STROUHAL NUMBER OF TWO-DIMENSIONSAL RECTANGULAR PRISMS IN CONFINED SMOOTH AND GRID TURBULENT FLOWS

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ABSTRACT

The criterion for the onset of vortex-induced vibration, the Strouhal Number, has been measured in the case of two-dimensional rectangular prisms exposed to smooth and grid turbulent flows and submitted to confining walls. Similitude of the flow geometry is lost when reattachment occurs on the leeward side of the prisms, as detected from the pressure distribution. The effect of confinement in smooth and turbulent flows increases the value of the Strouhal Number: if the area of the prism facing the flow occupies 20% of the channel cross section, the measured Strouhal Number would be 25% larger than that of blockage free conditions. In the case of short afterbody prisms, turbulence reduces the value of the blockage free Strouhal Number as compared to the one in smooth flow conditions; in the case of long afterbody prisms, the blockage free Strouhal Number is slightly increased.

1. INTRODUCTION

The shedding of vortices in the wake of a structure exposed to a fluid flow has long been observed; some of the first drawings of vortices shed downstream a pile in a water flow have been produced by Leonardo da Vinci. These vortices form at any flow velocity and generate pressure fluctuations on the structure's surface that can trigger its vibration if insufficiently damped. This onset of vortex-induced vibration of a structure can be predicted using the Strouhal Number in order to determine the flow velocity for which one of its modal frequencies matches the vortex shedding frequency.

The Strouhal Number is a similitude criterion associated to the external shape of the structure and its value is obtained most of the time using a non-vibrating structure. From an historical point of view, Cenek Vincent Strouhal (1878) used a manual "whirling" apparatus on which rigid rods and flexible wires of different diameter (D) could be mounted; he measured with precision the whirling speed (V) as the wire emitted an amplified Aeolian tone at a given frequency (f) and he concluded that the ratio $f \times D/V$ was almost a constant for rods and varied in the case of vibrating wires (M.M. Zdravkovich, 1997). In the description of Strouhal's apparatus, the rods and the wires were mounted vertically at a radius of 0,35m from the axis of rotation and their circular translation velocity was varied between 2 and 6 m/s; then, in order to complete a revolution, the wire, although it had traveled a distance of over 4000D, took less than one second, which could indicate that the wire traveled in its own wake and was exposed to some wake turbulences. Since the energy of turbulence produced by rods and grids decay as $t^{-5/2}$ by viscosity (Hinze, 1959), they would have been considerably reduced as the wire returns to its location.

In the case of circular cylinders exposed to higher Reynolds Numbers (5×10^4<Reynolds Number < 10^6), turbulence increases the value of the Strouhal Number (P.W. Bearman, 1968).

This presentation visits the case of two-dimensional rectangular prisms exposed to a smooth flow with superimposed grid turbulence and under different wall constraints: it is concerned with the combined effects of turbulence and blockage on the Strouhal Number. This is a part of an extensive research study dealing with the pressure distributions around rectangular prisms.

2. EXPERIMENTAL

2.1 Flow Considerations

The flow around rectangular prisms (geometrically defined by H, d, L, respectively the side, the frontal and the long axis dimensions) has been observed to be affected on one hand, by the presence of walls constraining the expansion of the flow past the separation point (blockage) and, on the other hand, by the turbulence contained in the oncoming flow. In the case of two-dimensional rectangular prisms, blockage modifies their pressure distribution by an acceleration of the flow while turbulence may induce an earlier reattachment of the shear layer on the side wall of the prism.

Because of this induced reattachment, the flow about a given afterbody length (H/d) prism in turbulent flow is often considered similar to that about a longer afterbody in smooth flow (Laneville A. et al., 1973). The combined effects of turbulence and blockage on the flow and the Strouhal Number are not well known.

2.2 Similitude

In the case of rectangular prisms mounted in a square test section channel (cross section C) and exposed to uniform flows (fluid characterized by ρ and μ, respectively its density and dynamic viscosity) with and without superimposed grid turbulence (defined by the variables U, u', v', w', L_x, L_y and L_z, respectively the mean flow velocity, the three velocity fluctuations components (r.m.s.) and the three turbulent length scales), the independent similitude criteria are H/d, L/d, Ld/C (or S/C), $\rho Ud/\mu$, u'/U, v'/U, w'/U, L_x/d, L_y/d and L_z/d.

Since the number of independent similitude criteria in turbulent flows increased largely as compared to the cases of smooth flows, care should be taken to keep constant as many similitude criteria as possible. The dependent similitude criteria used in this study are the pressure coefficient ($Cp = (p-p_\infty)/(0.5\rho U^2)$ where p and p_∞ are respectively the mean local and oncoming flow static pressures) and the Strouhal Number.

2.3 Methodology

In turbulent flows, varying d, the frontal dimension of the prism, to evaluate the effects of blockage modifies the value of the three turbulent length scale ratios as well as its aspect ratio. The alternative consists in keeping constant the flow and the prism's characteristics and in moving two of the channel walls in order to modify C instead of d (Awbi, H.B, 1978; 1983). This is the approach of the present research project: two false walls are mounted inside the wind tunnel test section to generate a smaller channel around the model.

Six families of rectangular prisms (with H/d= 0.5, 0.6, 0.8, 1.0, 2.0 and 3.0) were tested under five different solid blockage ratios (S/C= 6.6%, 9%, 12%, 15% and 20%) and three types of flows (smooth flow, grid turbulent flow with 5% and 10% intensities). The Reynolds Number was set to exceed 5×10^4. The value of H/d was the result of different sizes of the side wall: the frontal and base walls' dimension was kept constant (d=12cm). Pressure taps were machined on all the models' surfaces at mid span (L/2 with L=1,215m): a higher concentration of taps (18 to 24 taps according to the length H) was laid on the side walls to closely monitor the pressure distribution and detect the occurrence of flow reattachment. The models were mounted vertically in the wind tunnel test section and the two vertical false walls were then displaced within the test section to generate the confining effects. A Pitot tube and a normal hot wire were mounted within this channel internal to the wind tunnel test section in order to measure the dynamic head and the flow turbulent properties and the vortex shedding frequency.

Bi-planar square mesh grids were positioned upstream the channel, at a distance of at least thirty grid bar size, in order to generate a uniform turbulence at the model location.

3. RESULTS

3.1 Effect of Blockage

The shear layers of rectangular prisms with short afterbody are not expected to reattach easily since the geometry of the flow should be similar to that of a normal flat plate. The pressure distribution measured on the side of the prism with H/d=0,6 and in smooth flow is shown in Figure 1 in the case of five blockage ratios. The abscissa is the dimensionless distance from the upstream corner.

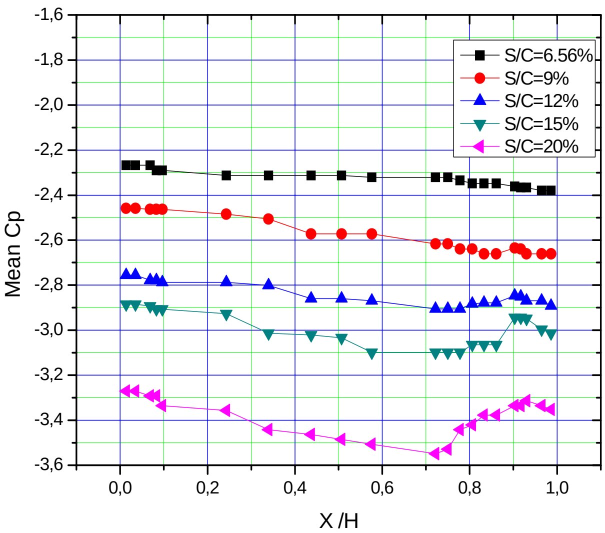

Figure 1 Side wall pressure distributions in the case of the H/d=0,6 prism in smooth flow.

As expected the local pressure becomes more negative as the blockage ratio increases and the pressure distribution remains similar for blockage ratios as high as 12%. For S/C>12%, a pressure recovery is observed as well as a reattachment at x/H=0,9. In the case of longer afterbody prisms, the effect of blockage is then expected to induce a reattachment. Complete similitude of the wake geometry and of the vortex-shedding process is not to be expected in the case of rectangular prisms exposed to a blockage causing reattachment.

3.2 Effect of Turbulence

Figure 2 shows the results in the case of the prism with H/d=2 exposed to three levels of grid turbulence but submitted to the identical wall constraint (S/C=9%).

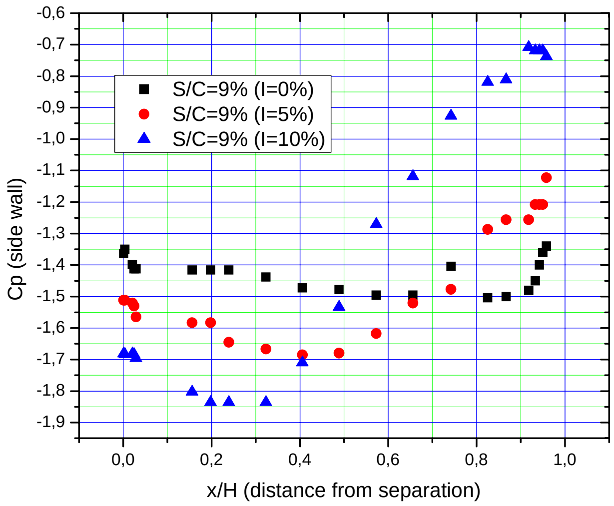

Figure 2 Side wall pressure distributions: case of the H/d=2 prism in confined turbulent flows.

The effect of turbulence for long afterbody rectangular prisms is relatively important. There is no evident similitude in the pressure distribution for a given H/d prism under the same constraint when the level of turbulence is varied. In this particular case, the flow does not reattach in smooth flow exposure and does when grid turbulence with 10% intensity has been superimposed to the oncoming uniform flow.

These observations suggest that the initial vorticity generated at the upstream corner of rectangular prisms is partly dissipated along the side wall before reaching the vortex formation region in the wake.

3.3 Strouhal Number

The Strouhal Number was determined using the value of the oncoming flow velocity. All the available data at this time are included in Figures 3 and 4.

The experimental data in the case of two-dimensional rectangular prisms clearly show that the measured Strouhal Number is modified by the effect of blockage whether in smooth flow or in uniform flow with superimposed grid turbulence. In the case of the prisms with H/d ≤ 2, as shown in

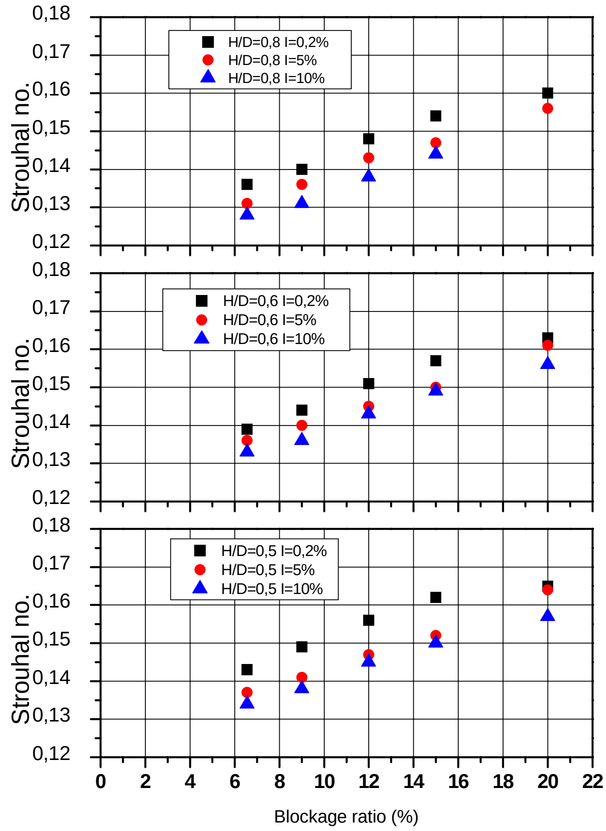

Figure 3 Strouhal Number for 0,5 ≤H/d ≤ 0,8

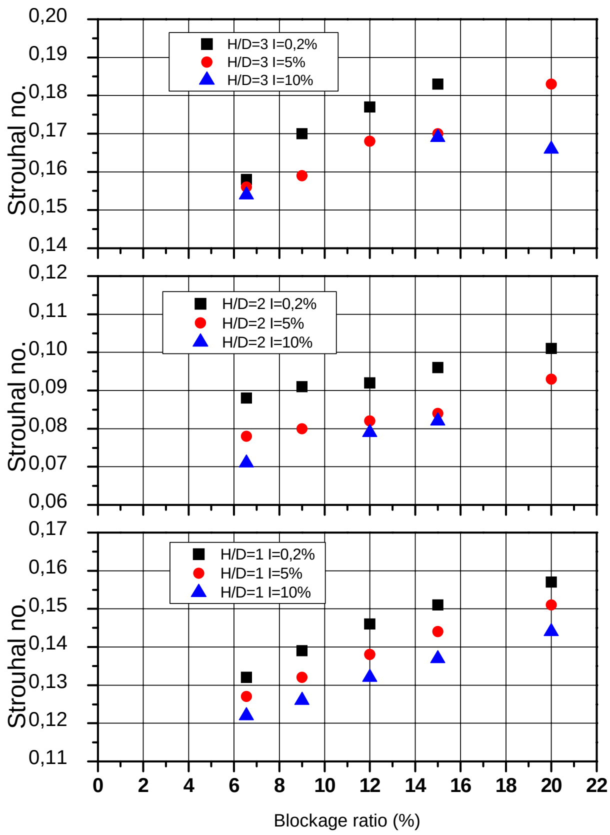

Figure 4 Strouhal Number for 1,0 ≤H/d ≤ 3,0

Figures 3 and 4, the value of the Strouhal Number increases almost linearly with the blockage ratio if S/C $\leq$ 12%; a non-linear behavior is nevertheless observed when the blockage ratio exceeds 12% and, in the particular case of the H/d=3 prism exposed to a 10% turbulence intensity, the Strouhal Number for S/C=20% is smaller than that for S/C=15%. This non-linear behavior suggests the occurrence of reattachment and that similitude might have been lost.

The effect of turbulence, at first, seems to reduce the value of the Strouhal Number but this assessment should be made using the value at S/C=0. This extrapolation is achieved by using the data obtained in absence of reattachment. Tables 1 and 2 show the results of this procedure adopting the hypothesis of a linear extrapolation in the direction S/C=0.

H/d	Strouhal Number (S/C=0)		
	Smooth Flow	u'/U=5%	u'/U=10%
0,5	0,1285	0,125	0,121
0,6	0,1248	0.1251	0,1195
0,8	0,121	0,1186	0,1145
1,0	0,1181	0,1138	0,110
2,0	0,0838	0,0735	0,0625
3,0	0,1415	0,1441	0,142

Table 1: Strouhal Number corrected for blockage.

H/d	Slope = d(Strouhal Number)/d (S/C)		
	Smooth Flow	u'/U=5%	u'/U=10%
0,5	0,00226	0,00180	0,00194
0,6	0,00215	0.00166	0,00195
0,8	0,00220	0,00194	0,0,00195
1,0	0,00225	0,00201	0,00180
2,0	0,00088	0,000705	0,00132
3,0	0,00298	0,00180	0,00178

Table 2: Slope of the Strouhal Number as function of S/C.

The effect of turbulence is then observed to reduce the value of the Strouhal Number for prisms with H/d $\leq$ 2 and to increase its value for longer afterbody prisms. These variations remain small but they nevertheless support the hypothesis that the flow about a given afterbody length (H/d) prism in turbulent flow can be considered similar to that about a longer afterbody in smooth flow. Table 2 reveals how turbulence modifies the constraining effect of the walls: as the level of turbulence is increased from smooth flow to 10% grid turbulence conditions, the slope is at first reduced and then increased in the case of most prisms with H/d $\leq$ 2 .

Considering a square section prism mounted in a channel under such conditions as S/C=20% and u'/U=10%, the Strouhal Number is 0,145 as compared to 0,118 in smooth flow and blockage free conditions; the flow velocity for the onset of vortex-induced vibration differs by 23% between these two conditions. Blockage plays the major role of the combination.

In the case of prisms in the range 2 < H/d < 3, reattachment causes the Strouhal Number to jump from a value of the order of 0,08 to 0,14; this difference, leading to a 75% difference in the flow velocity at the onset of VIV, result from small variations in blockage, turbulence or both.

4. CONCLUSION

The effects of the combination of wall confinement and grid turbulence on the flow around two-dimensional rectangular section prisms and the onset of vortex-induced vibration were investigated in a wind tunnel. This was achieved by measuring the pressure distributions and the Strouhal Number of different afterbody prisms. The methodology consisted in moving two false walls and superimposing grid turbulence on an otherwise smooth flow. In the range 5×10^4<Reynolds Number < 10^5, the followings are observed:

- The Strouhal Number of rectangular prisms with H/d $\leq$ 2 is reduced with turbulence once corrections for blockage effects have been applied. This reduction remains small: less than half of the level of turbulence percentage.
- In the case of longer afterbody prisms, the Strouhal Number in unconfined conditions is observed to increase slightly with turbulence.
- The constraining effect of the walls varies with the level of turbulence.
- The measured pressure distributions show that reattachment is induced by both wall constraints and turbulence, especially for blockage ratios larger than 12%.

The results support the hypothesis that the flow about a given afterbody length (H/d) rectangular section prism in turbulent flow is similar to that about a longer afterbody in smooth flow.

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