11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

FLUCTUATING LOADS ON CANTILEVERED CYLINDERS IN UNIFORM FLOW

C.J. APELT[1] and T.A. FOX[2]

[1]Dept of Civil Engineering, University of Queensland, QLD 4072, AUSTRALIA

[2]Heat Transfer and Fluid Flow Service, Harwell, UNITED KINGDOM

ABSTRACT

The fluctuating pressures and sectional forces on cantilevered circular cylinders with aspect ratios from 4 to 30 have been measured at Reynolds number 4.4×10^4 in a uniform flow with low turbulence and are compared with similar measurements at mid-span of a "long" cylinder. The distributions of r.m.s. pressures and forces vary with aspect ratio, A, if A<13 but for A≥13 the magnitude of each quantity at a given location is independent of A. If A>20 the effects of the free end are not measurable beyond 20 diameters from it. Frequencies of vortex shedding vary in step-like fashion along the cantilever; the variation is independent of A for A>10 but depends on A for A≤10. If A<7 vortex shedding does not occur.

INTRODUCTION

The measurements of fluctuating effects on cantilevered circular cylinders in low turbulence, uniform cross-flow in the upper subcritical range of Reynolds number reported here are part of a broader study of flows past circular cylinders. An extensive set of experiments carried out by West (1986) on cylinders in nominally two-dimensional conditions at subcritical Reynolds numbers, reported by West and Apelt (1992), demonstrated that many of the variations between published results for fluctuating effects can be attributed to "secondary" differences between the experimental facilities and methodologies. At the same Reynolds number, changes in parameters such as free-stream turbulence, surface finish on the cylinder, aspect ratio, end conditions and wind tunnel blockage can cause substantial changes in the fluctuating pressures and forces.

West (1986) showed that it is essential to fit suitable end plates to the cylinder to control end effects and that with end plates fitted, a cylinder with aspect ratio between end plates, $A = \ell/d$, of 10 or larger gives "long" cylinder results at mid-span. Here ℓ is the length between end plates and d is the diameter. In addition to r.m.s. pressures West (1986) measured local, sectional r.m.s. lift and drag coefficients from direct on-line integration of the fluctuating pressure distribution. The only other measurements of this kind known to the authors are those reported by Loiseau and Szechenyi (1972) for Reynolds numbers in the range 2.6×10^5 to 6.5×10^6 and by Ribeiro (1991) for Reynolds numbers (2.5 and 3.8) $\times\ 10^5$ and roughened cylinders.

The data for fluctuating pressures and forces on "long" cylinders obtained by West (1986) under carefully controlled conditions have provided the reference against which the effects of the free end on flows past cantilevered cylinders can be determined. Published information on fluctuating effects on cantilevered cylinders known to the authors is limited to pressure measurements by Farivar (1981) on cantilevers with A < 13, at an upper subcritical Reynolds number. These showed that the spanwise distribution of the maximum fluctuating pressure coefficient is dependent on A. If A < 7, C'_{pmax} is small and is constant along the length of the cantilever because vortex shedding does not occur when A is less than 7 (Okamoto & Yagita 1973). If A > 7 the value of C'_{pmax} is large and its spanwise variation is non-uniform; peak fluctuations occur at about half a diameter from the free-end, followed by a reduction in C'_{pmax} towards the fixed end of the cantilever. Farivar (1981) reported a reduction in the vortex shedding frequency towards the free-end for 10 ≤ A ≤ 12.5. The Strouhal number based on the surface pressure fluctuations showed the reduction to occur in two discrete steps and Farivar suggested that these discontinuities indicate the existence of isolated vortex loops within the wake, each of which has a different detachment frequency.

The experiments reported here were designed to determine the effects of the free end on flow past cantilevered cylinders for aspect ratios ranging up to those large enough for part of the cylinder to experience undisturbed, "long" cylinder conditions. The largest aspect ratio tested was 30 and it was found that, if A > 20, the disturbance from the free end is not measurable at distances greater than 20 diameters from it. The data measured for time-averaged pressures and local mean drag coefficients are reported in Fox and West (1991). This paper presents the data for fluctuating effects.

EXPERIMENTAL DETAILS

The experiments were carried out in a low-speed closed circuit wind tunnel of the Department of Civil Engineering at The University of Queensland. The working section has dimensions of 1.22m width × 0.8m height × 3.5m length and the flow is uniform to within ±0.3% with a freestream turbulence intensity of approximately 0.2% at the model station. The free-stream velocity U_0 was determined from the pressure difference between the tunnel contraction tappings measured with a Betz type micromanometer with resolution to 0.1mm of water.

All model cylinders used were 31.7mm in diameter and were of polished brass. In the experiments on "long" cylinders the model spanned across the larger dimension of the working section and was fitted at each end with end plates with dimensions recommended by Stansby (1974). The cantilever models entered the working section through a sealed hole in one side wall, an end plate was fitted at the support end and the free end was closed.

In both configurations, fluctuating pressures were measured with miniature pressure transducers which were mounted just below the surface of the model and which communicated to the surface through a 0.5mm diameter by 1.5mm long passage. Dynamic calibration of the transducers, mounted in position in the model, was carried out over the expected frequency range against a standard Bruel and Kjaer condenser microphone in a tuned resonant chamber. Details are given by West (1986). Ten transducers were mounted in a capsule which formed a short length of the cylinder, the ten pressure tappings being spaced around the circumference at one cross-section. Preliminary investigations had shown that the r.m.s. pressure distribution around the cylinder and the sectional r.m.s. lift could be measured with satisfactory accuracy with an appropriate arrangement of ten pressure tappings. For measurement of sectional r.m.s. drag a different arrangement of the ten pressure tappings was required. Spanwise variations of the r.m.s. pressures, lift and drag were measured by moving the appropriate capsule along the model cylinder.

The local sectional r.m.s. force was determined from the transducers in the capsule by conditioning each output signal according to the position of the transducer and performing an analogue summation on line. The accuracy of measurement of r.m.s. lift and drag is estimated as 2% and 6%, respectively.

The summed signal from the lift capsule was analysed with a B & K 2034 Signal Analyser to determine its frequency content and the dominant frequency, n, was used to calculate the Strouhal number, $S_t = nd/U_o$.

RESULTS : LONG CYLINDER

The r.m.s. pressures measured at mid-span of the cylinder with end plates fitted at each end are shown in Figure 1(a) as distributions of C'_p for five values of Reynolds number, R, in the upper subcritical range. C'_p is defined as $p'/(\frac{1}{2}\rho U_o^2)$ where p' is the r.m.s. pressure and ρ is the fluid density. The angular position $\theta=0$ corresponds to the upstream stagnation point and the distributions are symmetric about the diameter through $\theta=0$. The aspect ratio of the cylinder between end plates was greater than 14 in each case and "long" cylinder conditions (i.e. no end effects) existed at mid-span. The area blockage was 4 percent and no blockage correction has been applied. The distributions of C'_p are characteristic for sub-critical conditions. The maximum of C'_p near $\theta=80°$ is associated with separation of the laminar boundary layer and the maximum near $\theta=160°$ is associated with the formation and periodic shedding of the vortex wake. In the subcritical flow range increases in Reynolds number result in general increases in the magnitudes of C'_p without change to the basic shape of the distribution except that the maximum near $\theta=160°$ increases more rapidly than does that near $\theta=80°$.

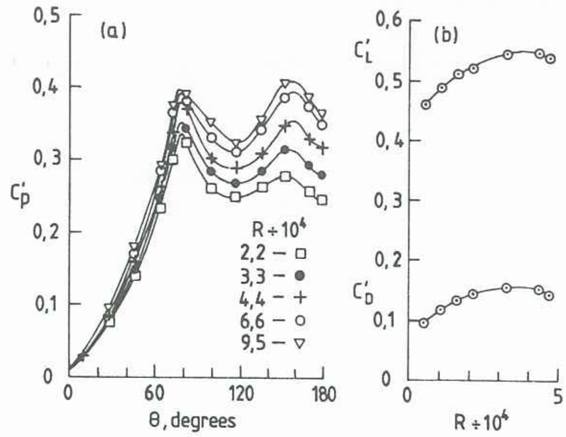

Figure 1. Long cylinder (A=35) in low turbulence (0.002); (a), r.m.s. pressure distributions at mid-span; (b), sectional r.m.s. Lift and Drag coefficients.

The local, sectional r.m.s. lift and drag force coefficients, C'_L and C'_D, corresponding to the r.m.s. pressure distributions are given in Figure 1(b). These vary smoothly with Reynolds number and each has a maximum near $R=8\times10^4$. This is not inconsistent with the C'_p curves since the fluctuating pressures are not perfectly correlated around the cylinder.

RESULTS : CANTILEVERED CYLINDERS

Since the r.m.s. pressures and forces measured for "long" cylinder conditions vary smoothly with Reynolds number over the part of the subcritical range studied, the experiments on cantilevered cylinders were carried out at one Reynolds number within the range i.e. 4.4×10^4. The aspect ratios of the cantilevered cylinders ranged from 4 to 30, the length, ℓ, in this case being that from the free end to the end-plate at the support end.

R.m.s. Pressures

The circumferential distribution of r.m.s. pressures measured on the cantilevered cylinders are shown in Figure 2(a) to (h). Each panel contains the distributions measured at the stated distance from the free end, y, for the different aspect ratios indicated.

The r.m.s. pressure distributions measured on a cantilever with aspect ratio 30 are included in each panel of Figure 2 for reference. For A>20, the effects of the free end are fully developed, do not extend beyond y/d=20 and are not changed by further increases in A.

For a cantilever with A = 4, the r.m.s. pressures are small everywhere. The distributions shown in Figure 2(a) to (d) are typical for A < 7 and are similar to those presented for A=5 by Farivar (1981). When A<7 vortex shedding does not occur, being suppressed by the flow over the free end.

At A = 7 vortex shedding occurs at locations away from the highly disturbed region near the free end and fluctuating pressures on the surface of the cylinder are significant. The distributions of C'_p in Figures 2(a) to (e) are similar in shape to those measured at the same locations for A=30, except at y/d = 0.61, though the magnitudes are smaller. Also for A=7 the variations along the cylinder of C'_p at given values of θ are similar to those for A=30. This suggests that the fluid mechanisms

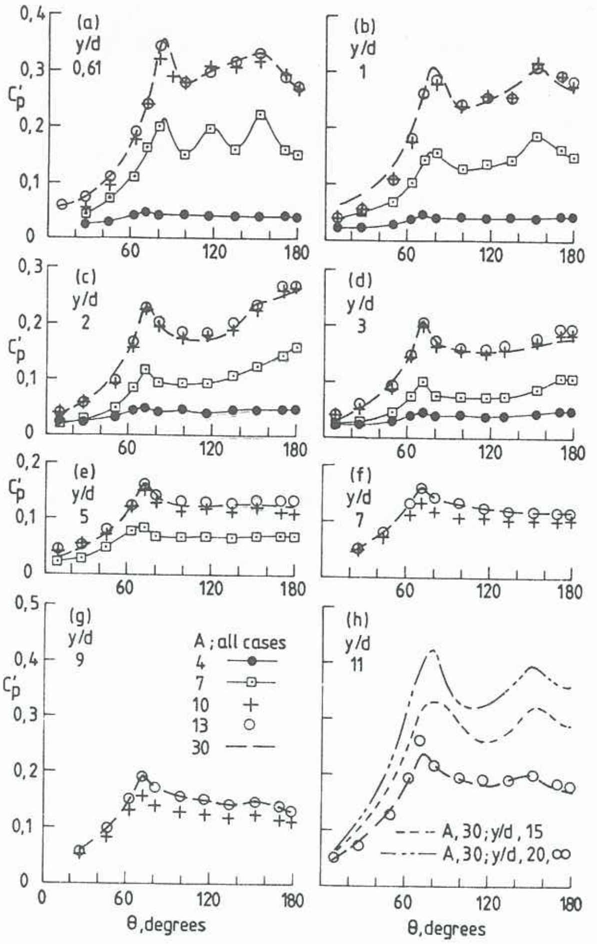

Figure 2. Cantilevered cylinders with A from 4 to 30; r.m.s. pressure distributions in low turbulence (0.002) at R=4.4×10^4.

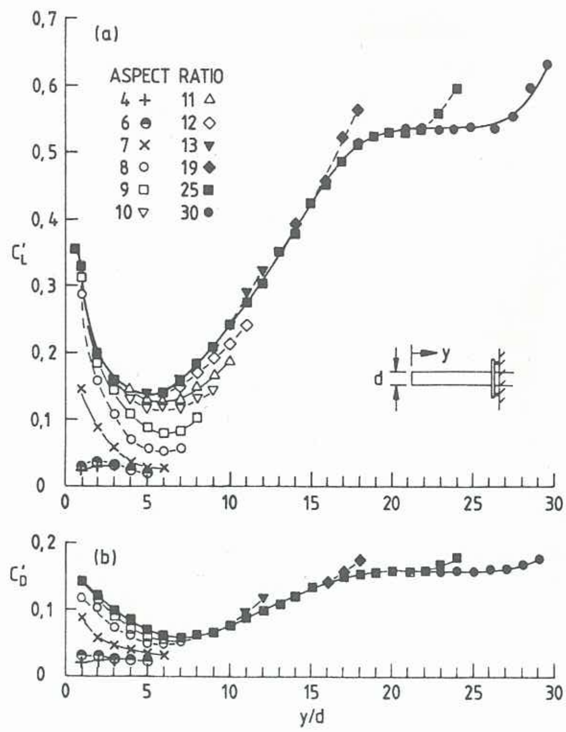

Figure 3. Cantilevered cylinders with A from 4 to 30; sectional r.m.s. Lift and Drag coefficients in low turbulence (0.002) at R=4.4×10^4.

occurring along the length of the A=7 cantilever are similar to those for the y/d < 7 region of the A=30 case. Flow in this region is dominated by the presence of strong downwash in the wake which forces the position of vortex formation to migrate downstream. The boundary at the fixed end of the A=7 cantilever appears to force the position of vortex formation further downstream, reducing the value of C'_p relative to the A=30 case at each location.

As A is increased beyond 7 the conditions near the free end become independent of aspect ratio and the effects from the fixed end are restricted to a region near it. For example, the distributions of C'_p measured at locations y/d ≤ 5 for A = 10 are almost the same as those measured at corresponding locations for A=30, whereas those in the region y/d > 5 show reduced magnitudes of C'_p for A=10. At A = 13 the distributions of C'_p are the same as those for A=30 at all locations y/d ≤ 11 within the accuracy of measurement (Figure 2(a) to (h)). Further increases in aspect ratio produce no measurable change in distributions of C'_p for y/d ≤ 11. The distributions measured at larger values of y/d for the case of A=30 are shown in Figure 2(h) and in this case the distributions at y/d ≥ 20 but away from the local influence of the end plate are the same as those for the "long" cylinder case presented in Figure 1 at corresponding conditions. This was verified by measurement of the r.m.s. pressure distribution at mid-span after the cantilevered cylinder model had been extended across the full span of the tunnel and fitted with a second end plate. As indicated in Figure 2(h), the same result was obtained for this case as at y/d = 20 for A=30.

<u>R.m.s. Force Coefficients</u>

The local sectional r.m.s. lift coefficients measured along cantilevers with aspect ratios 4 to 30 are presented in Figure 3(a). These divide into aspect ratio dependent groups which are consistent with the r.m.s. pressure distributions discussed above. For A < 13, the distributions of C'_L are similar to the spanwise variation of the maximum fluctuating pressure coefficient presented by Farivar (1981) and divide into the same two aspect ratio dependent groups. In the first group, for A < 7, the value of C'_L is small because of the complete suppression of vortex shedding. In the second group, for 7 ≤ A < 13, the value of C'_L is significant and the distributions form a family of curves of similar shape. These exhibit a local peak in the fluctuating lift near the free-end, followed by a reduction in the value of C'_L to a minimum near y/d=6. This is consistent with the downstream migration of vortex formation in this region. Conversely, upstream migration of the vortex formation position at locations beyond y/d=6 leads to increases in fluctuating lift with distance from the free end. As A increases in this second group, the effect of the boundary at the fixed end on downwash in the wake is reduced and progressively longer lengths of the cantilever from the free-end display the local value of C'_L associated with cantilevers with A ≥ 13.

For cantilevers with A ≥ 13 the distribution of C'_L is identical to that for the case A=30 except for the local deviation in the vicinity of the end plate. There is a local peak near the free-end, a reduction in the region y/d < 5, and an increase with y/d beyond y/d=5. If the cantilever is sufficiently long, as for example when A=25 or 30, the flow conditions associated with an infinitely long cylinder are established in the region beyond y/d=20 where the value of C'_L is that for "long" cylinder conditions.

The local sectional drag coefficients for cantilevers with aspect ratios from 4 to 30 are shown in Figure 3(b). The general pattern of distributions of C'_D is similar to that for C'_L in Figure 3(a). The distributions can be divided into the two aspect ratio related groups previously identified. In the first group, when A < 7, C'_D is very small and remains constant along the cylinder because of the suppression of vortex shedding. In the second group, when A ≥ 7, the variation of C'_D along the cylinder is similar to that already described for C'_L and tends, with increasing aspect ratio, towards that for a cantilever of A=30. Indeed, for A ≥ 10 the value of C'_D at each location is, within the accuracy of the experiment, identical to that for the A=30 cantilever.

Strouhal Number

The Strouhal numbers based on the dominant frequency in the local lift fluctuations for aspect ratios in the range 7 to 30 are shown in Figure 4. It was not possible to determine a dominant frequency in the spectra of lift signals measured on cantilevers of A < 7 because of the absence of vortex shedding from the cylinder.

Figure 4 shows that the Strouhal numbers exhibit a step-like variation along the length of the cantilever which is unique to a given aspect ratio when A ≤ 10 and identical to the A=30 case when A > 10. This suggests a cellular structure to vortex shedding which does not change with aspect ratio when A > 10 (consistent with the results of Farivar (1981) for the range 10 ≤ A ≤ 12.5) but is aspect ratio dependent when A ≤ 10. In the latter case, as A increases from 7, the Strouhal number associated

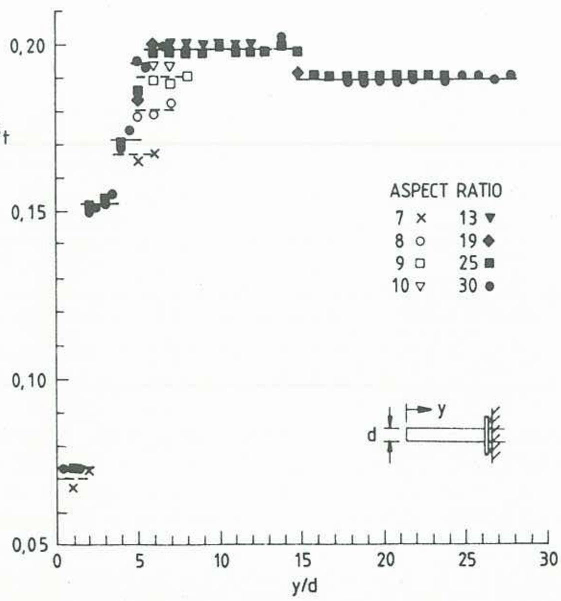

Figure 4. Cantilevered cylinders with A from 7 to 30; local Strouhal Numbers in low turbulence (0.002) at R = 4.4×10^4.

with the final cell at the fixed end increases towards the value achieved at the corresponding location on cantilevers with A > 10. However, the cellular structure in the region y/d < 5 is unaffected by changes in A over the full range considered.

CONCLUSIONS

The main features of the fluctuating effects on cantilevered circular cylinders with aspect ratios in the range 4 to 30 which have been measured in uniform flow with low turbulence at high subcritical Reynolds number are summarised in the following paragraphs.

The distributions of r.m.s. pressures and forces along the cantilever vary with aspect ratio if A < 13 but for A ≥ 13 the magnitude of each quantity at a given location is independent of A.

For aspect ratios in the range 7 ≤ A < 13, the distributions of r.m.s. forces along the cantilever can be divided into two regions. Near the free end, the r.m.s. quantities are independent of A, whereas near the fixed end the values vary with A and are reduced relative to those associated with A=13.

If A > 20 the effects of the free end are not measurable beyond 20 diameters from it.

Strouhal numbers exhibit a step-like variation along the length of the cantilever which is independent of A when A > 10 and varies with A when A ≤ 10. If A < 7 vortex shedding does not occur.

REFERENCES

FARIVAR, Dj (1981) Turbulent uniform flow around cylinders of finite length AIAA Jour., 19, 275-281.

FOX, T A and WEST, G S (1991) Experiments on smooth cantilevered circular cylinders in low-turbulence uniform flow. Part 1: Mean loading with aspect ratios in the range 4 to 30. Research Report No CE130, The University of Queensland Department of Civil Engineering, Brisbane.

LOISEAU, H and SZECHENYI, E (1972) Analyse expérimentale des portances sur un cylindre immobile soumis à un écoulement perpendiculaire à son axe à des nombres de Reynolds élévés. Rech. Aérosp., 5, 279-291.

OKAMOTO, T and YAGITA, M (1973) The experimental investigation on the flow past a circular cylinder of finite length placed normal to the plane surface in a uniform stream. Bull. Japan Soc. Mech. Eng., 16, 805-814.

RIBEIRO, J L D (1991) Effects of surface roughness on the two-dimensional flow past circular cylinders II : fluctuating forces and pressures. Jour. Wind Eng. and Ind. Aero., 37, 311-326.

STANSBY, P K (1974) The effects of end plates on the base pressure coefficient of a circular cylinder. Aero. Jour., 78, 36-37.

WEST, G S (1986) Experiments on circular cylinders in the sub-critical and transitional regimes with smooth and turbulent incident flow. PhD Thesis, The University of Queensland, Brisbane.

WEST G S and APELT C J (1992) Measurements of fluctuating pressures and forces on a circular cylinder in the Reynolds number range 10^4 to 2.5 × 10^5 Jour. Fluids and Struct. (to be published).