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EFFECT OF LOCAL AIR COMPRESSIBILITY ON THE AERODYNAMICS OF RECTANGULAR PRISMS AT MACH NUMBERS BELOW 0.3

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Abstract: *It is generally accepted that the upper limit of the incompressible regime in air is a Mach number of 0.30. In many cases this rule of thumb can bring definite limitations to the maximum Reynolds number that can be achieved during sub-scale wind-tunnel tests where compressibility effects need to be limited to represent as accurately as possible full scale conditions. In this research, the sensitivity to compressibility effects of rectangular prisms with sharp edges was studied in a pressurised wind tunnel where the Reynolds number and Mach number of the experiments could be controlled independently while keeping the model dimensions constant. Typically a constant Reynolds number was achieved at two or three Mach numbers by varying the pressure in the test section to compensate for the increase or decrease in wind speeds. Compressibility effects were observed for some cases even for tests carried out at Mach number below 0.30. This paper describes the experimental conditions, presents the cases where compressibility effects are suspected and proposes a rationale for the observations.*

1 INTRODUCTION

The compressibility of the air is not a property that generally influences the action of wind on buildings and bridges or the aerodynamic loads on surface vehicles. Air is considered incompressible below a Mach number (Ma) of 0.30 corresponding approximately to a wind speed of 100 m/s. Such a wind speed is well in excess of most design wind speed of structures with a few exceptions, e.g., the instability limit for bridges in Hong Kong has been established at 92-100 m/s and high speed trains and race cars can travel above 100 m/s. However, for practical purposes, air can be considered incompressible for the aerodynamics of bodies that do not fly.

Wind-tunnel tests on detailed models at reduced scale is the common approach taken to study the aerodynamics and to predict wind effects. If the flow is in the incompressible regime at full scale conditions, it should also be kept in the same regime in the wind tunnel. However, for cases where the body is or might be sensitive to Reynolds number (*Re*), there is a need to compensate for sub-scale model dimensions by increasing the wind speed to maximize *Re*. The necessity to reach high *Re* in model scale experiments while keeping the flow in the incompressible regime has promote the use of pressurised wind tunnels or wind tunnels with very large test section, e.g. Refs. [1] and [2]. Pressurised wind tunnels can keep *Ma* constant while increasing the test section pressure to raise the air density and thus *Re*. In the same manner, *Re* can be held constant while *Ma* is changed.

To verify if the aerodynamics of a bluff body with sharp edges were influenced by compressibility near Mach 0.30, a study was conducted at the National Research Council Canada (NRC) and is presented in this paper. This study is part of comprehensive research program on *Re* effects on rectangular prisms reported in Refs. [3] and [4].

2 Influence of compressibility on the aerodynamics

2.1 Summary of the experiments

Experiments were carried out on rectangular prisms with fineness ratios (width-to-depth) of 2, 3 and 4 in the 2D test section of the 1.5 m Trisonic Blowdown Wind Tunnel of the NRC for a *Re* range of $0.15 \cdot 10^6$ to $4 \cdot 10^6$ based on the prisms constant depth *D*, for a *Ma* range of 0.075 to 0.30. Three edge configurations were investigated: square edges, small chamfers and large chamfers (see Fig. 1). Each configuration was swept through a pitch angle range of $-2°$ to $+10°$ (positive nose-up) in increments of 2°.

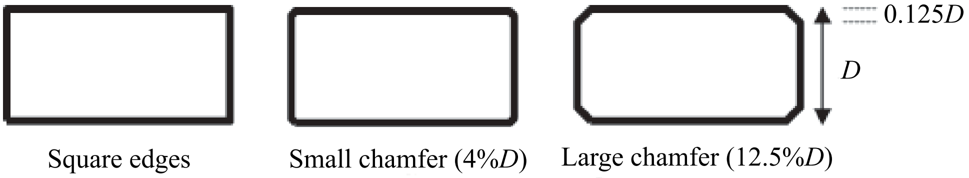

Figure 1: Cross-sections and edge configurations investigated

The measurements included: drag, lift and pitching moment using sidewall force balances; surface pressures on a chord-wise strip and span-wise variations of the base pressures using pressure scanners embedded in the model; and, the wake dominant frequencies using a hot-wire probe. Data acquisition was performed at a high sampling rate (4800 Hz) for all forces, surface pressures and wake fluctuations for ≈8 seconds per data point at a specified angle of attack. Most of the experiments were carried out in smooth flow with a turbulence intensity of 0.3%. Tests in turbulent flow were also made using a bi-planar grid providing an intensity of longitudinal turbulence of 5% with corresponding integral length scales of 35 mm.

A detailed description of the experiments is presented by D'Auteuil in Ref. [3]. The experiments have shown that the fineness ratio, the edge configuration, the angle of attack, and the wind turbulence affected the aerodynamics of the prisms and these effects appeared to be influenced by *Re* suggesting that there is a limit to the insensitivity of bluff bodies with sharp edges to *Re* as reported by D'Auteuil, Ref. [3].

With the specific objective to depict possible compressibility effects, tests points at constant *Re* for varying *Ma* were done and a partial list is shown in Table 1.

2.2 Fineness ratio 2, large chamfers

Fig. 2 presents the variations of drag, lift and pitching moment coefficients, respectively C_D, C_L and C_M with angle of attack, at constant *Re*= $2.5 \cdot 10^6$ for three *Ma*, for a fineness ratio of

Table 1: Test conditions investigated in the compressibility study

Models	Edges	Re (10^6)	Ma	Flow
2:1	large chamfer	2.5	0.30, 0.23, 0.15	smooth
3:1, 4:1	large chamfer	2.5	0.30, 0.15	smooth
2:1, 3:1, 4:1	small chamfer	2.0	0.30, 0.15	smooth
2:1, 3:1, 4:1	large chamfer	1.0	0.30, 0.265	turbulent
2:1, 4:1	square edges	1.0	0.30, 0.265	turbulent

2 with large chamfers in smooth flow. A gradual sign reversal of C_L variation with angle of attack around 0° was observed between *Ma*= 0.15 and 0.30 while the drag and pitching moment coefficients were only slightly affected. Note also the non-zero value of C_L at 0°, however all three curves converged to a near zero C_L at the same angle of attack indicating a slight model asymmetry common to all three tests.

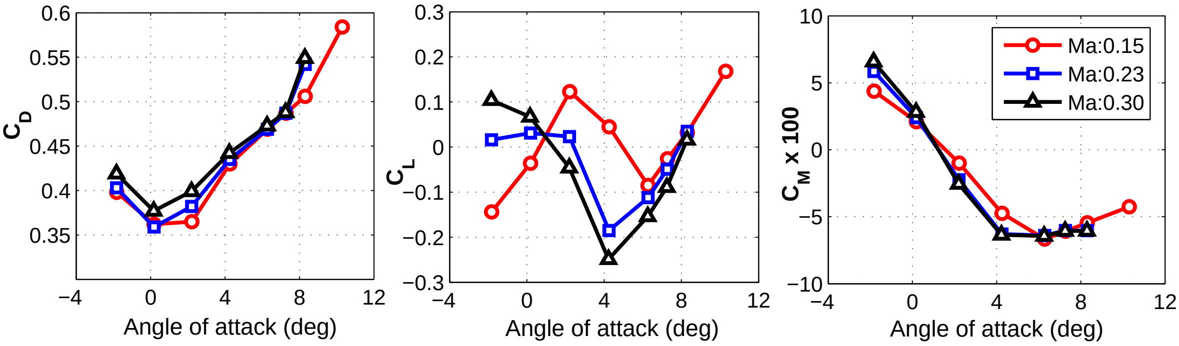

Figure 2: Variations of C_D, C_L and C_M with angle of attack at constant *Re*= $2.5{\cdot}10^6$ for three *Ma*, for a fineness ratio of 2 and large chamfers in smooth flow.

The sign reversal of the C_L slope around 0° is an important aerodynamic change which could lead to galloping instability based on the Den Hartog criteria, Ref. [3]. This slope reversal of C_L is not dissimilar to the slope reversal seen for the same prism when turbulence was added to the flow or when *Re* was increased while *Ma* was kept at 0.15, Ref. [3]. These effects are linked to the state of the boundary layer near the separation point and the location of the separation point, being either at the first or second edge of the chamfer.

It was verified that the turbulence intensity in the test section for the smooth tests varied only slightly between *Ma*= 0.30 and *Ma*= 0.15 (from ≈0.25% to 0.45%, Ref. [5]) ruling out the possibility that the slope reversal was caused by a change in the flow conditions.

The slope reversal of C_L was not observed for the 3:1 or 4:1 prisms with large chamfers indicating that compressibility effects were dependent on the fineness ratio of the body. However, a sign reversal of the pitching moment slope was observed for the 3:1 prism with large chamfer between *Ma*= 0.15 and 0.30. Adding turbulence (5%) to the flow eliminated the slope reversal of C_L keeping it positive at *Ma*= 0.15 and 0.30 for the 2:1 prism with large chamfers. Graphs showing the variations of the force coefficients with *Ma* and all other parameters of Table 1 will be reported in the full paper.

3 Discussion

An inspection of the surface pressure distribution is necessary to understand further the nature of the observed compressibility effects. To verify that the pressures measured on the centerline chord-wise strip were representative of the variations of Fig. 2, coefficients obtained from integration of surface pressures (2D) were compared to the coefficients obtained from the force balances (3D). For most cases the C_L were in good agreement, the C_D were under or over- estimated depending on the case and the C_M matched well up to 4° to 6°. The span-wise variations of the base pressure also indicated good 2D flow conditions for angles below 6° in smooth flow.

All pressure coefficients (C_p) calculated in this study take into account the effect of compressibility based on the adiabatic and isentropic flow equations which relate absolute pressure, air density, air temperature and Mach number. It is believed that some of the variations shown in Fig. 2 could be explained by local instantaneous surface pressures near the leading edges reaching extreme negative values, entering well in the compressibile regime. Examples of mean pressure field variations are presented in Fig. 3 at constant *Re* ($2.5 \cdot 10^6$) for three *Ma*.

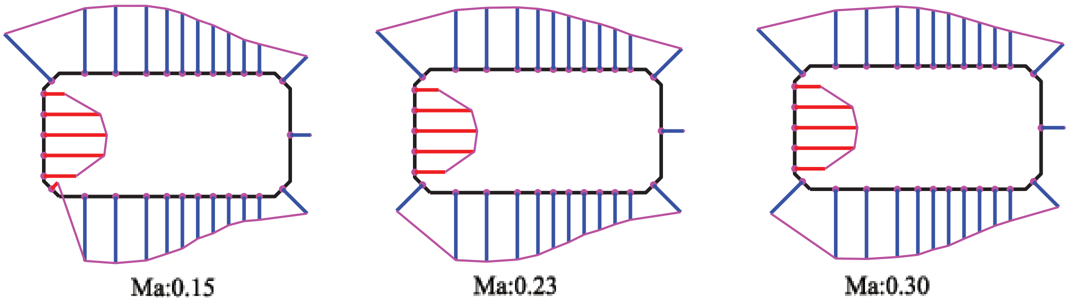

Figure 3: Variations of mean C_p as a function of *Ma* at +2° for a 2:1 rectangular prism with large chamfer in smooth flow. Inwards vectors: pressure; outwards: suction; C_p=1 for a vector length of $D/2$; flow from left.

At +2°, the pressure tap on the lower leading edge chamfer showed a positive pressure at *Ma*= 0.15 and a growing negative pressure as *Ma* passed from 0.23 to 0.30. The pressure distribution near the leading edge chamfer was found to differ for the three *Ma* indicating a changing flow structure that could be attributed to compressibility effects. The extreme values of C_p will be presented in the full paper.

4 Conclusions

An experimental investigation on rectangular prisms in a pressurised wind tunnel has shown that the aerodynamics of bluff bodies can be affected by the compressibility of the air even for a Mach number lower than 0.30. The maximum wind speed for an experiment should thus be selected with care when attempting to maximize the Reynolds number by compensating for a reduced geometrical scale with increased wind speed.

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