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THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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Turbulent flow around circular cylinder in oscillatory inlet conditions

In the present paper the response of the flow around stationary circular cylinder due to inlet stream oscillations has been discussed. The unsteady flow field was analysed on the base of complete set of mean velocity profiles, Reynolds and coherent stress components and spectral records in the near–wake region.

Nomenclature

C_D – drag coefficient,

$C_p = \frac{2(p-p_0)}{\rho \overline{U}_0^2}$ – surface pressure coefficient,

c_p' – coefficient of pressure fluctuations,

d – diameter of the cylinder,

E_2 – contribution of periodic lateral motion energy in the total turbulent kinetic energy,

f_0 – frequency of the inlet flow disturbances,

f_s – vortex shedding frequency,

f_{s0} – Strouhal frequency of a stationary cylinder in a uniform incident flow,

n_0 – angular velocity of the shutters,

$U(t)$ – instantaneous flow velocity,

$u_i', \tilde{u}_i$ – random and periodic velocity fluctuations components,

$\overline{U}_i$ – time mean velocity,

$\overline{U}_0$ – mean velocity of the incident flow,

x_i – coordinate axes, defined in Fig. 3,

Θ – angular coordinate of the position around cylinder.

1. Introduction

The particular feature of the velocity and pressure fields around the bluff bodies in turbulent flows is both random and periodical nature of their time dependence. The oscillating flow field component is a direct result of an alternate vortex generation and shedding into the body wake. On the other hand the organised time–dependent fluctuations of the flow surrounding the bluff body can

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be caused by the periodical external disturbances of the incident stream. Recent review given by Griffin and Hall (1991) has confirmed the fact that, in the case of stationary rigid bluff body placed in an oscillatory incident flow the phenomenon of vortex shedding resonance or lock–on is observed. It occurs when the incident mean flow has a periodical component characterised by properly matched frequency and amplitude. This opinion agrees exactly with the results of Armstrong et al. [1-2] and earliest researches of Jarża and Słomczyński [4]. They emphasised a particularly strong resonance between the inlet flow disturbances and the vortex shedding, providing a promising observation for modifications and control of the near-wake of a bluff-body.

The aforementioned works revealed the limits of the lock-on regime for incident flow periodical disturbances. According to Fig. 1 (Jarża, Słomczyński [4]) lock-on initiates at around $f_0/f_{s0} = 1$ with synchronisation of f_{s0} and f_s, but then the shedding frequency f_s tends towards the subharmonic of the driving frequency f_0. The value $f_0/f_{s0} = 0.5$ is kept constant over relatively wide range of reduced velocity $U_0/(f_0 \times d)$. For the rates f_0/f_{s0} between $2.2 \div 2.7$ the vortex and inlet oscillations frequencies unlock and the vortex shedding frequency is again equal to f_{s0}. The present experimental research has been undertaken in order to explain to what extent the turbulent structure of a two–dimensional wake flow may be affected by the incident flow oscillations. The special attention has been put on the response of the flow around stationary circular cylinder due to lock–on conditions. A method of signal processing based on the phase averaging technique made it possible to consider the instantaneous values of velocity U_i as superposition of the mean $\overline{U}$ as well as periodic $\widetilde{u}_i$ and random u_i' turbulent component

$$U(t) = \overline{U} + u_i'(t) + \widetilde{u}_i(t) \tag{1}$$

2. Experimental arrangement

The investigations were carried out in an open–circuit wind tunnel at the Institute of Thermal Machinery of the Technical University of Częstochowa. The test section was (0.5×0.6)m $(W \times H)$ and ≈ 4 m long. The free-stream turbulence did not exceed 0.1% at speeds up to 10 m/s.

The circular cylinder of 0.08 m in diameter and 0.5 m long was positioned 1.5 m from the entrance to the working section, perpendicular to the free-stream direction. The controlled oscillations of the incident flow were introduced by means of the set of two shutters rotating in phase at the down stream end of the wind-tunnel measuring section. For the schematic of the arrangement see Fig. 2. The generated velocity perturbations were periodic with the fundamental frequency f_0, corresponding to the angular velocity of the shutters ($f_0 = 2 \times n_0$). The amplitudes of disturbance harmonics were small compared with the fundamental frequency amplitude. The additional control measurement taken by means of the X hot-wire probe confirmed that the incident flow velocity had a large periodical component in the streamwise direction only superimposed upon the mean fluid motion.

The complex flow field around the cylinder was studied using the multichannel DISA 55M CTA System. A method of signal processing based on the phase averaging technique was applied. The instantaneous pressure signals were transmitted from taps at the surface of the cylinder to the Honeywell pressure transducer mounted inside the model.

3. Discussion of the results

3.1. Characteristics of turbulent wake development behind a circular cylinder in oscillatory flow

The main part of experimental results obtained here deals with the near wake flow region and includes the mean flow evolution as well as the turbulent structure described by random and periodical fluctuations components. The unsteady flow field was analysed on the base of a complete set of profiles of measured quantities obtained at different distances x_1/d (see Fig. 3) and selected values of inflow oscillations frequency f_0. During the experiment the conditions of lock-on occurrence were fulfilled as well as the state outside the range of resonant synchronisation.

According to schematic sketch in Fig. 3, the degree of the wake-flow non uniformity can be characterised by the parameter $\Delta\overline{U}_{1m}/\overline{U}_0$. The profiles of mean longitudinal velocity component presented exemplary in Fig. 4 for different values of driving frequency f_0 and corresponding with the sample distance $x_1/d = 3$ behind cylinder allow to find the empirical dependence between the level of mean-flow uniformity, coordinate x_1 and inlet frequency f_0. The results shown in Fig. 5 reveal that the inlet periodical disturbances intensify the process of mean velocity field stabilisation. One can observe the progressive reduction of the wake-depth $\Delta\overline{U}_{1m}$ as f_0 increases. The influence of external flow disturbances is particularly strong for lock-on conditions, achieved in the present experiments for the driving frequency range $f_0 \approx 21 \div 28$ Hz (see Fig.1).

In the near wake-flow the presence of lateral mean velocity component $\overline{U}_2$ is strongly marked as a result of vortex street circulation. The experimental distributions of lateral mean velocity component for the distance $x_1/d = 3$ and a wide range of driving frequencies f_0 are presented in Fig. 6. The characteristic shape of $\overline{U}_2$ velocity profile results from different sense of velocity vector on both sides of the wake-center-line. The effects of incident flow oscillations are visible through the changes of local extremum corresponding to the vortex street formation and development. An increase in distance x_1/d results in a change of profile depth $\Delta\overline{U}_{2max}$ shown in Fig. 7 for different values of inlet flow frequency f_0. The experimental data form the common band with the local maximum due to vortex formation process.

Simultaneously with the measurements of mean flow pattern, all the components of double-velocity correlation tensor were determined to describe the sta-

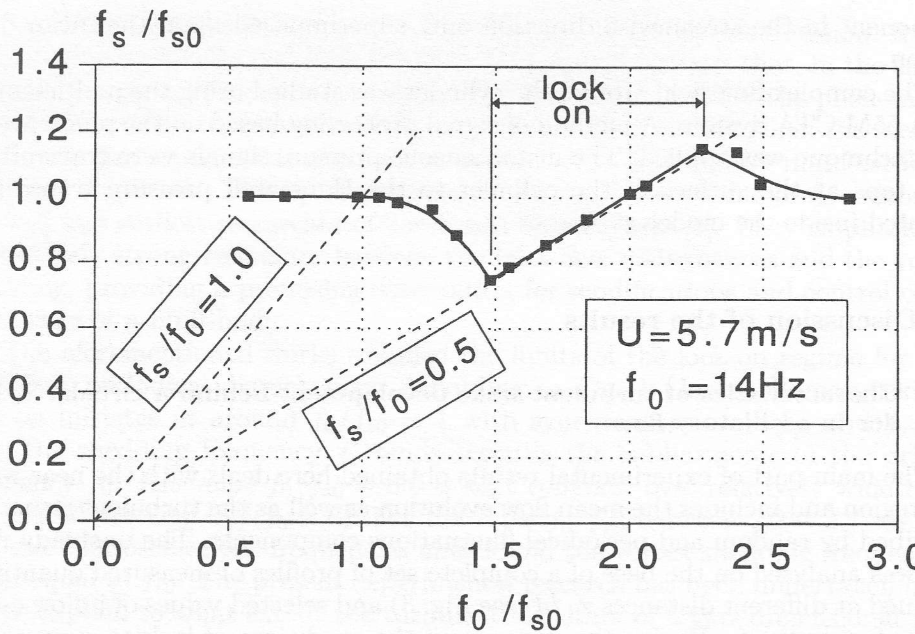

Fig. 1. Variation of reduced shedding frequency f_s/f_{s0} versus driving frequency f_0/f_{s0} (Jarża, Słomczyński [4]).

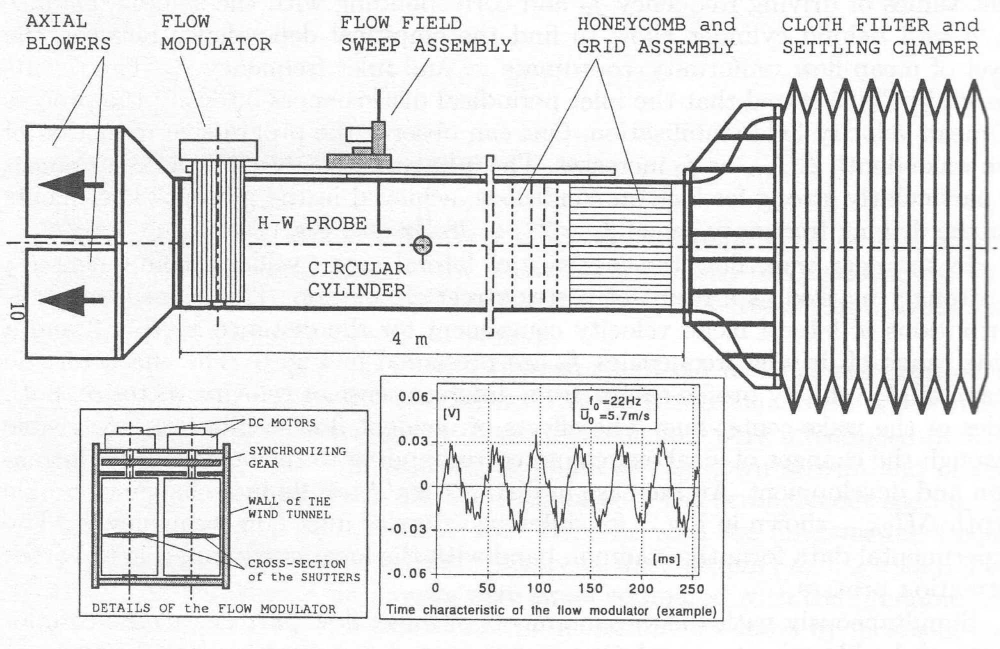

Fig. 2. Schematic of the experimental facility.

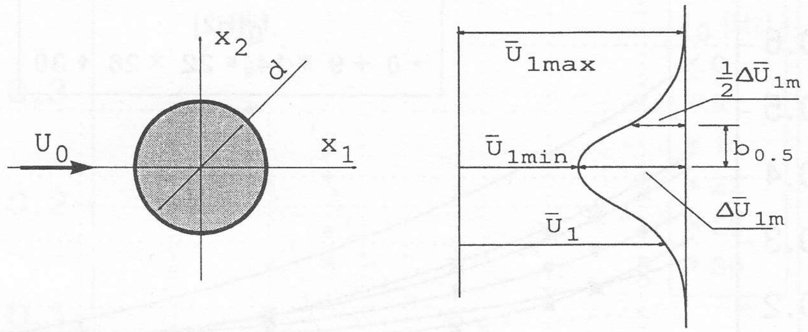

Fig. 3. Schematic sketch of mean velocity profile.

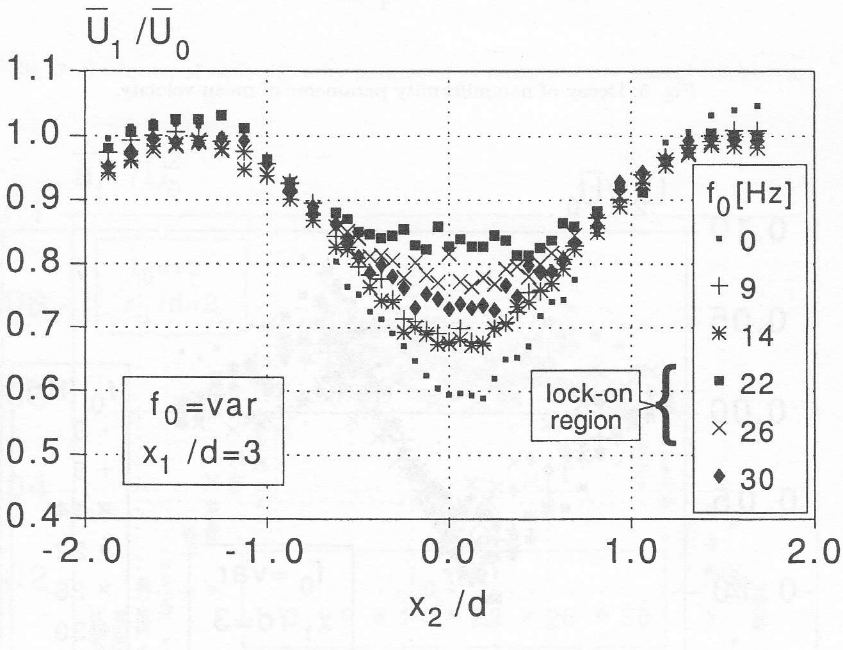

Fig. 4. Profiles of mean velocity longitudinal component across the wake flow.

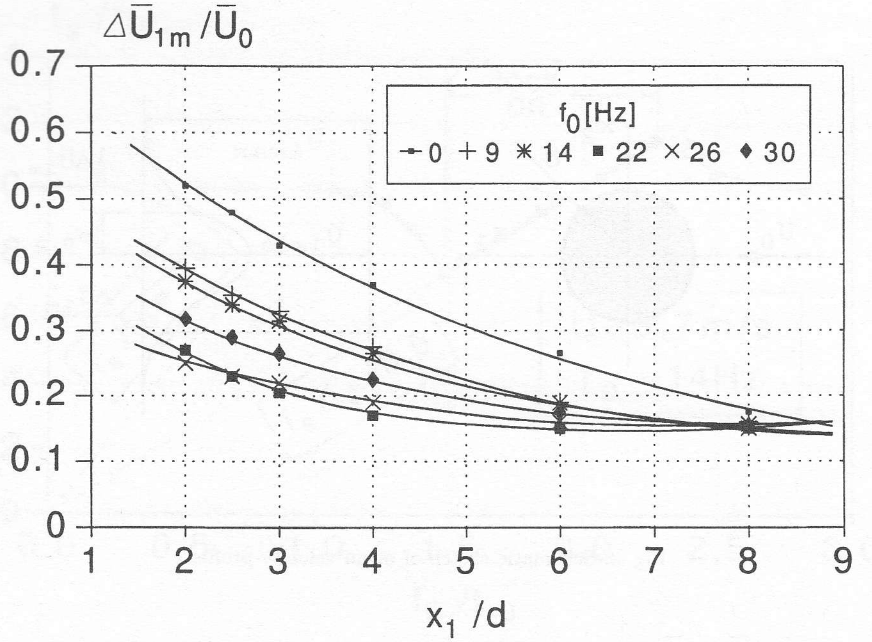

Fig. 5. Decay of nonuniformity parameter of mean velocity.

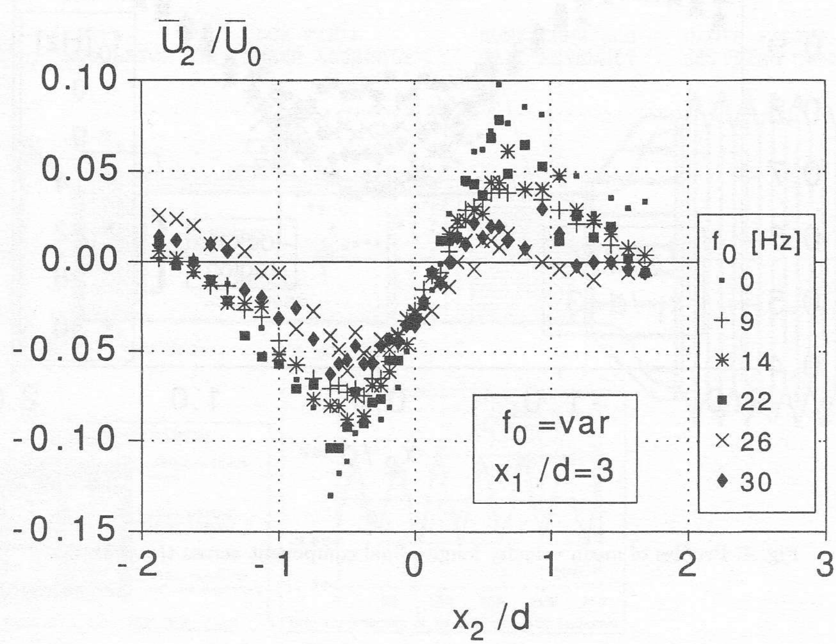

Fig. 6. Experimental distribution of mean velocity lateral component in the wake cross section $x_1/d = 3$.

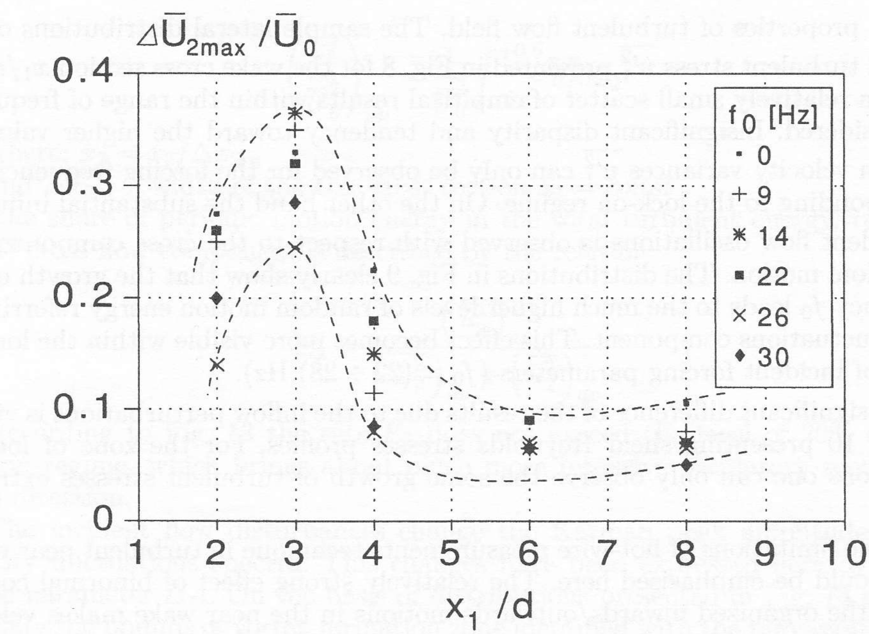

Fig. 7. Evolution of nonuniformity parameter of mean velocity lateral component.

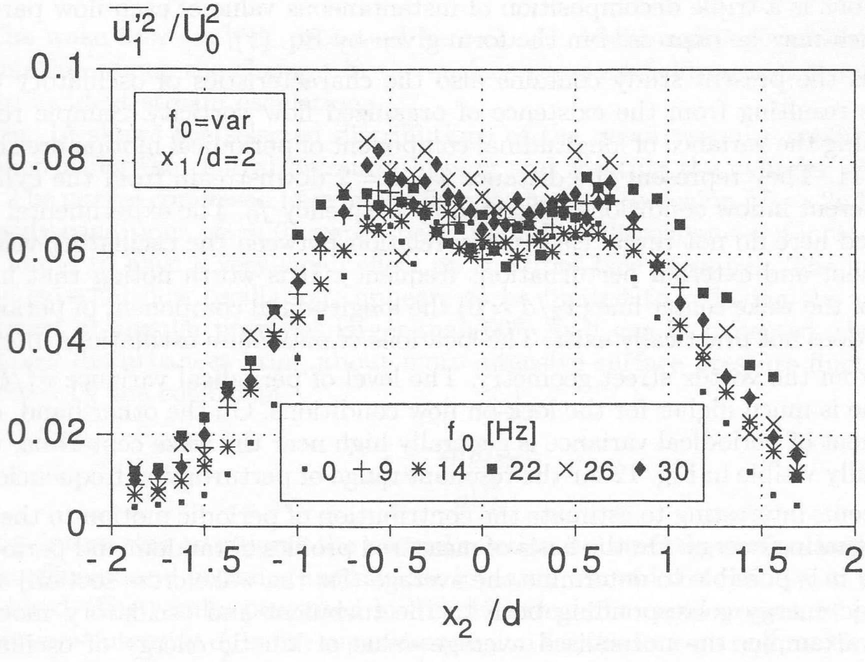

Fig. 8. The sample lateral distributions of the normal turbulent stress $\overline{u_1'^2}$.

tistical properties of turbulent flow field. The sample lateral distributions of the normal turbulent stress $\overline{u'^2_1}$ presented in Fig. 8 for the wake cross section $x_1/d = 2$ reveal a relatively small scatter of empirical results within the range of frequency f_0 considered. Insignificant disparity and tendency toward the higher values of random velocity variances $\overline{u'^2_1}$ can only be observed for the forcing frequencies f_0 corresponding to the lock-on regime. On the other hand the substantial influence of incident flow oscillations is observed with respect to the cross component $\overline{u'^2_2}$ of random motion. The distributions in Fig. 9 clearly show that the growth of the frequency f_0 leads to the much higher levels of random motion energy referring to cross fluctuations component. This effect becomes more visible within the lock-on range of incident forcing parameters ($f_0 = (22 \div 28)$ Hz).

No significant difference of the results due to the inflow perturbations is visible in Fig. 10 presenting shear Reynolds stresses profiles. For the zone of lock-on conditions one can only observe the some growth of turbulent stresses extremal values.

Some limitations of hot-wire measurements technique in turbulent near wake-flow should be emphasised here. The relatively strong effect of binormal cooling due to the organized inwards/outwards motions in the near wake makes velocity measurements in this region extremaly difficult. Therefore some of the results presented here should be treated as the rough estimation of the velocity field characteristics.

The main feature of the flow field around cylinder affected by incident stream oscillations is a triple decomposition of instantaneous value of each flow parameter, which may be expressed in the form given by Eq. (1).

Thus the present study contains also the characteristics of oscillatory components resulting from the existence of organized flow vorticity. Sample results concerning the variance of longitudinal component of periodical motion are shown in Fig. 11. They represent the distance $x_1/d = 2$ downstream from the cylinder and different inflow conditions described by frequency f_0. The experimental data presented here do not reveal clearly any relation between the oscillating velocity component and external perturbations frequency. It is worth noting that in the region of the wake center line ($x_2/d \approx 0$) the longitudinal component of periodical motion does not practically exist. The locations of maximum oscillations intensity result from the vortex street geometry. The level of periodical variance $\overline{\widetilde{u}^2_1}/\overline{U}^2_0$ in this zone is much higher for the lock-on flow conditions. On the other hand, cross component of periodical variance is generally high near the wake centerline, what is specially visible in Fig. 12 for the resonant range of perturbation frequencies f_0.

It seems interesting to estimate the contribution of periodic motion to the overall fluctuating energy. On the basis of measured profiles of random and periodical variance it is possible to determine the average (for the wake cross section) value of kinetic energy corresponding both to the turbulent and oscillatory motions. For the example, the normalised average value of kinetic energy of oscillatory flow can be expressed as

$$\left(\frac{\overline{\tilde{u}_i^2}}{\overline{U}_0^2}\right)_{av} = \frac{1}{\overline{U}_0^2}\int_{-0.5}^{+0.5}\overline{\tilde{u}_i^2}d\hat{x}_2 \tag{2}$$

where: $\hat{x}_2 = x_2/\Delta x_{2m}$
and Δx_{2m} – width of the test cross section $x_1 = const$.
The share of periodic motion energy in the total turbulent energy, referring to the cross flow component is described by the relation:

$$E_2 = \frac{\left(\overline{\tilde{u}_2^2}\right)_{av}}{\left(\overline{u_2'^2}\right)_{av} + \left(\overline{\tilde{u}_2^2}\right)_{av}} \tag{3}$$

According to Fig. 13 the rate E_2 does not exceed the level of 20% even in lock-on regime, which brings about much more intensive oscillatory motions in cross direction.

The incident flow disturbances change the Karman peak amplitude in the velocity fluctuations spectra. This changes have been expressed here by means of the parameter ΔA. On the basis of distributions presented in Fig. 14 one can estimate the bounds of vortex formation zone identified with the maximum of ΔA location. As it can be seen here, the inlet flow oscillations intensify the vortex forming, specially in lock-on conditions.

3.2. Pressure field around cylinder affected by incident stream oscillations

The wake flow analysis presented here can be additionally completed by the information about the changes in the surface pressure field around the cylinder due to incident stream oscillations.

Fig. 15 shows the selected distributions of the mean pressure coefficient C_p obtained using the central pressure tapping and rotating the cylinder about its axis. The curves composed here were taken in the lock-on region ($f_0 = 26$ Hz) and in steady conditions ($f_0 = 0$) respectively. Periodical disturbances of incident flow were found to have a very small effect on the front-face pressures. The influence of the external flow oscillations appears to be limited to reducing the pressure coefficient at angular positions larger than 60°. As it can be expected, the periodic inflow disturbances bring about more intensive surface pressure fluctuations expressed by the coefficient

$$c_p' = \frac{2p'_{RMS}}{\rho\overline{U}_0^2} \tag{4}$$

It is interesting to observe the mutual relation between the surface mean pressure coefficient and pressure fluctuations intensity around the cylinder in the flow considered. The results presented in Fig. 15 reveal the rapid growth of pressure fluctuations intensity c_p' in the separation region for the lock-on regime. The mean drag coefficient C_D estimated on the base of results presented in Fig. 15 increases

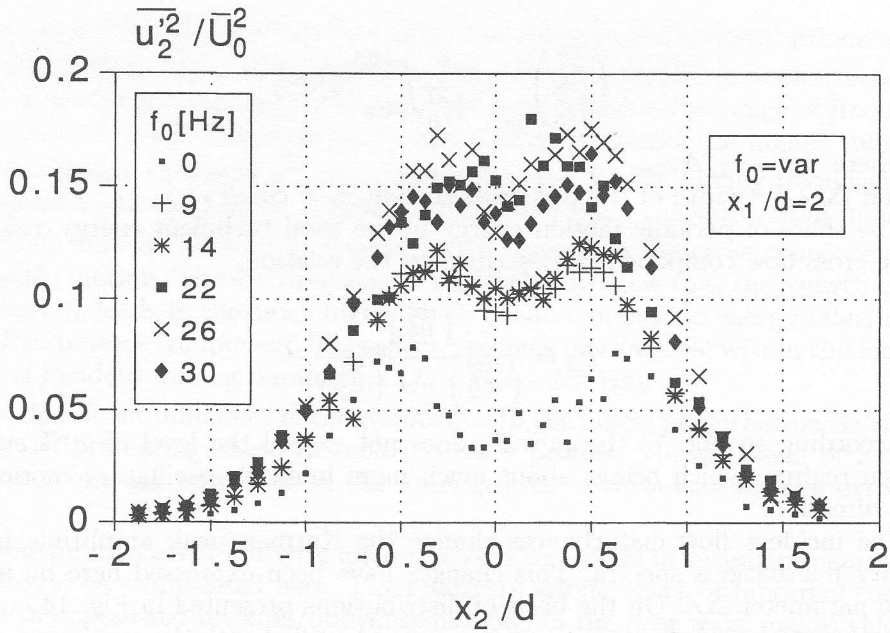

Fig. 9. Variation of random velocity component $\overline{u_2'^2}$ in the wake cross section $x_1/d = 2$.

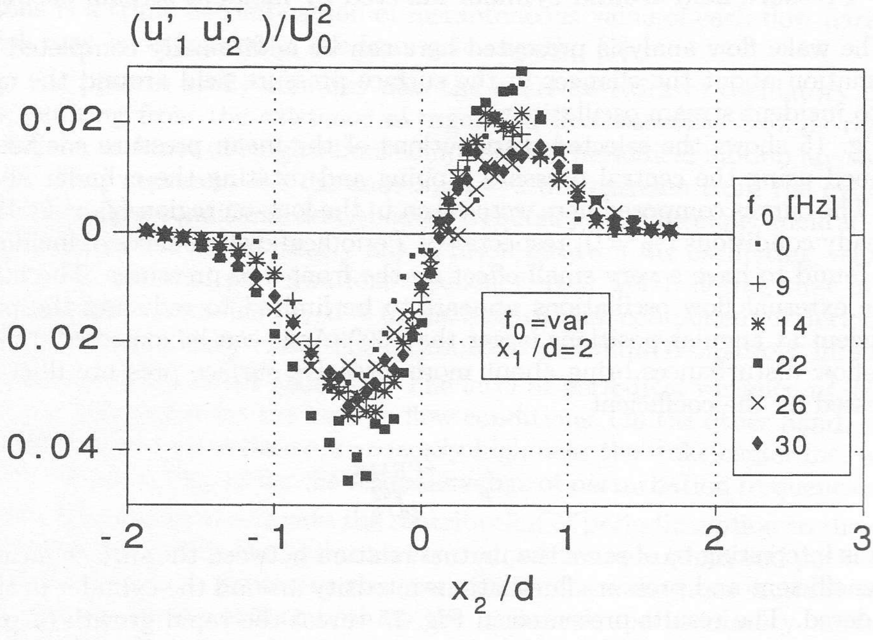

Fig. 10. Shear Reynolds stresses across the wake flow for different values of f_0.

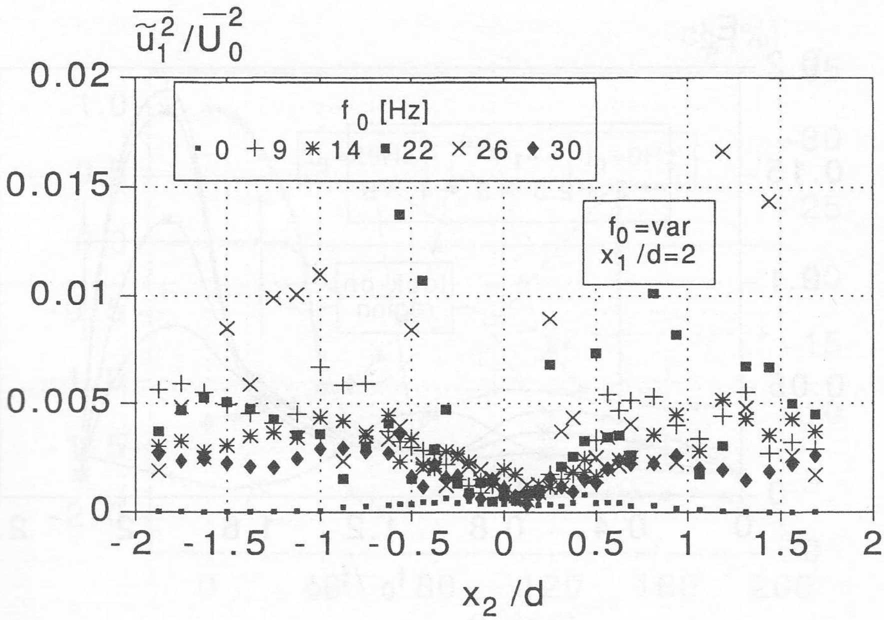

Fig. 11. Variance of longitudinal component of periodical motion in the wake affected by incident stream oscillations.

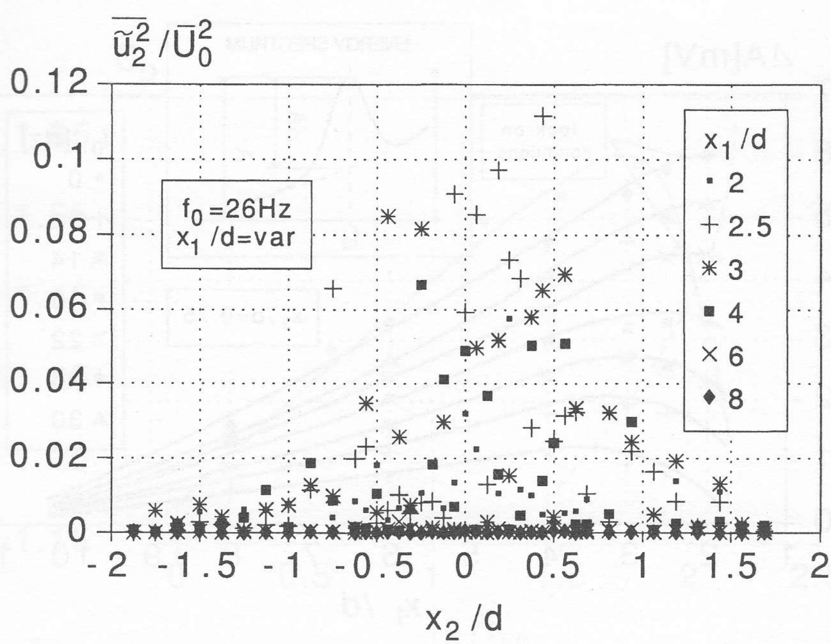

Fig. 12. Cross component of periodical variance across the wake-flow for different values of f_0.

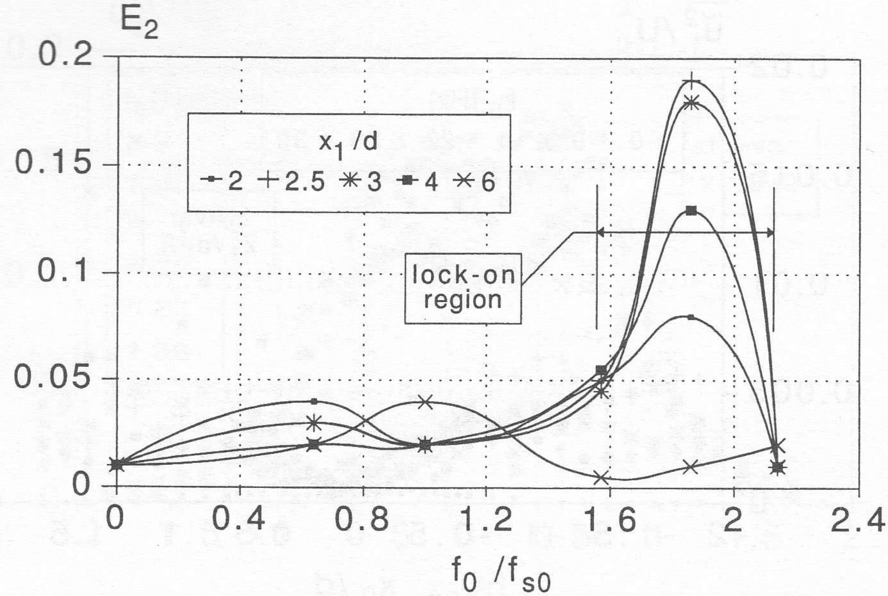

Fig. 13. Share of periodic motion energy in the total turbulent kinetic energy referring to cross component.

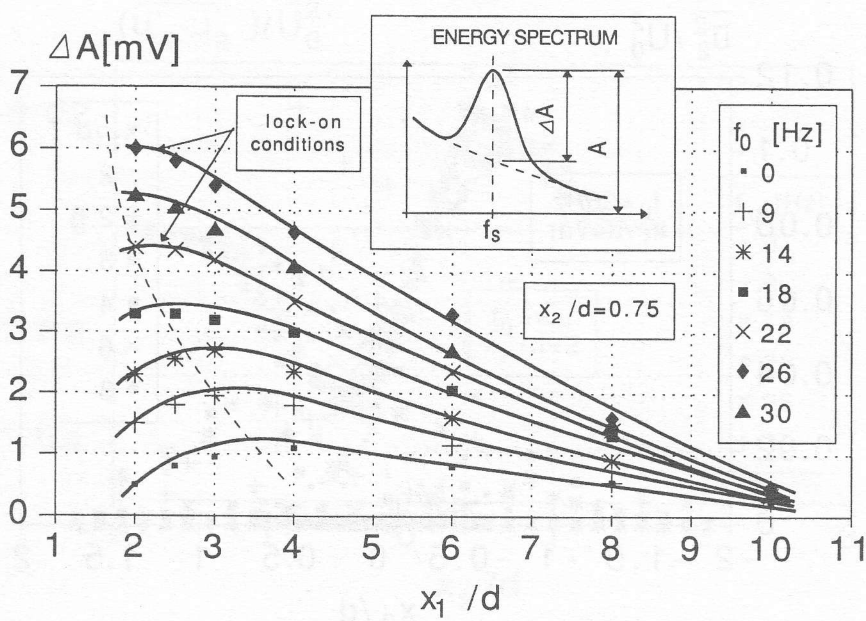

Fig. 14. Changes of Strouhal peak amplitude in velocity fluctuations spectrum for vortex formation zone behind cylinder in oscillatory flow.

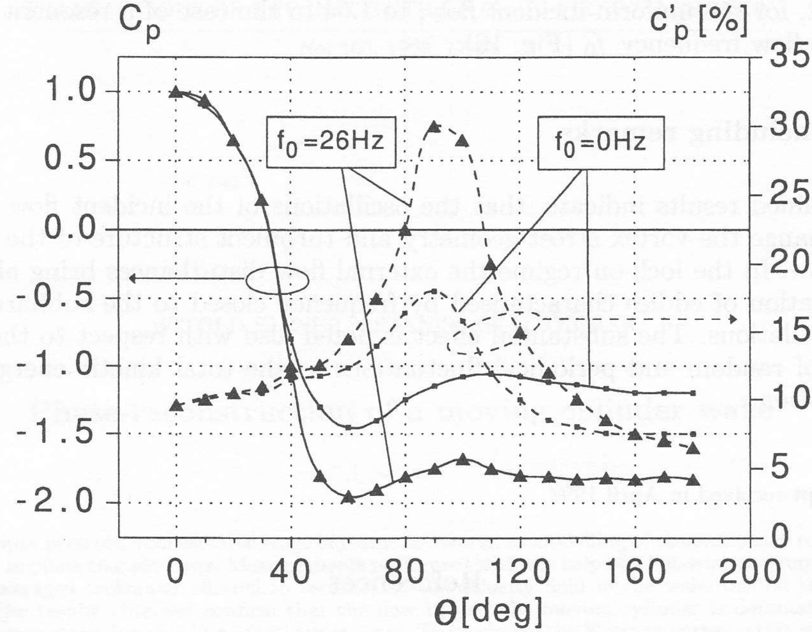

Fig. 15. Distribution of mean and fluctuating components of pressure coefficient around cylinder surface.

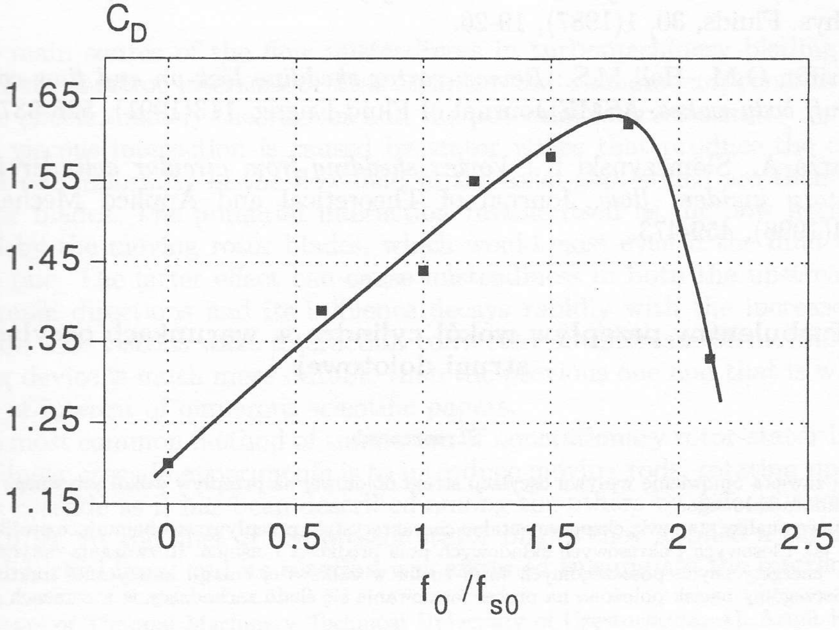

Fig. 16. Effect of inlet flow oscillations on the mean drag coefficient of circular cylinder.

from 1.2, for the uniform incident flow, to 1.64 in the case of a resonant value of incident flow frequency f_0 (Fig. 16).

4. Concluding remarks

Obtained results indicate, that the oscillations of the incident flow considerably change the vortex street geometry and turbulent structure of the cylinder wake flow. In the lock-on regime the external flow disturbances bring about the amplification of eddies characterised by frequency closed to the subharmonic of inlet oscillations. The substantial effect is noted also with respect to the contribution of random and periodical fluctuations to the total kinetic energy of the fluid motion.

Manuscript received in April 1998

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Turbulentny przepływ wokół cylindra w warunkach oscylacji strugi dolotowej

Streszczenie

Praca zawiera omówienie wpływu oscylacji strugi dolotowej na przepływ wokół sztywnego nieruchomego cylindra kołowego.

Podstawę analizy stanowią eksperymentalne charakterystyki przepływowe obejmujące profile zarówno średnich jak i losowych i okresowych składowych pola prędkości i ciśnień. Rozważania dotyczą również udziałów energetycznych poszczególnych form ruchu w całkowitej energii kinetycznej fluktuacji przepływu. Szczególny nacisk położono na proces formowania się śladu zachodzący w warunkach rezonansu *lock-on*.