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By

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Submitted to the School of Mechanical Engineering, Chalmers University of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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# CONTENTS

ABSTRACT
DISSERTATION
INTRODUCTION
SHORT REVIEW OF THE PAPERS
- Papers 1 and 2
- Papers 3 and 4

SUMMARY OF RESULTS
- Mean drag, base pressure and Strouhal number
- Measurements of fluctuating lift
- Transition frequency
- Length scales in near wake
- Mean and RMS pressure distributions
- Conditional sampling

ACKNOWLEDGEMENTS
REFERENCES
PAPERS 1 TO 4

**ABSTRACT**

This thesis presents an experimental investigation of Reynolds number and freestream turbulence effects on the flow and fluid forces for a circular cylinder. The work is concentrated on measurements of the vortex shedding frequency (Strouhal number), mean and RMS pressure coefficients and on hot wire investigations in the near wake region (length scales).

The combined effects of Reynolds number, Re, and a low-intensity freestream turbulence (Tu=1.4 %) on the variation of the Strouhal number and of the bandwidth of the vortex shedding frequency are examined ($Re \approx 50$-$2 \cdot 10^5$). At Reynolds numbers less than about $10^3$, the results indicate that the flow is rather insensitive to an increase in the turbulence intensity from Tu=0.1 % (smooth flow) to Tu=1.4 % (longitudinal integral length scale of the freestream turbulence, $\Lambda$, greater than about three diameters). At higher Reynolds numbers, the influence of freestream turbulence is significant, especially concerning the pressure forces on the cylinder.

It is found that the flow seems to exhibit a basic change at a Reynolds number of about $5 \cdot 10^3$ in smooth flow (at around $4 \cdot 10^3$ with a turbulence intensity of 1.4 %). A sub-division of the subcritical regime at this Reynolds number is proposed. Probably, the vortex shedding changes from one mode which is correlated over large axial (spanwise) distances with a well defined frequency to a mode in which the shedding frequency varies with time, the axial correlations being much smaller. It is indicated that the fluctuating (sectional) pressure forces are very small in the first mode of shedding.

At Reynolds numbers greater than about $10^4$, in subcritical flow, an increase in the turbulence intensity results in an increase in the pressure forces (scale of the freestream turbulence less than 0.5 diameters). It is indicated that the effect of changing the scale of the freestream turbulence from 0.1 to 0.5 diameters is negligible in this range (Tu=1.3 %). In addition, there is a slow increase in the pressure forces with increasing Reynolds number in this range.

In smooth flow, the subcritical regime extends to about $Re = 2 \cdot 10^5$ while at Tu=1.4 % the corresponding value is about $1 \cdot 10^5$. A detailed study at Tu=1.4 %, $\Lambda/D = 0.1$, of the changes in the flow and fluid forces (wall pressure and shear stress) from Re=$1.1 \cdot 10^5$ to Re=$2.3 \cdot 10^5$ is presented. In this range, the flow changes smoothly from a precritical state with strong vortex shedding to a state with reattachment and subsequent turbulent separation (weak vortex shedding).

The variations of the mean and fluctuating pressure forces are found to be strongly correlated to variations in the vortex formation length (subcritical and precritical regimes).

A conditional sampling technique has revealed that the suction peaks occurring in the base region, associated with strong vortex shedding, are related to the creation of major vortices which roll up close to the cylinder surface.

Results on the Reynolds number dependence of the ratio between the transition frequency in the shear layers to the fundamental shedding frequency in the Re-range $2 \cdot 10^3$ to $5 \cdot 10^4$ are presented.

Keywords: Circular cylinder, cross flow, Reynolds number, freestream turbulence, fluid forces, pressure fluctuations, shear stress, vortex shedding, Strouhal number, near wake.

**DISSERTATION**

This dissertation is based on the following papers:

1. C. Norberg and B. Sunden, Influence of stream turbulence intensity and eddy size on the fluctuating pressure forces on a single tube, ASME-Symposium on Flow-Induced Vibrations, New Orleans 1984, Vol.1, pp. 43-56 (1984).

   (This paper was presented at the ASME Winter Annual Meeting, Symposium on Flow-Induced Vibrations, New Orleans, Dec. 1984)

2. C. Norberg, Interaction between freestream turbulence and vortex shedding for a single tube in cross-flow, Journal of Wind Engineering and Industrial Aerodynamics, Vol.23, pp. 501-514 (1986).

   (Also presented at the 6th Colloquium on Industrial Aerodynamics, Aachen, June 1985)

3. C. Norberg and B. Sunden, Turbulence and Reynolds number effects on the flow and fluid forces on a single tube in cross-flow, Journal of Fluids and Structures, Vol.1, No.3 (1987) (in press).

4. C. Norberg, Effects of Reynolds number and a low-intensity freestream turbulence on the flow around a circular cylinder, Publication No. 87/2, Department of Applied Thermodynamics and Fluid Mechanics, Chalmers University of Technology, Gothenburg (1987) (to be submitted for international publication).

## INTRODUCTION

The flow around a circular cylinder in cross flow has been the subject of extensive research for more than a century. The collected knowledge about this seemingly simple flow configuration, is however, far from complete. One motive for this research is that the circular cylinder is a very common element in engineering equipment. For instance, in tubular heat exchangers, where the heat transfer rate and pressure drop are of vital importance, vibration problems might occur due to the flow-induced forces. Building aerodynamics and off-shore equipment are other examples where the flow around and the fluid forces on cylindrical objects are of great importance. The flow around a circular cylinder also involves many phenomena of fundamental importance in the field of fluid mechanics.

The vortex shedding phenomenon is a characteristic feature in all two-dimensional bluff-body flows. The word two-dimensional in this context does not mean that the flow is strictly two-dimensional but that the aspect ratio (length to diameter) is high enough in order to maintain a two-dimensional mean flow (when a turbulent wake is generated behind the cylinder the flow has been found to have important three-dimensional ingredients). The alternate shedding of vortices results in steady and unsteady drag forces in line with the flow and unsteady lift or side forces perpendicular to the flow direction. The vibration of cylindrical structures due to vortex shedding excitation can be an important mechanism leading to structural failure.

The basic parameter in incompressible flow is the Reynolds number, Re ($Re = U_o D/\nu$, $U_o$-freestream velocity, D-cylinder diameter and $\nu$-kinematic viscosity of the fluid). With increasing Reynolds number the flow displays a number of so-called flow regimes, see Table 1. The classification in Table 1 generally follows the terminology put forward by Morkovin [1], Roshko [2,3] and Zdravkovich [4]. The only modification of the classification indicated by the results of this investigation is the division of the subcritical regime (see paper 4). At a Reynolds number of about 50 we have the onset of vortex shedding. The vortex shedding has been found to persist up to very high Reynolds numbers (greater than $10^7$) with a possible exception in a narrow range in the critical regime.

Table 1. Flow regimes for a circular cylinder in smooth cross flow.

| Regime | Re-range[1] | Features |
|---|---|---|
| Symmetric | $<50$ | Domination of viscous effects |
| very low Re[2] | $<5$ | Attached flow |
| twin-vortex[3] | 5-50 | Pair of twin-vortices |
| Stable[2] | 50-160 | Stable laminar vortex street |
| Transition | 160-300 | Transition to turbulence after roll-up |
| Subcritical | $300\text{-}2\cdot10^5$ | Transition before roll-up |
| Lower[2] | $3\cdot10^2\text{-}5\cdot10^3$ | Stable shedding frequency |
| Upper | $5\cdot10^3\text{-}2\cdot10^5$ | Wander in shedding frequency |
| Critical | $2\cdot10^5\text{-}3\cdot10^6$ | Very sensitive to disturbances |
| pre- | $2\cdot10^5\text{-}4\cdot10^5$ | Narrowing of wake, fall in drag |
| para-[2,4] | $4\cdot10^5\text{-}8\cdot10^5$ | Spanwise coherent bubble(s), low drag |
| super-[2,4] | $8\cdot10^5\text{-}3\cdot10^6$ | Incoherent bubbles, rise in drag |
| Postcritical[5] | $3\cdot10^6\text{-}1\cdot10^7$ | Turbulent boundary layer, vortex shedding |
| Ultimate[2] | $>1\cdot10^7$ | Transition near stagnation point |

[1] The Reynolds number ranges are dependent on experimental conditions. The approximate ranges indicated are supposed to be valid for "ideal conditions" and open to discussion.

[2] Subregimes may exist.

[3] In the range from about Re=35 to 50 a wavy wake appears.

[4] May be absent with disturbances like freestream turbulence and surface roughness.

[5] or Transcritical (Roshko)

In addition to the Reynolds number the flow has been shown to be dependent on factors related to surface roughness, flow constraints (aspect ratio and blockage), end conditions, disturbances (e.g. freestream turbulence and acoustic noise) and cylinder vibration. In the present work the main objective has been to further investigate the effects of the Reynolds number and of the freestream turbulence with special emphasis on the flow and fluid forces associated with vortex shedding. The cylinders used were all mounted as rigidly as possible, made as smooth as possible and equipped with end plates in order to improve the end conditions. The reader is referred to the individual papers for further information about the experimental conditions.

## SHORT REVIEW OF THE PAPERS

### Papers 1 and 2

The first two papers contains experimental data obtained in a wind tunnel having a cross-section of 0.5 x 0.4 $m^2$ (height x width). By using different turbulence-generating grids and by placing the cylinder (D=41 mm) at various downstream locations in the working section, the effects of both the turbulence intensity and the scale of the turbulence could be examined (Tu=1.3-4.1 %, $\Lambda$/D=0.1-0.5). The reference condition (no grid) had a turbulence intensity of less than 0.1 %.

The first paper indicated that the effect of the turbulence scale was negligible, at least for Tu=1.3 %, at the two Reynolds numbers investigated (Re=$2.7 \cdot 10^4$ and $4.1 \cdot 10^4$). An increase in the turbulence intensity from 0.1 % to 3.2 % ($\Lambda$/D=0.3) gave a substantial increase in both the mean and the fluctuating pressure forces on the cylinder. The fluctuating pressures on the cylinder surface were measured with a pinhole microphone.

In the second paper the Reynolds number range was extended (Re$\approx 2 \cdot 10^4$ to $8 \cdot 10^4$). The dependence of the turbulence intensity was further investigated, and some basic changes in e.g. the RMS-pressure distributions around the cylinder, when entering the critical regime at Tu=4.1 %, were presented. The vortex formation length as well as the width of the separated shear layers were found to be important length scales in the near wake region. The downstream development of the width of the shear layers, as determined in the paper, showed a good collapse when scaling with the vortex formation length. The fluctuating sectional forces on the cylinder were estimated using phase and coherence information from two-point measurements of the fluctuating wall pressures (pinhole microphones).

### Papers 3 and 4

The experimental results given in papers 3 and 4 were obtained from measurements in a wind tunnel having a cross-section of 1.25 x 1.80 $m^2$ (height x width). The effects of both Reynolds number and a low-intensity freestream turbulence (Tu=1.4 %) were presented. The reference condition was again at a turbulence intensity of less than 0.1 %.

In paper 3, the emphasis was on the variations in the upper subcritical and critical regimes (D=41 and 120 mm). The Reynolds number range was from about $2 \cdot 10^4$ to $3 \cdot 10^5$. The strong dependence of the turbulence intensity found in the earlier papers was confirmed. The Reynolds number at the beginning of the critical regime was reduced by a factor of about two with additional turbulence (from about $Re=2 \cdot 10^5$ to $1 \cdot 10^5$). Distributions of both mean and RMS coefficients of the wall pressure and the wall shear stress (hot-film) around the cylinder were presented. The distributions at Tu=1.4 % revealed the build-up of a reattachment zone with subsequent delayed separation when entering the critical regime. It was suggested that the appearance of a turbulent zone, at about 105 degrees from the stagnation line, can serve as a physical definition of the boundary between the subcritical and (pre)critical regime. It was also found, using a conditional sampling technique, that the suction peaks occurring in the rear part of the cylinder, in the vortex shedding process, are related to the creation of a major vortex which rolls up close to the surface.

In the final paper (paper 4) the use of cylinders with small diameters enabled measurements down to $Re \approx 50$. Accurate measurements of the Strouhal number variation with Re and the influence of the low-intensity freestream turbulence were given. Together with the information from e.g. the bandwidth of the vortex shedding frequency, different flow regimes could be distinguished. It was found that the flow seems to exhibit a basic change at a Reynolds number of about $5 \cdot 10^3$ ($4 \cdot 10^3$ with turbulence). A sub-division of the subcritical regime at this Reynolds number was proposed. At the boundary between the so-called lower and upper subcritical regime the relative bandwidth of the shedding frequency changed by about one order of magnitude. In addition, the axial correlations appeared to have a local maximum at this Re. In the beginning of the upper subcritical regime the axial correlations showed a rapid decrease with increasing Re. In addition, the mean and RMS base pressure coefficients change dramatically in this region.

## SUMMARY OF RESULTS

In this section, the present papers are referred to as [P1-P4].

### Mean drag, base pressure and Strouhal number

In Figs.1, 2 and 3, the present data (from [P3,P4]) on the mean drag coefficient, the mean base pressure coefficient and the Strouhal number versus Reynolds number ($Re=10-10^7$), respectively, are collected together with results from other investigations. The curves drawn in these figures have been smoothed in order to suppress the scatter in the reported data (the present data showed a relatively small scatter, however). The reader is referred to the individual papers for more detailed information (see reference list). It should be pointed out that different results have been found in the critical regime ($Re \approx 2 \cdot 10^5$ to $3 \cdot 10^6$ in smooth flow) for increasing and decreasing Reynolds numbers (hysteresis effects, see e.g. Schewe [7]).

Reviews on the basic variations with Reynolds number have been presented by e.g. Morkovin [1], Roshko and Fiszdon [8] and Berger and Wille [9]. In addition, discussions on the flow around a circular cylinder can be found in almost all text-books in fluid mechanics. The comments in the present summary will be restricted to new and/or additional information from the present work and its relation to previous investigations.

The present mean drag coefficients were obtained from integration of the mean pressure distributions. The data points in Fig.1 have been corrected for blockage according to the method of Allen and Vincenti [10]. The coefficients at Tu=0.1 %, see Fig.1, are in general agreement with the well-established data of Wieselberger [5]. Wieselberger measured the total drag (friction drag + pressure drag) acting on the whole length in an open-jet flow. It is noticeable that the present data (only pressure drag) in smooth flow are higher than Wieselberger's data at $Re < 10^4$. According to Thom [11], the friction drag coefficient amounts to about 0.04 at $Re=10^4$ (decreasing with increasing Re). The present data represent sectional forces which are assumed to be higher than the integrated forces of Wieselberger (end effects). At the higher turbulence intensity, Tu=1.4 %, the sudden drag coefficient reduction occurs at a Reynolds number of about $1 \cdot 10^5$. This is in agreement with e.g. Fage and Warsap [12] (see also [13]).

The present results on the mean base pressure coefficient and on the Strouhal number show a noticeable consistency regarding the overlapping Reynolds number ranges due to the different diameters [P3,P4]. A general agreement with previous results was observed.

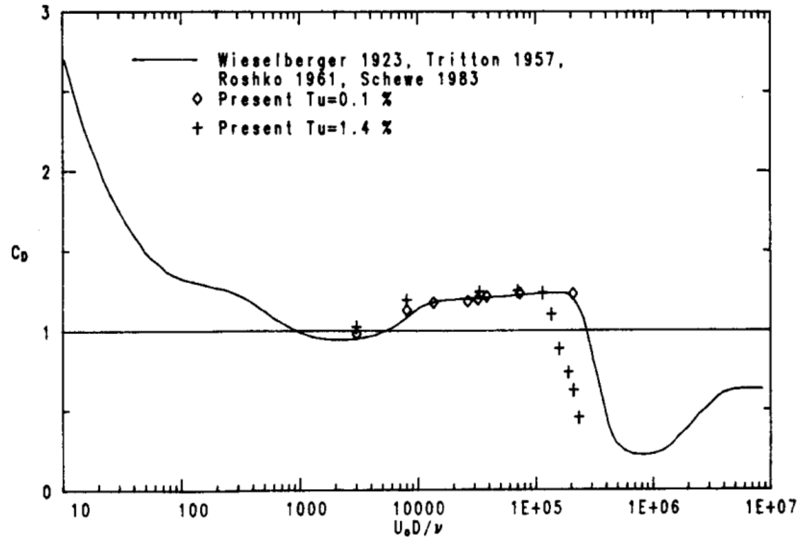


Fig.1 Mean drag coefficient vs Reynolds number

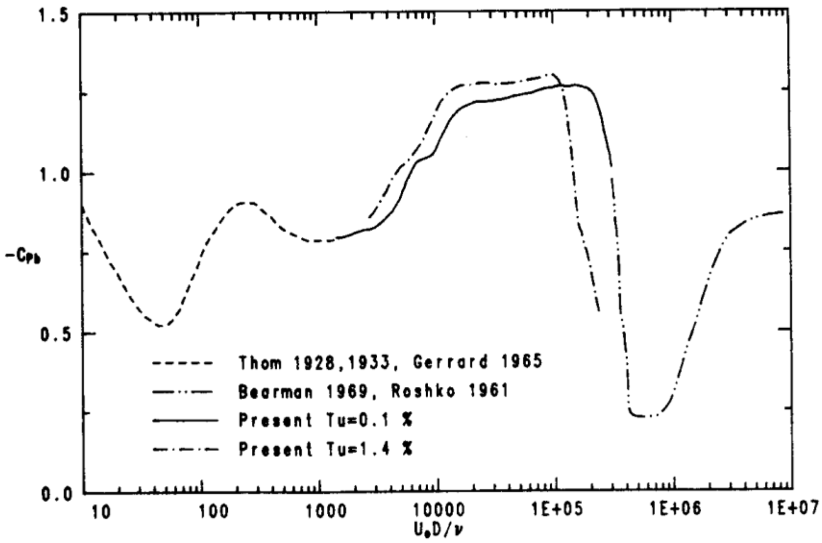


Fig.2 Mean base pressure coefficient vs Reynolds number

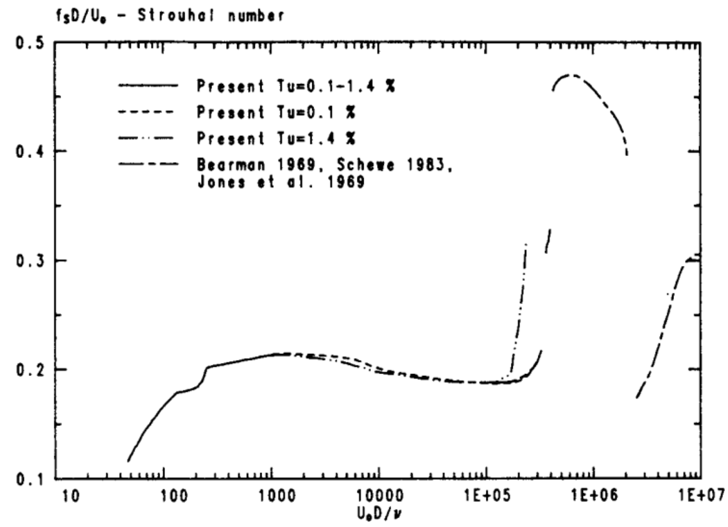


Fig.3 Strouhal number vs Reynolds number

At Reynolds numbers less than about $10^3$, the present data on the Strouhal number suggested that the flow was rather insensitive to additional freestream turbulence of a low intensity (Tu=1.4 %). At these Re, in the present case, the integral length scale of the freestream turbulence was relatively large compared to the cylinder diameters. The results on the corresponding bandwidths of the shedding frequency suggested that the shedding frequency responds instantaneously to velocity variations imposed by the freestream turbulence ("quasi-stationary flow"). It should be pointed out, however, that the freestream turbulence might have a completely different influence at other scales and intensities.

The Reynolds number at which the vortex shedding started was found to be about 48. In the stable regime (Re≈48-160), the present Strouhal number variation was continuous (within the experimental accuracy). In addition, the Strouhal numbers were in support of the so-called "Roshko relation" in the stable regime [2]. The vortex shedding measurements also indicated that the transition regime extended from about Re=160 to Re=265.

The flow seemed to exhibit a basic change at about $5 \cdot 10^3$ ($4 \cdot 10^3$ with turbulence). A sub-division of the subcritical regime at this Reynolds number was proposed (for simplicity the sub-regimes were denoted the lower and upper subcritical regimes, respectively), see Table 1. Probably, the vortex shedding changes from one mode which is correlated over axial (spanwise) distances with a well defined frequency to a mode in which the shedding frequency varies with time, the axial correlations being much smaller (see figures in [P4]). It seems to be a correlation between the apparent change in the mode of shedding and the substantial changes in both the mean and the fluctuating forces on the cylinder. Further measurements are needed in order to clarify the apparent change in the vortex shedding process.

## Measurements of fluctuating lift

Table 2 summarizes measurements of the fluctuating lift acting on a circular cylinder as reported in the Reynolds number range from $10^3$ to $10^7$. Smoothed data on some of the measurements of the RMS lift coefficient can be found in Fig.4. As seen in Table 2, the experimental conditions as well as the methods of measuring the fluctuating lift show great differences. Again the reader is referred to the individual references for more detailed information.

Despite the large deviations between the different data sets in Fig.4 the general trend with increasing Reynolds number appears to be as follows: (i) a rapid increase in the beginning of the upper subcritical regime, (ii) a much slower variation between say $Re=10^4$ and $Re=10^5$, the RMS lift coefficient being rather high, (iii) a rapid decrease when entering the critical regime, and finally (iv) low values at very high Reynolds numbers (greater than about $3 \cdot 10^5$). It should be noted that the present RMS lift coefficients were estimated from a formula [39] which contained the RMS pressure coefficient at 90 degrees from the stagnation point ($\alpha=90^o$) and the cross-correlation coefficient between the opposite points $\alpha=-90^o$ and $\alpha=90^o$ The present results should be regarded as tentative, especially in the critical regime[1]. It is worth noting that the effect of freestream turbulence, in the present case, was an increase in the RMS lift coefficient at Reynolds numbers lower than the sudden decrease when entering the critical regime, see also [P2]. This is in contradiction to the results of Cheung and Melbourne [40], see Fig.4. In addition, the variations in the RMS pressure coefficients, as reported by Cheung and Melbourne, show noticeable deviations from the present results [P3]. The reasons for these discrepancies are unclear at the present time.

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1 In addition, the present coefficients measured with the larger cylinder (D=120 mm, B=11 %) are corrected for blockage (to join the coefficients measured with the smaller cylinder (D=41 mm, B=4 %), see [P3].).

Table 2. Measurements of fluctuating lift on a stationary circular cylinder in cross flow. Key to the table on the following page. The reader is referred to the individual references (see reference list) for more information. Measurements in air if not otherwise stated.

| Author(s) | Year | Ref | $Re \cdot 10^{-4}$ | L/D | B[%] | $\ell$/D | Remark |
|---|---|---|---|---|---|---|---|
| Drescher | 1956 | 18 | 11 | 3.1 | 24 | sect. | $\tilde{C}_{LP}$, water |
| McGregor | 1957 | 19 | 4-12 | 28 | 3 | sect. | $C'_P$ |
| Macovsky | 1958 | 20 | 2-10 | 12 | 8 | 2.0 | $\tilde{C}_L$, water |
| Fung | 1960 | 21 | 20-140 | 5.7 | 10 | 1.7 | - |
| Humphreys | 1961 | 22 | 4-60 | 6.6 | 15 | total | $\tilde{C}_L$ |
| Keefe | 1961 | 23 | 5-10 | 3,18 | 4 | 1.0 | end plates |
| Gerrard | 1961 | 24 | 0.4-20 | 20 | 5 | sect. | $C'_P$ |
| Bishop & Hassan | 1964 | 25 | 0.4-11 | 3 | 8 | total | $\tilde{C}_L$ |
| Schmidt | 1965 | 26 | 40-80 | 8.1 | 15 ? | sect. | $C'_{LP}$ |
| Schmidt | 1966 | 27 | 60-800 | ? | ? | ? | - |
| Jones et al. | 1969 | 17 | 100-1000 | 5.3 | 19 | 2.3 | air, freon |
| van Nunen | 1972 | 28 | 50-800 | 6 ? | 17 ? | sect. | $C'_{LP}$ |
| Loiseau & Szech. | 1972 | 29 | 26-65 | 4.4 | 22 | sect. | $C'_{LP}$ |
| Bublitz | 1972 | 30 | 10-66 | 8.0 | open | total | - |
| Batham | 1973 | 31 | 11-24 | 6.6 | 5 | sect. | $C'_P$, FST |
| Kacker et al. | 1974 | 32 | 2-20 | 4.5 | 8 | 0.2-4 | - |
| Huthloff | 1975 | 33 | 1-10 | 6.2 | open | total | end plates |
| Richter & Naud. | 1976 | 34 | 2-30 | 8.6 | 17-50 | 6.8 | water |
| Sonneville | 1976 | 35 | 1-6 | 12.9 | 6 | total | - |
| So & Savkar | 1981 | 36 | 3-200 | 3.6,8 | 16,32 | 1-5.3 | water, FST |
| Mohr | 1981 | 37 | 1-6 | 23.6 | 9 | sect. | $C'_{LP}$ |
| Moeller | 1982 | 38 | 0.4-3 | ? | open | 0.3 ? | - |
| Kiya et al. | 1982 | 39 | 3-4 | 11 | 9 | sect. | $C'_P$, FST |
| Schewe | 1983 | 7 | 2-700 | 10 | 10 | total | - |
| Cheung & Melbourne | 1983 | 40 | 6-60 | 3.6,6.7 | 6-15? | total | FST |
| Bychov & Kovalenko | 1983 | 41 | 10-50 | 6.7 | 15 | 1.7 | FST |
| Moeller & Leehey | 1984 | 42 | 0.3-4 | 25.6 | 3 | 0.3 | water |
| Mulcahy | 1984 | 43 | 3-20 | 7.5 | 8 ? | 1-3 | water, FST |
| Szepessy | 1987 | 44 | 5-13 | 0.25-12 | 7 | sect. | $C'_{LP}$ |
| Present | 1987 | P3 | 1-30 | 9,12 | 4,11 | sect. | $C'_P$, FST |

## Key to Table 2

L/D - aspect ratio

B - model blockage

ℓ/D - active length of force sensing element to diameter

sect. - sectional forces (ℓ/D≈0)

total - forces on the whole cylinder

$C_L$ - lift determined from force measurements

$C_{LP}$ - lift determined from pressure integration

(′) denotes RMS-values

(˜) denotes that only amplitudes were measured

$C_P'$ - lift determined from RMS pressure coefficients

FST - effects of freestream turbulence are included

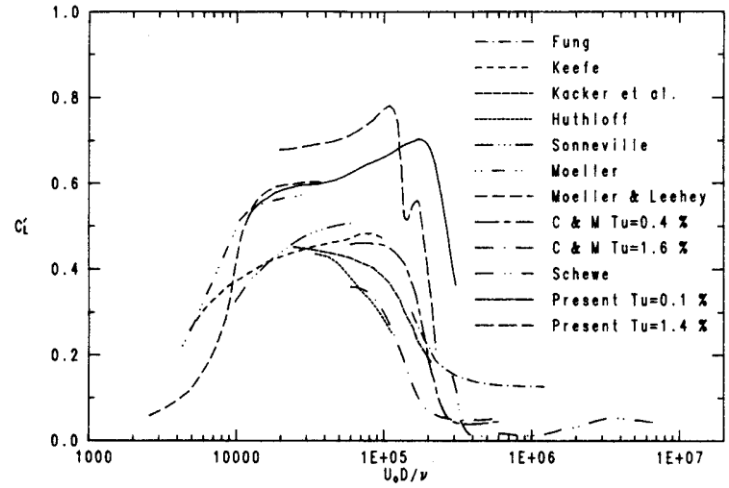



Fig.4 RMS lift coefficient vs Reynolds number (see Table 2 for details, C & M - Cheung and Melbourne 1983 [40]).

## Transition frequency

The ratio between the transition frequency in the separated shear layers to the fundamental shedding frequency was measured in the subcritical regime (Tu=0.1 %, $Re=2\cdot10^3$ to $5\cdot10^4$), see Fig.5 (from [P4]). The transition frequency was determined from spectra of the velocity fluctuations in the shear layers (hot wire measurements). These spectra revealed the broad-band nature of the shear layer oscillations ("secondary vortices" [48]) associated with the transition.

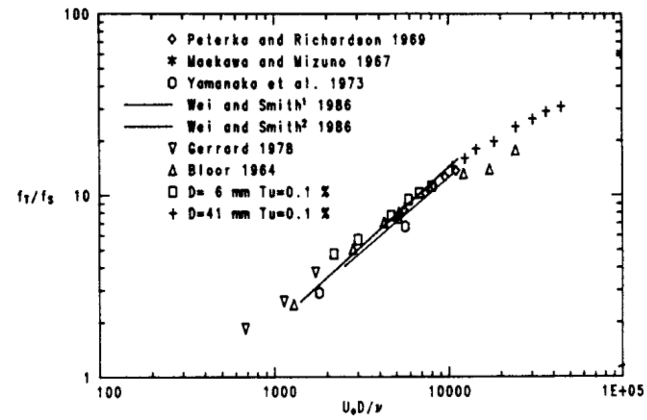



Fig.5 Transition frequency to vortex shedding frequency versus Reynolds number (from [P4]).

## Length scales in the near wake

A loose definition of the so-called near wake is the region behind the cylinder where important interactions occur between the separated flow and the cylinder itself [8]. These interactions or feed-back mechanisms may scale on different length scales.

In paper 2, a comparative study of four cases (D=41 mm), two at the same Reynolds number ($Re=2.7 \cdot 10^4$) but at different turbulence intensities (Tu=0.1 and 1.3 %) and two at the same turbulence intensity (Tu=4.1 %) but at different Reynolds numbers ($Re=4.2 \cdot 10^4$ and $Re=5.5 \cdot 10^4$), was presented. The observation by Gerrard [15], that the so-called vortex formation length ($L_F$) has a close connection to the pressure forces on the cylinder was confirmed in this study. For the cases at the same Re the increase in Tu gave an increase in the pressure forces connected to a decrease in $L_F$ (subcritical flow). For the cases at Tu=4.1 % (precritical flow) an increase in the Reynolds number gave a decrease in the pressure forces coupled to an increase in $L_F$. The changes in the vortex formation length were found to be coupled to opposite changes in the width of the separated shear layers. This width was termed the diffusion length ($L_D$) in accordance with the terminology used by Gerrard [51]. With the definition used in this work, see e.g. [P2], the downstream development of $L_D/D$ (D-cylinder diameter) showed a collapse of data when scaling with the vortex formation length (i.e. $L_D/D$ versus $x/L_F$, x-distance from cylinder axis). In Fig.6, some additional points from a case at $Re=3.2 \cdot 10^4$, $Tu=0.1$ %, see [P3], have been plotted together with a line representative for the cases in [P2] (smoothed data).

Also the wake width was measured in the present investigation (hot wire measurements, see [P2-P4]). It appears that the wake width, as determined in these papers, decreases to a minimum at some distance downstream of $x=L_F$ in the subcritical regime. This position can be seen as the location where the vortices lose their connection to the cylinder and begin to be convected in the wake. In the beginning of the critical regime ($Tu=1.4$ %) a rapid narrowing of the wake with increasing Re was observed.

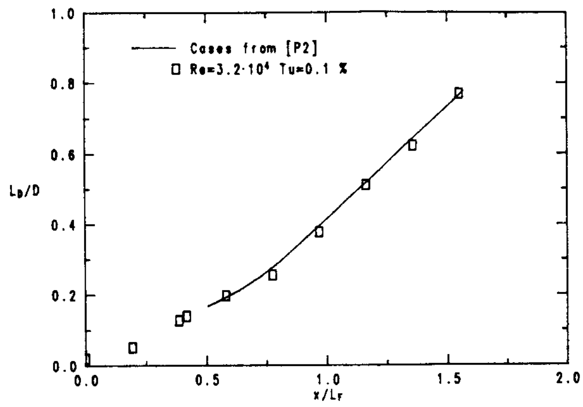



Fig.6 Diffusion length to diameter ($L_D/D$) versus distance from cylinder axis scaled with the vortex formation length ($x/L_F$). The line is based on data points in paper 2 [P2].

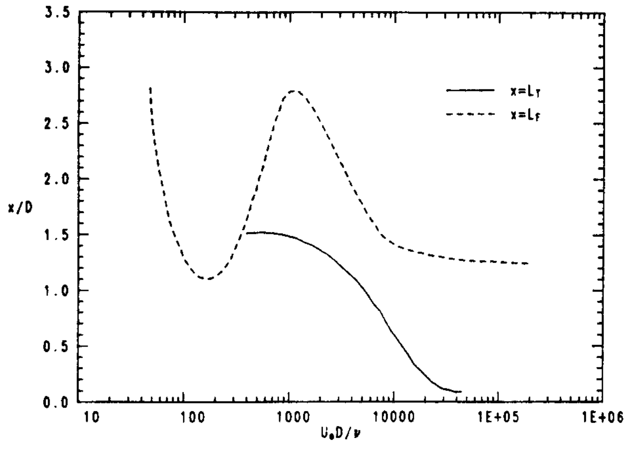



Fig.7 The vortex formation length ($x=L_F$) and the position of transition in the shear layers ($x=L_T$) versus Reynolds number. The smoothed lines are based on data as compiled by Bloor [50] ($L_T$) and Norberg [P4] ($L_F$).

As shown by the experimental results of Bloor [50] and Schiller and Linke [52], the position of transition from laminar to turbulent flow in the shear layers, moves upstream with increasing Re in the subcritical regime. These experimental results are summarized by a single curve in Fig.7 (reproduced from the paper by Bloor [50], position of transition at $x=L_T$, x-distance from cylinder axis). Also shown in Fig.7 is a curve (dotted line) for the vortex formation length. This smoothed curve has been constructed from the data points as compiled in [P4]. The relatively large spread in the results reported on these lengths imply that the variations, as shown in Fig.7, should be treated as tentative. More accurate measurements are needed.

The effect of additional freestream turbulence, on the vortex formation length, seems to be an effective increase in the Reynolds number (at least for Re greater than about $10^3$). This was indicated in [P4], see also Gerrard [51].

It is interesting to note that the Reynolds number where the two lengths appear to coincide happens at Re≈350 (Fig.7). By extrapolating the data in Fig.5, it is indicated that the transition frequency approaches the vortex shedding frequency at about the same Re. This is consistent with the observation that the transition occurs before the vortices roll up in the subcritical regime [50]. Regarding the downstream development of the width of the separated shear layers, it is believed that the variation, as shown in Fig.6, only is representative for Reynolds numbers higher than about $3 \cdot 10^4$ in the subcritical and precritical regimes. At lower Re the variation of the position of the transition is likely to have a major influence on this development, see e.g. Gerrard [53].

## Mean and RMS pressure distributions

The distributions of mean and RMS pressure distributions ($C_p$ and $C_p'$ vs $\alpha$, $\alpha$-angle from stagnation point) shown in Figs.8-10, are compiled in order to illuminate some of the characteristic features on the separate effects of Reynolds number and of freestream turbulence.

In Fig.8, effects of Reynolds number in smooth flow (Tu=0.1 %) are depicted. The $C_p$-distributions in Fig.8a have been corrected for blockage effects [3]. Perhaps the most noticeable feature in Fig.8a is the lowering of the mean pressure coefficients, especially in the base region, with increasing Reynolds number, see also Fig.2. The more or less constant pressure coefficient in the wake region for the case at $Re=3 \cdot 10^3$ [P4] is an indication of a very quiescent near wake in the lower subcritical regime. At higher Re, in the upper subcritical regime, the mean coefficients show a decreasing slope with increasing $\alpha$ indicating a much more violent flow in the near wake. This behavior is consistent with the shrinking of the vortex formation region, see Fig.7. As already mentioned, the effect of an increase in the turbulence intensity at these Re appears to be similar to an effective increase in the Reynolds number, see also [P4]. The increase in Re (or turbulence intensity) appears to be associated with an upstream movement of the mean separation point. This is indicated by the upstream shift in the positions of minimum $C_p$ and maximum $C_p'$ , see Fig.8. The strong dependence of the Reynolds number and of the freestream turbulence intensity on the fluctuating pressures around the cylinder, in the subcritical regime, is evident from Figs.8b and 9a.

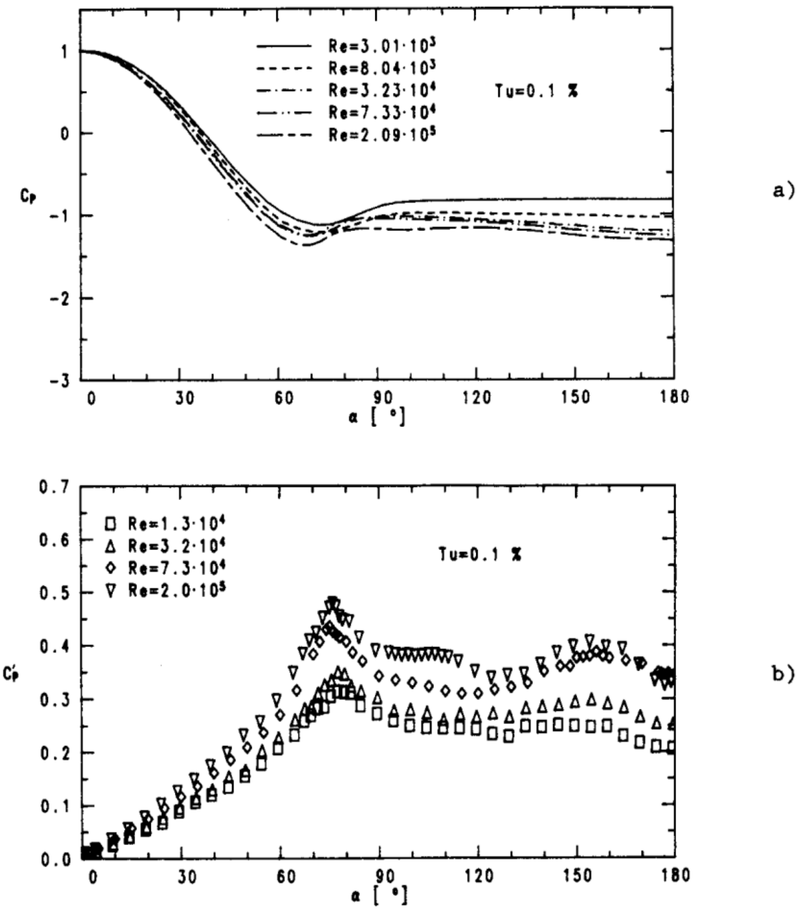
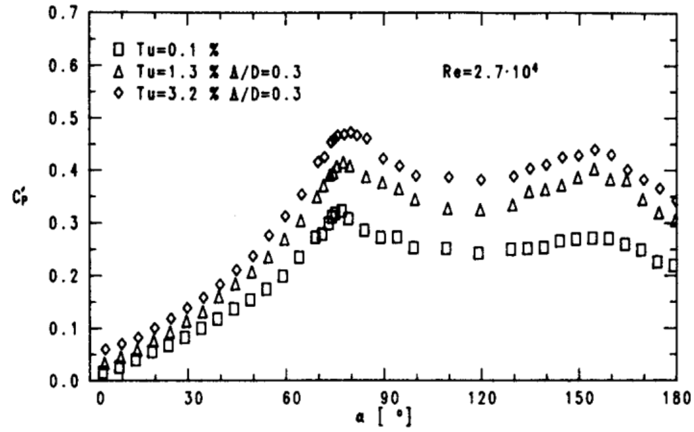


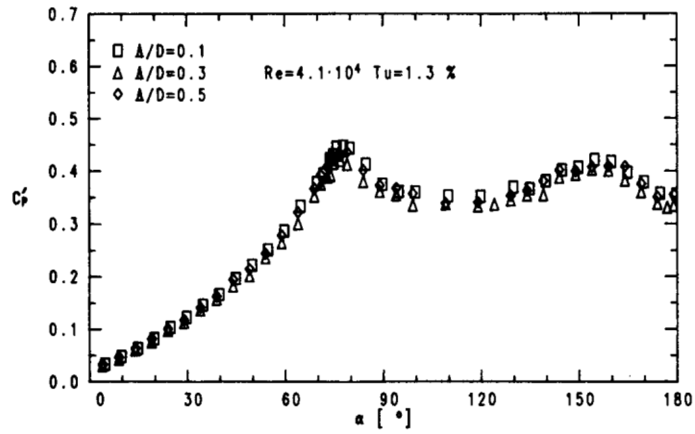

Fig.8 a) Mean- and b) RMS-pressure distributions at different Reynolds numbers (subcritical regime, Tu=0.1 %). Note : mean coefficients corrected for blockage.

An interesting point is the build-up of a secondary maximum at around $\alpha$=150$^{\circ}$ in the RMS distributions (Re > $10^4$). This seems to be coupled to the occurrence of suction peaks of large amplitude in this region [P1,P2]. This effect will be discussed further in a later section.

The $C_p'$-distributions in Fig.9b at a constant Reynolds number ($4.1\cdot10^4$) and at a constant turbulence intensity (Tu=1.3 %) indicate an negligible effect from the scale of the freestream turbulence ($\Lambda$/D=0.1-0.5, $\Lambda$-longitudinal integral length scale [P1,13]). This independence of the scale was also found at Re=$2.7\cdot10^4$.




a)




b)

Fig.9 RMS-pressure distributions showing a) effect of freestream turbulence intensity (Re=$2.7 \cdot 10^4$) and b) effect of freestream turbulence scale (Re=$4.1 \cdot 10^4$, Tu=1.3 %). Subcritical regime.

The fluctuating pressures at frequencies around the vortex shedding frequency are, due to the alternate shedding, out-of-phase between opposite sides of the cylinder [P1,P2]. In addition, the energy content of the fluctuations around the vortex shedding frequency is completely dominating over the major part of the cylinder in the subcritical regime. Thus, there is a strong correlation between the changes in the RMS-distributions and in the sectional lift forces.

The distributions in Fig.10 show the variations in the pressure coefficients with Reynolds number when entering the critical regime at Tu=1.4 % (from [P3]).

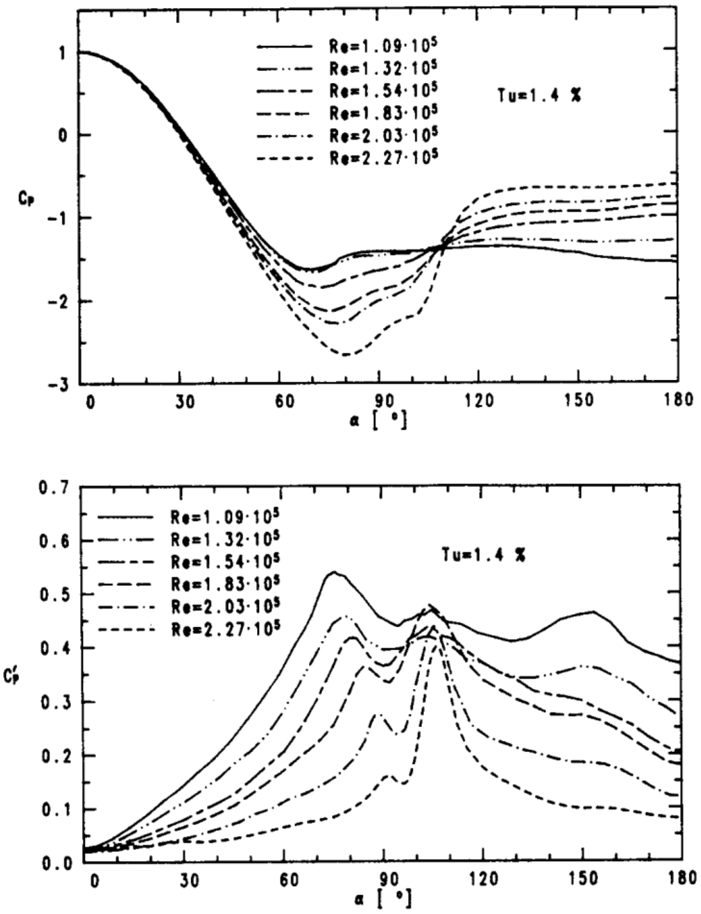



Fig.10 a) Mean- and b) RMS-pressure distributions at different Reynolds numbers (critical regime, Tu=1.4 %).

In Fig.10, there is a gradual change in the general character of the distributions with increasing Reynolds number. In this Reynolds number range, the flow changes from an early precritical state ($Re=1.1\cdot10^5$) with strong vortex shedding to a (para)critical state with laminar separation followed by reattachment and subsequent turbulent separation (weak vortex shedding). Please note the similarity between the case at $Re=1.1\cdot10^5$, Tu=1.4 % in Fig.10 and the case at $Re=2.0\cdot10^5$, Tu=0.1 % in Fig.8. The mean position of laminar separation, associated with the first maximum in the RMS-distributions, see Fig.10, shifts downstream from about $\alpha=77^\circ$ at $Re=1.1\cdot10^5$ to about $\alpha=90^\circ$ at $Re=2.3\cdot10^5$. The gradual increase of the second maximum at around $\alpha=105^{o}$ in the RMS-distributions is attributed to the build-up of reattachment of the boundary layer. It is suggested that the appearance of this maximum ("turbulent zone" [P3]), can serve as a physical definition of the boundary between the subcritical and (pre)critical regimes[1]. The measurements of the wall shear stress around the cylinder (hot film, see [P3]), indicated that reattachment was present for Re greater than about $1.5 \cdot 10^{5}$ (Tu=1.4 %). It is interesting to note that the relative bandwidth of the dominating frequency, as measured in the wake region, showed a maximum around this Re, see [P3].

No hysteresis effects were observed in these measurements. In addition, the distributions around the cylinder were all symmetric with respect to freestream direction. This was believed to be a result of a smearing effect due to the small scale turbulence. It is worth noting that the present $C_{Pb}$- and Strouhal number variations in smooth flow (Tu=0.1 %, Re $< 3 \cdot 10^{5}$) compare favourable with the results of Bearman [16]. Bearman did observe asymmetric flow in the critical regime at Re $> 3 \cdot 10^{5}$ but limitations in the tunnel speed did not permit measurements at such high Reynolds numbers in the present case.

## Conditional sampling

As mentioned earlier, an intrinsic feature of the vortex shedding at high Re seems to be the appearance of large negative peaks in the base region of the cylinder. These suction peaks were used as a triggering condition in a conditional sampling procedure, see [P3]. The wall pressure variations (pinhole microphone) at $\alpha=150^{o}$ were used for detecting these "events". Conditional averages of the wall pressure variations around the cylinder, velocity variations in the near wake (hot wire) and wall shear stress variations (hot film) were analyzed. Shown in Fig.11 are the time averaged pressure distribution ($\bar{C}_p$) and the conditionally averaged pressure distribution ($\tilde{C}_p$) at the time for the suction peak. The arrow in Fig.11

1 the term "recirculating region" used in [P2] is misleading. Although some recirculation is present, the term "turbulent zone" is more appropriate due to the strong mixing in this region.

represents the force vector (non-dimensional components $\tilde{C}_D$ and $\tilde{C}_L$) acting on the cylinder at the moment for the suction peak ($\bar{C}_D$ and $\bar{C}_L$ are the time-averaged components).

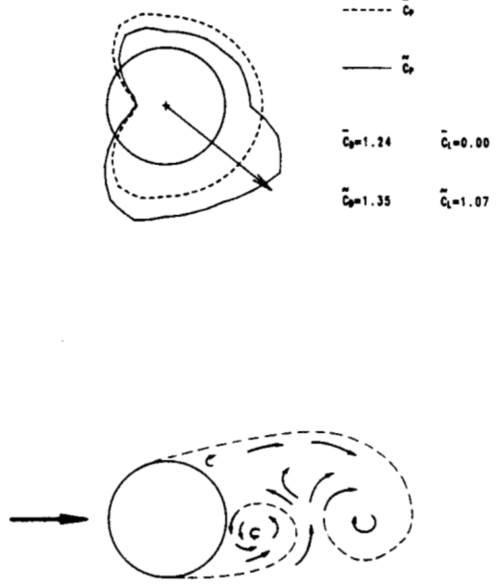



Fig.11 Mean and conditionally averaged pressure distributions ($\bar{C}_P$, $\tilde{C}_P$) together with the suggested general flow pattern associated with the triggering condition (see [P3] for details).

It is suggested that the suction peak event is related to the creation of a major vortex which rolls up (unusually) close to the cylinder surface (see Fig.11 for a general sketch). It is believed that this behavior is coupled to the low-frequency pulsations of the formation region [53,35].

Further measurements, preferably with techniques which can resolve flow direction (e.g. flow visualization and laser velocimetry) are needed in order to get a clearer picture of the different feed-back mechanisms in the near wake region.

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