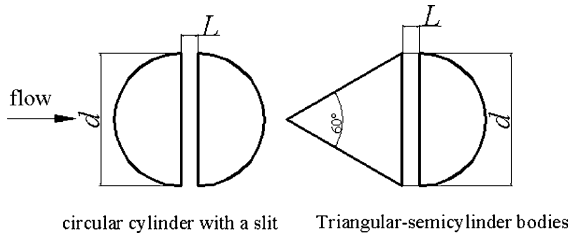


Fig. 1. The bluff body combinations of a circular cylinder with a two dimensional slit along the diameter [14].

made by a number of researchers. Kawano and Miyata [16] improved the signal-to-noise ratio by using an adaptive low-signal-cutoff discriminator function. Amadi-Echedu et al. [1,2] applied signal processing and system identification techniques to enhance the measurement quality of vortex flowmeter. Pankanin and Grzegorz [17] optimized the bluff body geometry and the sensor location to improve the frequency stability and the linearity of the flowmeter characteristic.

One method of improving low-flowrate sensitivity and repeatability of the vortex flowmeter is to use two bluff bodies in series or tandem separated by a narrow gap.

Honda and Yamasaki [10] investigated the stability of the vortex shedding from bluff bodies. Igarashi [11,12,15] investigated the regularity of the vortex shedding and the strength of the vortices from circular cylinder bodies in a uniform flow. Igarashi [14] then went on to investigate the performance of a circular cylinder with a two dimensional slit along the diameter and a triangular–semicylinder bodies. They showed that a circular cylinder with a two dimensional slit along the diameter satisfying condition: $d/D = 0.20$–0.30 and $L/d = 0.15$–0.16, and a triangular–semicylinder bodies satisfying condition: $d/D = 0.20$–0.30 and $L/d = 0.15$–0.16, generate strong and regular vortex shedding (Fig. 1).

His works led us to understand that a cylinder with a two dimensional slit placed along the diameter results in the most stable and regular vortex shedding. Those works showed that a circular cylinder split into two halves by a narrow gap gave more regular and stable vortex shedding than a number of single bluff bodies of different shapes. However, they did not mention about the flow resistance of the vortex shedder. Then, Igarashi [13] measured the flow resistances of several cylindrical vortex shedders under a turbulent flow condition through a circular pipe over a wide range of Reynolds number and the opening ratio.

Bentley and Benson [4] investigated experimentally the performance of a number of rectangular bluff body combinations and found that the higher repeatability of vortex shedding may be obtained with optimal dual bluff body combinations. They tested combinations of two and three rectangular bluff bodies in series and showed that certain combinations gave higher repeatability over a range of flow conditions than a single rectangular bluff body. Bentley and Benson then went on to propose condition for optimum vortex shedding in combinations of two rectangular bluff bodies

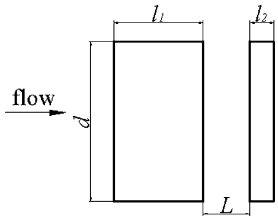


Fig. 2. The bluff body combinations of two rectangular bluff bodies in tandem [4].

in tandem. In particular, they showed that the dual rectangular bluff body combinations satisfying condition (A):

$$\frac{l_1}{d} = 0.500, \qquad \frac{L}{d} = 0.400, \qquad \frac{l_2}{d} = 0.100, \qquad \frac{d}{D} = 0.1, \tag{2}$$

with a deeper rectangle upstream of a narrower rectangle, gave the highest repeatability of all the combinations tested (Fig. 2).

This work was then extended to combinations of rectangular, triangular, and chevron shaped bluff bodies in series [5]. A combination satisfying condition (A) but with the downstream rectangle replaced by a triangle again gave the highest repeatability of the combinations tested (Fig. 3).

Recently, Bentley and Mudd [6] investigated the visualization characteristic of vortex shedding in open channel flow for a single rectangle bluff body and two dual bluff body combination (one is dual rectangle combination, another is upstream rectangle and downstream triangle combination).

However, most previous works, which were aimed at improving low-flowrate sensitivity and repeatability of the vortex flowmeter by using two bluff bodies in series or tandem separated by a narrow gap, did not mention anything about vortex shedding of upstream triangle combinations and downstream triangle combinations in series. In the industry, most currently used single vortex shedder is triangle cylinder. Bentley et al. [5] suggested that downstream triangle dual bluff body combination gave the highest repeatability of the combinations. Then, dual bluff body combinations, which separately have these features, should be tested.

Then, Fu and Yang [9] investigated the hydrodynamic vibration characteristic of dual triangle-section bluff body combinations in series by numerical simulation. Their work suggested that dual triangle-section bluff bodies combinations in series can increase signal-to-noise ratio of vortex

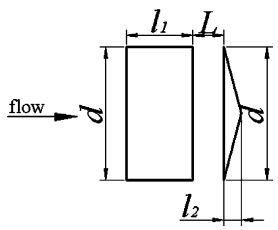


Fig. 3. The bluff body combinations of upstream rectangular combinations and downstream triangle combinations in series [5].

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flowmeter and reduce flux lower limit value of vortex flowmeter.

This paper presents the results obtained in flowmeter experiment apparatus. A number of dual triangulate bluff body combinations for vortex flowmeter in a circular pipe are used in the present study. The vortex shedding performance of these different size and geometries body combinations are tested. Finally, some implications of these results on the design of dual triangulate are discussed.

2. Experimental apparatus and procedure

Experiments were performed in a flowmeter experimental apparatus. The schematic diagram of the experimental apparatus is shown in Fig. 4.

As shown in Fig. 4, the flowmeter experimental apparatus is composed of five parts.

- (I) is a straight circular pipe having inner diameter $D = 50$ mm and 5 m length, which is located on 100 D downstream from the inlet of the pipe. Flow is conditioned by this upstream of test section. Flow through the test section has a fully developed turbulent flow. A mean uniformity of the flow is less than ±3% and a free stream turbulence intensity of that is less than 0.7% over a velocity range of 2–60 m/s.
- (II) is tested flowmeter. In order to optimize test number, through orthogonal collocation method, nine pairs of dual triangulate bluff body combinations in different sizes and separations ranged from 40 to 65 mm are used in present study. Table 1 lists the geometry and parameters of the bluff bodies and Table 2 names the test number for the different dual bluff body combinations. In an extended program of work, we have measured the performance of wide variety of combinations of two triangulate bluff bodies in series. This program has shown that for any combination geometry the most regular shedding is obtained if the separations distance L is larger than 40 mm. Then, the separation distance L ranged from 40 to 65 mm in test.

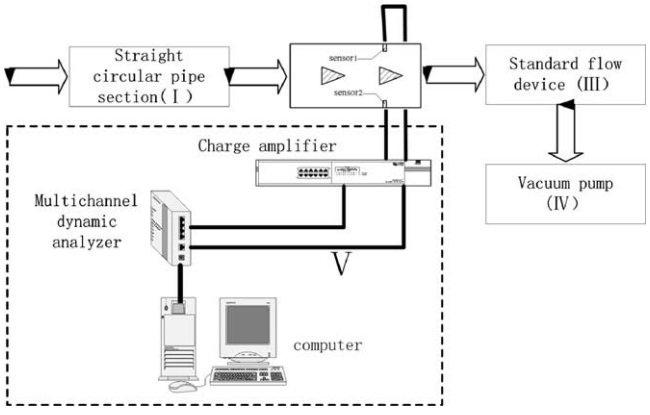
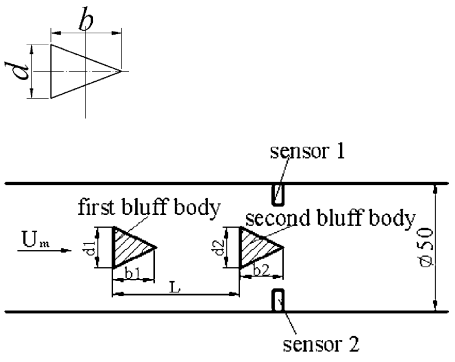


Fig. 4. Flowmeter experimental apparatus.

Table 1
Shape and dimension of bluff body

Bluff body number (mm)	1	2	3	4	5	6	7	8	9
d	15	15	15	13	14	13	14	14	13
b	21	22	20	17	18	18	19	20	19



- (III) is a standard flow device. It is composed of five nozzle flowmeter and the various of flowrate can be obtained by the different nozzle combinations. The experimental volume flow is the calculation flow of nozzle flowmeter. To clarify the Reynolds number effect on the flow characteristics, the mean velocity U_m was set over a range from 2 to 60 m/s. The mean velocity U_m was specified by $Q/(\pi D^2/4)$, where Q is the volume flow rate measured by the nozzle flowmeter. Those flow velocities correspond to the Reynolds number of the pipe, $R_e = U_m(D/\nu)$, ranged from 5.59×10^3 to 1.6765×10^5.
- (IV) is vacuum pump, which is used to generate pressure gradient in experimental system.
- (V) is computer measurement system. It is composed of charge amplifier, multi-channel dynamic analyzer and computer. As shown in Fig. 1, the sensor signals are amplified by charge amplifier, and then, are transmitted to computer through the multichannel dynamic analyzer.

The vortex shedding frequency is obtained based on measured fluctuating pressure by piezoelectric press sensor. The two piezoelectric sensors were symmetrically stuck on the lateral side of the second bluff body as shown in Table 1.

Table 2
Dual bluff body number

Dual bluff body number	First bluff body number	Second bluff body number	Characteristic of dual bluff body
1	4	4	$d_1 = d_2$
2	5	8	
3	3	1	
4	6	7	$d_1 < d_2$
5	9	2	
6	7	3	
7	2	5	$d_1 > d_2$
8	8	6	
9	1	9	
Reference for comparison in experiment			No. 4 bluff body

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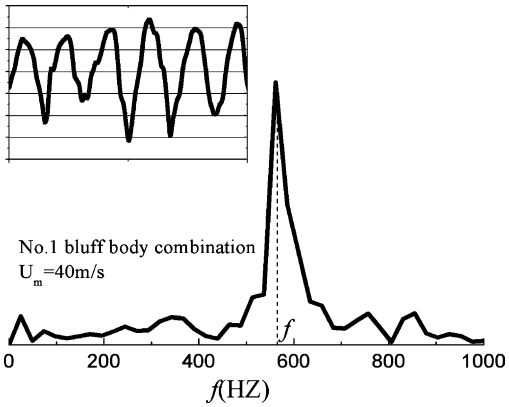


Fig. 5. Fluctuating pressure and its power spectrum.

3. Reference value for comparison in experiment

The typical result obtained in the test vortex flowmeter is shown in Fig. 5. The specified frequency is equals to the vortex shedding frequency f.

In order to establish a reference value for comparison, approach velocity and shedding frequency were measured for single bluff body over a velocity range of 4–60 m/s. Using air as the working fluid and the bluff body wide range of 13–15 mm, the Reynolds number (Re) varied from 5.59×10^3 to 1.6765×10^5. In order to optimize test number, we choose five single bluff bodies (Nos. 2, 4, 5, 6, and 7) to study vortex shedding frequency characteristic of single bluff body. A plot of Strouhal number versus Reynolds number and mean velocity for the five bluff bodies studied is shown in Fig. 6. For a given bluff body, the Strouhal number is fairly constant over the entire Reynolds number range tested. The Strouhal number mean value and the error ε for the five bluff bodies studied are shown in Table 3.

The linearity of the Strouhal number is evaluated quantitatively by the error ε. The error ε is defined by the following

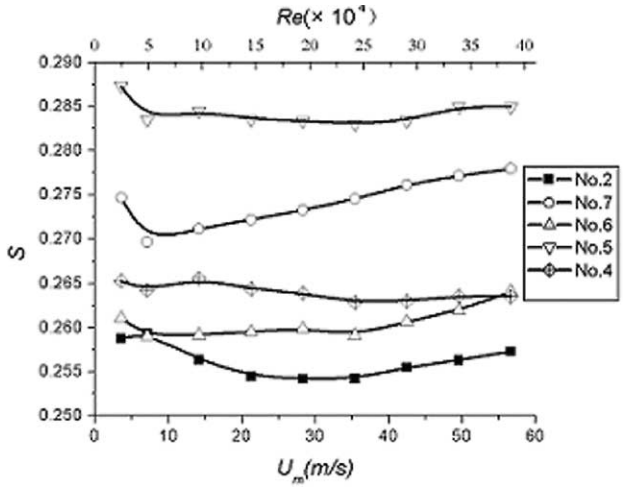


Fig. 6. Strouhal Number of single bluff body.

Table 3

Bluff body number	$\overline{S}$	ε (%)	U_{min} (m/s)
2	0.25627	0.636	4
7	0.27407	0.88	4
6	0.26049	0.536	4
5	0.28429	0.386	4
4	0.26403	0.306	4

Eq. (3):

$$\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\frac{|S_i - \overline{S}|}{\overline{S}} \tag{3}$$

($\overline{S}$ is the Strouhal number mean value, S_i is the Strouhal number of No. i U_m, N is the number of test U_m).

In Fig. 6, the Strouhal number is affected by the b and d of bluff body, and is affected by the U_m. The minimum velocity of measurement (U_{min}) for single bluff body is 4 m/s, which is quoted by Igarashi [14].

In Table 3, the error ε is affected by the b and d of bluff body. The error ε of No. 4 bluff body is minimal. However, the results of ε for a commercial vortex flowmeter was shown a value of ε as 0.79–1% ($2\text{m/s} < U_m < 20\text{m/s}$, $D = 150$ mm, mean value of S is 0.25–0.26) by Igarashi [14]. The uncertainty in the error ε of Strouhal number results mainly comes from the uncertainty in flowmeter experimental apparatus. The base error of flowmeter experimental apparatus is 0.5%. If thinking the base error of flowmeter experimental apparatus, the error ε of No. 4 bluff body is about 0.806%. Therefore, No. 4 bluff body is chosen as the reference for comparison in experiment.

4. Experimental results and discussion

4.1. Flow resistance of vortex shedders

The pressure distributions on the pipe are nearly constant in the region located 1D upstream and 2D downstream from the vortex shedder. The resistance coefficients for vortex shedder is defined by:

$$K = \frac{p_1 - p_2}{0.5\rho U_m^2} \tag{4}$$

where P_1 is the upstream pressure, P_2 is the downstream pressure, ρ is the density of work fluid (air), K is a non-dimensional number. The value of K is nearly constant regardless of the Reynolds number because of the unchanged location of separation point [13].

In order to simplified discussion in paper, the representative effects of Reynolds number, Re, and the opening size, L, on the flow resistances of vortex shedders based on different sized triangulate bluff body geometries were selected form nine bluff body combinations. The detailed effects of Reynolds number, Re, and the opening size, L, on the flow resistances of representative bluff body combinations and

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single bluff body are showed in Fig. 7. The main results of experimental of flow resistance of vortex shedders are as fellows:

(1) When $Re > 40,000$, the flow resistance for all bluff body combination of vortex shedders is nearly constant regardless of the Reynolds number, d_1 and d_2.
(2) The flow resistances of these dual bluff body combinations are larger than the flow resistance for single bluff body, But When $d_1 = d_2 = 13$ mm, $L = 40$, 45, 50, and 55 mm, the flow resistances of these dual bluff body combinations are less than or equal to the flow resistance for single bluff body.
(3) Except for No. 1 bluff body combinations, when $L = 40$ mm, $d_1 = d_2$ or $d_1 < d_2$, the flow resistances of bluff body combinations approximated to the flow resistance for single bluff body (as shown in Fig. 7(a–c)).
(4) When $d_1 > d_2$, the flow resistance for these bluff body combinations is larger than the flow resistance for single bluff body used in the industry regardless of the Reynolds number Re and opening length L (as shown in Fig. 7(d)).
(5) Except for No. 1 bluff body combinations, as opening length (L) increase, the flow resistances of bluff body combinations (K) increase.

4.2. Strouhal number

The vortex shedding frequency is obtained based on measured fluctuating pressure by piezoelectric press sensor. In order to investigate on fluid oscillation characteristics of body combination of vortex shedders at the symmetrically lateral side of second bluff body, two piezoelectric sensors are symmetrically stuck on the lateral side of second bluff body.

For these vortex shedders, these linearities of different bluff body combination have noticeable difference. The vortex shedding Strouhal number varies with its shape and the slit length L. In order to simplified discussion in paper, the better Strouhal number linearities bluff body combinations were selected form nine bluff body combinations. The detailed linearity of Strouhal numbers of optimization bluff body combinations and single bluff body are showed in Fig. 8. Fig. 8 presents the comparison between the Strouhal number of optimization bluff body combinations and single bluff body. The Strouhal numbers of these dual triangulate bluff body combinations are less than that of single bluff body. The Strouhal numbers of single bluff body is almost constant $S = 0.265$ for U_m in the range between 4 and 60 m/s, but those of dual triangulate bluff body combinations are scattered and the value is about 30% smaller

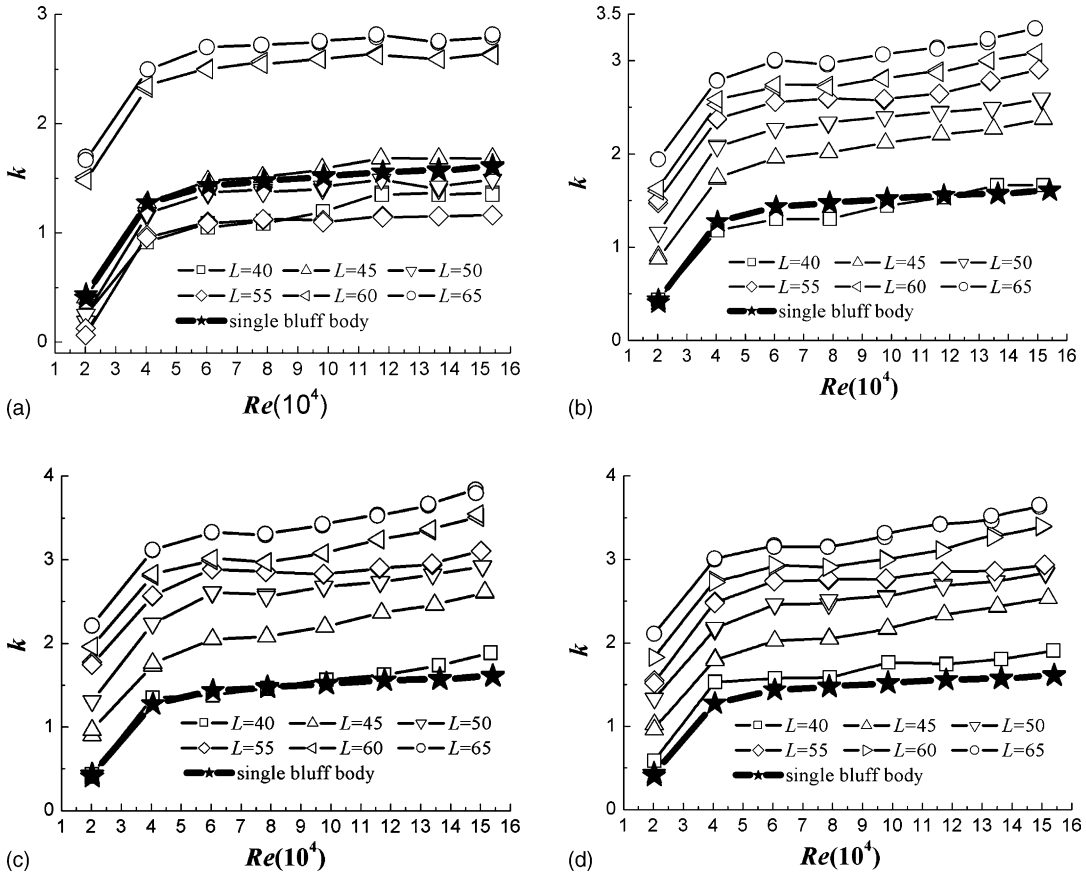


Fig. 7. Effect of Reynolds number and opening length on flow resistance ($d_1 > d_2$); (a) No. 1 bluff body combination ($d_1 = d_2$); (b) No. 2 bluff body combination ($d_1 = d_2$); (c) No. 6 bluff body combination ($d_1 < d_2$); (d) No. 9 bluff body combination.

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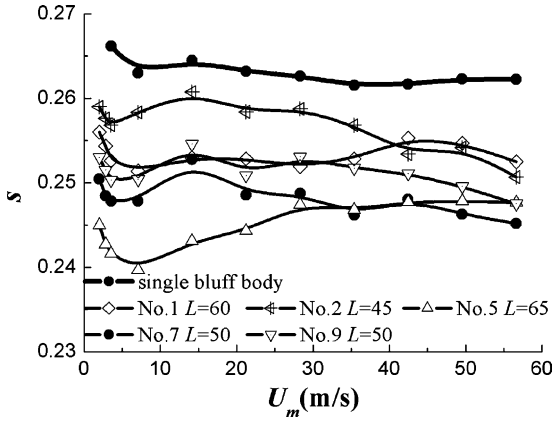


Fig. 8. Optimization bluff body combination and single bluff body Strouhal number.

than that of the single bluff body. Most of these, it is possible to measure the vortex shedding frequencies from a dual triangulate bluff body combination for a minimum velocity $U_{\min} = 2.5$ m/s, but it is possible to measure the vortex shedding frequencies from the single bluff body for a minimum velocity $U_{\min} = 4$ m/s. The flow range of application of U_{m} the new type two vortex shedders is extremely wide as compared to that of the single bluff body.

The linearity of the Strouhal number is evaluated quantitatively by ε. The error ε is defined by the following equation:

$$\varepsilon = \frac{1}{N}\sum_{i=1}^{N} \left|S_i - \overline{S}\right| / \overline{S} \tag{5}$$

($\overline{S}$ is the Strouhal number mean value, S_i is the Strouhal number of No. i U_{m}, N is the number of test U_{m})

The correlations of vortex shedding Strouhal number error of optimization dual triangulate bluff body combinations and single bluff body versus opening length is shown in Fig. 9. the results of a single bluff body having the same shape as that of a commercial vortex shedder presents $\varepsilon = 0.806\%$. The error ε for the dual triangulate bluff body combinations is larger than that of the single bluff body and is affected by opening length L, but there exists the optimum opening length L. For example, for No. 1 dual triangulate bluff body the optimum opening length L equals 60 and 65 mm. The error in these cased is same as that of single bluff body.

4.3. Sensitivity of the detection of vortex shedding frequency

The sensitivity is defined by the integration value around the specified frequencies in the power spectrum, but this method lead to noticeable error. Therefore, the sensitivity of the detection of the vortex shedding frequency is evaluated on the basis of the fluctuating pressure coefficient C'_p The vortex shedding frequency was obtained on the basis of f frequency analysis of the fluctuating pressure p' at the lateral side of the second bluff body portion. The strength of the vortex shedding and the regularity were defined by the fluctuating pressure coefficient:

$$c_{p'} = \frac{(\overline{p'^2})^{0.5}}{0.5pU_m^2} \tag{6}$$

According to the discussion above, the No. 1 dual triangulate bluff body combination is the optimum combination for dual vortex shedding flowmeter. The sensitivity of No. 1 dual triangulate bluff body combinations is studied at present. The correlations between C'_p and L in various U_{m} for No. 1 dual triangulate bluff body combinations are shown in Fig. 10.

The C'_p of No. 1 dual triangulate bluff body combinations is larger than that of a single body. The C'_p of No. 1 dual triangulate bluff body combinations increases in the low-velocity region, this fact indicates that the sensitivity increases with the decrease U_{m}. The C'_p of a single body is nearly constant regardless of U_{m}. When $L = 35$–50 mm ($L/d = 2.7$–3.9), the C'_p of No. 1 dual triangulate bluff body combinations increases with L. When $L = 50$–60 mm ($L/d = 3.9$–4.6), the C'_p of No. 1 dual triangulate bluff body combinations decreases with L. When $L = 60$–65 mm ($L/d = 4.6$–5), the C'_p of No. 1 dual triangulate bluff body combinations is nearly constant.

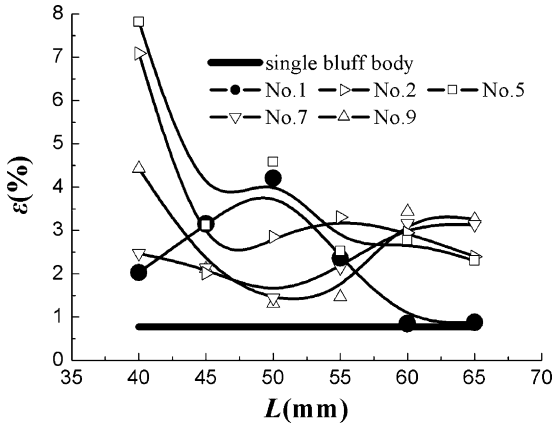


Fig. 9. Strouhal number error.

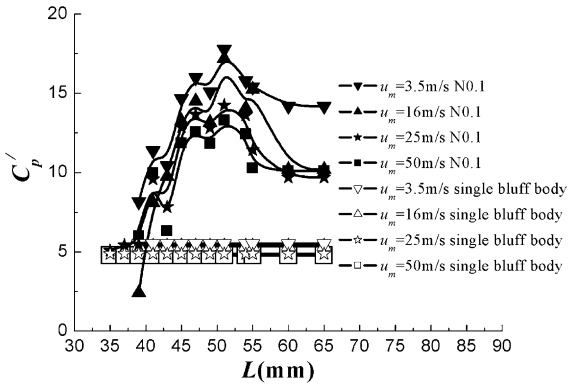


Fig. 10. R.M.S. fluctuating pressure.

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5. Conclusions

Experimental studies were carried out to investigate the performance of new type vortex shedder used in Karman vortex flowmeter. The results led to the following conclusions:

(1) The resistance coefficients for dual triangulate bluff body combinations vary with the opening length L. The value of those increase with L for all combinations and those are larger than the resistance coefficient of a single bluff body except for some combinations of equilateral dual triangulate bluff body.
(2) The fluctuating pressure just behind the separation point on the second shedder is best adapted for the sensor of the vortex shedding frequency.
(3) Sensitivity of the detection of vortex shedding frequency caused by the dual triangulate bluff body combinations is better than that of the a single bluff body. This fact indicates that improve the sensitivity low-flowrate sensitivity by using dual triangulate bluff body combinations in vortex flowmeter.
(4) The linearity of the Strouhal numbers of dual triangulate bluff body combinations varies with opening length L and d_1 and d_2. The best linearity of the Strouhal numbers of dual triangulate bluff body combinations is same as that of a single bluff body.
(5) The best size of dual triangulate bluff body corresponds to $d_1 = d_2 = 13\,\text{mm}$ ($d/D = 0.26$).
(6) For dual triangulate bluff body, the optimum width of the opening length corresponds to $L = 60$–$65\,\text{mm}$ ($L/d = 4.6$–5). In these cases, the strong vortex generates and regular vortex shedding occurs.

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