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# VORTEX SHEDDING FROM CIRCULAR CYLINDER IN OSCILLATORY INCIDENT FLOW

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The response of the flow around stationary circular cylinder due to incident stream oscillations has been discussed here. The results demonstrate that the phenomenon of vortex-shedding lock-on is observed when the inlet mean flow has a periodical component characterized by properly matched frequency and amplitude. The effect of incident periodical changes on the surface pressure fluctuations in and outside lock-on regime has also been studied.

## Notations

$a$ – amplitude of cylinder vibration
$c_p$ – surface pressure coefficient
$c_p'$ – coefficient of pressure fluctuations
$D$ – diameter of the cylinder
$E_s$ – amplitude of the Strouhal peak in power spectra of pressure fluctuations
$f_0$ – frequency of the inlet flow disturbances
$f_s$ – vortex shedding frequency
$f_{s0}$ – Strouhal frequency of a stationary cylinder in a uniform incident flow
$f_v$ – frequency of the cylinder vibrations

$n_0$ – angular velocity of the shutters
$U_0$ – mean velocity of the incident flow
$\theta$ – angular coordinate of the position around cylinder
$\epsilon$ – reduced amplitude of the inflow disturbances.

## 1. Introduction

The periodic flow separation and vortex formation that accompany the flow past a bluff obstacle have been observed for many years, but still many questions concerning this problems remain unanswered. Many studies, eg., Bearman (1967) and Morkovin (1964), focused on the physics of vortex street generation. More recent investigations (cf Browne et al. (1989); Cimbala et al. (1988)) have provided valuable insight into evolution of the overall near- and far-wake vortex patterns.

The important object of this interest is the periodic force affecting the bluff-bodies over a wide range of Reynolds number. This oscillating force is a direct result of the alternate generation and shedding into the wake of vortices from either side of the body. The growth and shedding of an individual vortex changes symmetry of the boundary layer, where cumulative effect is a time-dependent pressure load. The fluctuating lift force has a frequency equal to the vortex shedding frequency whereas the frequency of fluctuating drag force is twice the shedding frequency.

The organized and periodic shedding of vortices is a cardinal cause of the resonant oscillations, if one of the natural frequencies of the body immersed in the flow is near the vortex shedding frequency. In the case of flexible and lightly dumped structures the resonant oscillations can be excited normal or parallel to the incident flow. For more common cross flow oscillations the body and the wake have the same frequency near one of the characteristic frequencies of the structure (Fig.1). This coincidence of the vortex and vibration frequencies is commonly termed "lock-on". The frequency bandwith of lock-on phenomenon determines the velocity range over which such self-induced oscillations can occur.

Bishop and Hassan (1964) showed, for a circular cylinder, that lock-on was accompanied by a substantial increase not only in the oscillatory lift but also in the mean drag force. This reinforcement is closely related to changes in the flow field in the near wake of the body. So, the occurence of lock-on can lead to the failure of bluff structures.

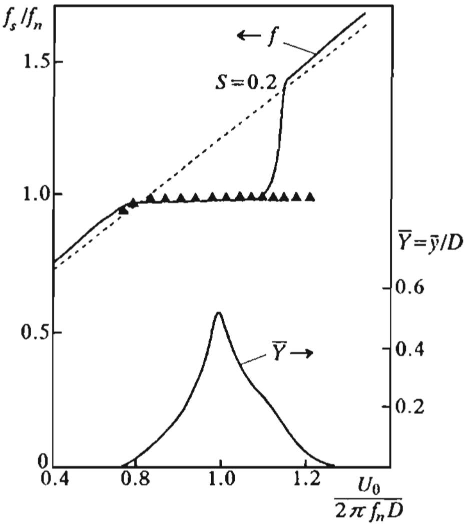

Fig. 1. Frequency and amplitude of the vortex-induced oscillations of circular cylinder (cf Sarpkaya (1979))

Vortex lock-on and resonance phenomena have numerous practical engineering applications. These applications abound in off-shore exploration and drilling, naval and marine hydrodynamic and underwater acoustic. Other areas of engineering practice impacted by these phenomena are civil and wind engineering, nuclear and conventional power generation and electric power transmition.

The locking-on was first studied with reference to the self-induced oscillations of lightly dumped cylinders (cf Ferguson and Parkinson (1967)). For better understanding the parameters which influence the lock-on phenomenon Tanida et al. (1976) and Griffin and Ramberg (1976) showed that the lock-on resonance is also induced when a cylinder is forced to oscillate normal to the flow or in-line with the incident flow over an appropriate range of imposed frequencies and amplitudes. For bodies oscillating in the streamwise direction, the lock-on phenomenon tends towards occurence at frequencies approximately twice the Strouhal frequency for a rigid cylinder, since each of the alternating vortices independently induces a fluctuating drag component. The works devoted to vortex shedding from oscillating bluff cylinders have been reviewed by Sarpkaya (1979) and Bearman (1984).

The aim of this paper is to answer a still discussed question: does the phenomenon of lock-on occur also in the case of fixed cylinder when the incident mean flow has a sufficently large periodical component superimposed upon it.

Earlier researches (cf Hatfield and Morkovin (1973)) were inconclusive, probable because both the amplitude and frequency of the fluid oscillations were too low. Recent review given by Griffin and Hall (1991) has confirmed the fact that the phenomenon of vortex shedding resonance or lock-on is also observed when a bluff body is placed in an oscillatory incident flow and there is a complete equivalence between this case and in-line oscillations of the cylinder. This opinion agrees exactly with the results of Armstrong et al. (1986) who emphasized a particularly strong resonance between the inlet flow disturbances and the vortex shedding, providing a promissing mean for modifications and control of the near-wake of a bluff-body. But even today, the frequency bandwidth of lock-on phenomenon and the threshold values of flow oscillation amplitude that are required for the lock-on have been evaluated for only a limited number of conditions. This problem has been considered in the present paper too, where the response of the flow around circular cylinder due to incident periodic disturbances is discussed.

## 2. Conditions of lock-on occurence

It results from the studies mentioned above (cf Armstrong et al. (1986); Griffin and Hall (1991)) that the phenomenon of vortex shedding resonance or lock-on is observed also when a bluff-body is placed in an incident mean flow with a periodic component superimposed upon it. In this case the cylinder remains stationary, but the vortex lock-on resulting from the inflow disturbances modifies the character of near-wake flow.

The experimental works of Armstrong et al. (1986), (1987) and Barbie et al. (1986) revealed the limits of the lock-on regime for incident flow periodical disturbances. The aforementioned results show some remarkable similarities with those obtained in earlier experiments by Griffin and Ramberg (1976), which were carried out to examine the vortex lock-on for a cylinder oscillating in line with an incident uniform flow.

The vortex lock-on regime measured by Barbie et al. (1986) is compared with that of Griffin and Ramberg (1976) in Fig.2. The vertical axis represents two different measures of perturbation amplitude. For the experiments of Griffin and Ramberg (1976), the"peak-to-peak" amplitude of cylinder displacement is given by $2a/D$; for the experiments of Barbi et al. (1986) the normalized "peak-to-peak" incident velocity perturbation is expressed by $\Delta U/\pi f_0 D$. The horizontal axis is the ratio of the external disturbation frequency ($f_v$ or $f_0$) and the Strouhal frequency $f_{s0}$ of a stationary cylinder.

The results for an oscillating cylinder obtained by Tanida et al. (1976) and of Tatsuno (1976) are also shown in this figure.

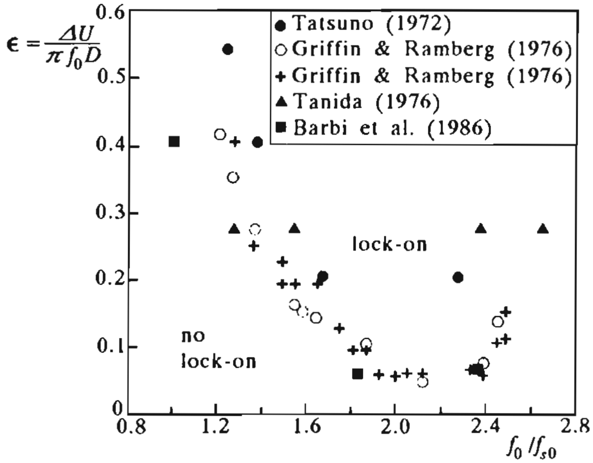

Fig. 2. Limits of the lock-on regime as a function of amplitude and frequency for in-line oscillations or inlet flow perturbations

Generally there is a good agreement between the bounds of the lock-on regime for two different types of external disturbances, however some scattering of results is observed at the highest amplitudes. This is most likely due to the Reynolds number effect as noted by Barbi et al. (1986).

So, the limits of lock-on existence can be characterized by the group of mutualy related features which consists of the amplitude and frequency of external disturbances and a bluff-body natural shedding frequency. The generation of the inlet conditions which make it possible to study the vortex lock-on in the context of the active flow control around the circular cylinder is of great importance in the undertaken experimental work.

## 3. Experimental arrangement

The experiment was performed in an open-circuit subsonic wind tunnel in the Thermal Machinery Institute at the Technical University of Częstochowa. The measuring section was 0.5 m wide, 0.6 m high and 4,1 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 cylinder had pressure tappings of 0.75 mm in diameter drilled along the center line at $0.5D$ distances. It was possible to rotate the object with a position error of less than 0.5%.

The cylinder covers 8% of the chanel cross-sectional area, but the pressure measurements have not been corrected for the effects of blockage. The preliminary tests showed a reasonable agreement with the results of West and Apelt (1982) for cylinders having the same blockage and aspect ratios.

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 test section. The shutters comprised two pairs of rectangular plates that fitted into two vertical steel rods. For the scheme see Fig.3.

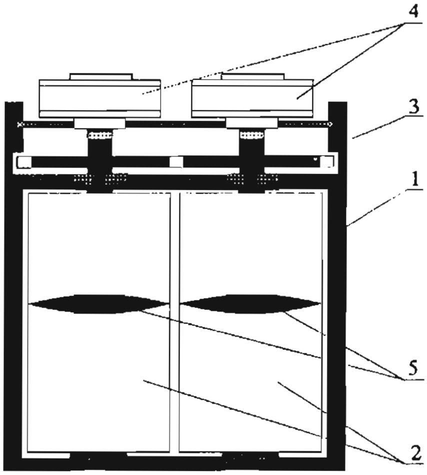

Fig. 3. Generator of the inlet flow oscillations; 1 – wall of the wind tunnel, 2 – rotating shutters, 3 – synchronizing gear, 4 – DC motors, 5 – cross-sections of the shutters

The complex flow field around the cylinder was studied using different measuring techniques suitable for unsteady flows.

The instantaneous pressure signals were transmitted from taps at the surface of the cylinder to the Honeywell pressure transducer, within a range of 0 to 35 mbar, mounted inside the model. The transducer provided an output voltage linearly proportional to the input pressure in a specified operating range. The resonance frequency of pneumatic line was well above the frequency range investigated.

The velocity circuit consisted of DISA 55M System Constant Temperature Anemometer equipped with hot-wire probe of DISA 55 type, 55D35 rms voltmeter, 55M25 linearizer and mean value voltmeter. An IBM PC/AT microcomputer was used as the central unit for the data aquisition system.

The analysis of measurement data was carried out by means of a conventional time averaging procedure. Thus, the measuring signals contained the combined information about both the periodic and random flow field components.

## 4. Characteristics of the inlet flow disturbances

The pressure oscillations, which propagated upstream as an acoustic wave, were generated by rotating shutters. The associated velocity perturbations were periodic, with the fundamental frequency $f_0$ corresponding to the angular velocity of the shutters ($f_0 = 2n_0$). Spectra of the perturbation velocity showed that the amplitudes of disturbance harmonics were generally small compared with the fundamental frequency amplitude.

The rotational frequency of shutters was measured using the optical transducer E21 CPP PZO and the frequency HP meter.

Experimental tests showed that the frequency $f_0$ could be set within 0.1% of the desired value and its drift was less than 0.1% during the experiment. It should be emphasized that the investigations into the disturbed channel flow were made with the working section empty.

A sample oscillogram of the hot-wire signal recorded at the cylinder position for the shutters frequency $n_0 = 11\,\mathrm{Hz}$ is presented in Fig.4. The sensitivity characteristic of the sensor used in measurements, additionaly shown in Fig.4, allows determination of the corresponding velocity time dependence. It can be seen that the incident mean flow has a large longitudinal periodic component superimposed on it. The additional control measurement taken by means of the $X$ hot-wire probe confirmed that the incident flow velocity oscillates in the streamwise direction only.

The uniformity of the disturbance amplitude across the working section was tested. With the mean velocity of $5.5\,\mathrm{m/s}$ and the oscillations frequency $f_0 = 22\,\mathrm{Hz}$ the amplitude, measured in terms the variance of the mean of the signal, was found to be constant to within 1%.

The variation of the inlet oscillations amplitude with the perturbation frequency at a mean velocity of $5.67\,\mathrm{m/s}$ is shown in Fig.5. Introducing the reduced amplitude of the inflow oscillations, defined after Barbi et al. (1986)

$$\epsilon = \frac{\Delta U}{\pi f_0 D}$$

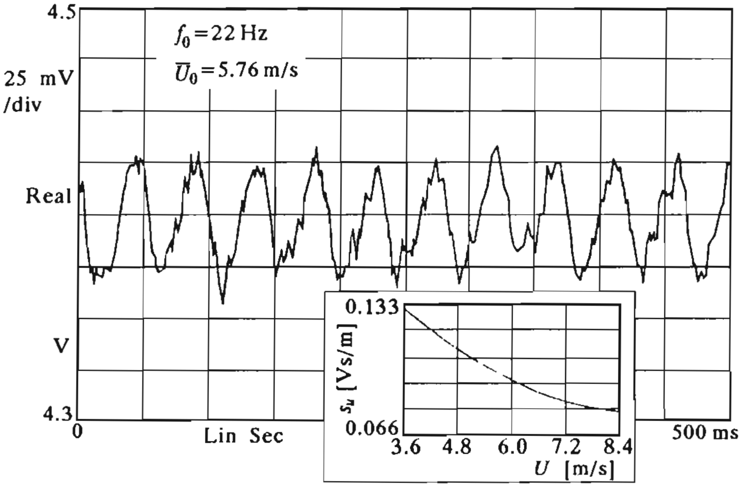

Fig. 4. Sample trace of the hot-wire signal in an oscillatory incident flow

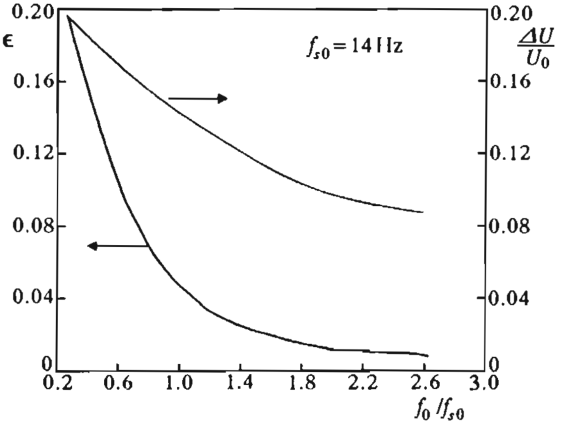

Fig. 5. Characteristics of the inlet flow disturbances

one can estimate the range of this parameter in the present work. Its values correspond to the experimental conditions of the earlier investigations of Barbi et al. (1986). According to Fig.2 some of the present values of $\epsilon$ reach the bound of lock-on regime.

## 5. Experimental results

The research described here focuses on the interpretation of fluctuating pressure signals measured on the cylinder surface. It was possible to detect the vortex shedding frequency $f_s$ from power spectra of pressure fluctuations recorded at different angular positions around the cylinder.

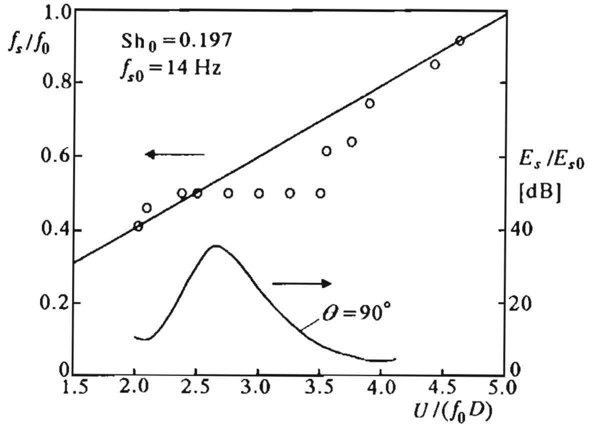

Fig. 6. Vortex-shedding frequency versus reduced velocity for the range of $f_0$ considered

The inverse of Strouhal number, formed using driving frequency $f_0$ and mean velocity $U_0$ is plotted versus $f_s/f_0$ in Fig.6. The slope of the line drawn here is a constant equals to 0.197 and it represents the Strouhal number for the Karman vortex street in the case of steady inlet flow. The locking phenomenon occured as a plateau near $f_s/f_0 = 0.5$. It means that over a range of reduced velocity $U_0/f_0D$ the vortex shedding frequency remained at half of the inlet oscillation frequency. The resonant point occurs when the reduced velocity has a value equal to half of the inverse of Strouhal number for vortex shedding in a steady incident flow (Sh=0.197). One can observe in Fig.6 that the resonant point lies within the lock-on range, close to its lower limit. This results may be compared with the findings of Bearman and Currie (1979) for the case of a circular cylinder in forced vibrations, in which the resonant point was localized at the beginning of the lock-on range. The present results are also in good agreement with those of Tanida et al. (1976) for in-line oscillations of the cylinder.

Fig.7 reveals that lock-on initiates at around $f_0/f_{s0} = 1$ with synchronization of $f_0$ and $f_s$, but then the shedding frequency tends towards the

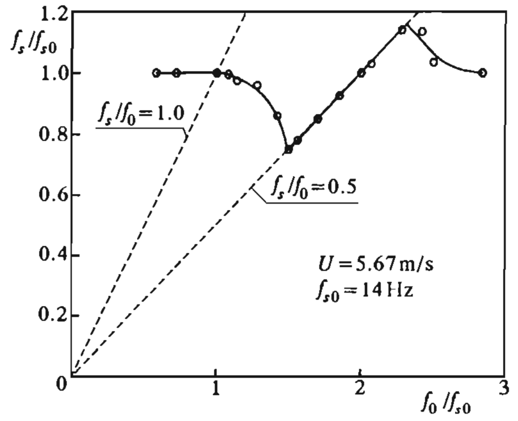

Fig. 7. Variation of reduced shedding frequency $f_s/f_{s0}$ versus driving frequency $f_0/f_{s0}$

subharmonic of the driving frequency. For the values of $f_0/f_{s0}$ between $2 \div 3$ the vortex and perturbations frequencies unlock and the vortex shedding frequency is again equal to $f_{s0}$.

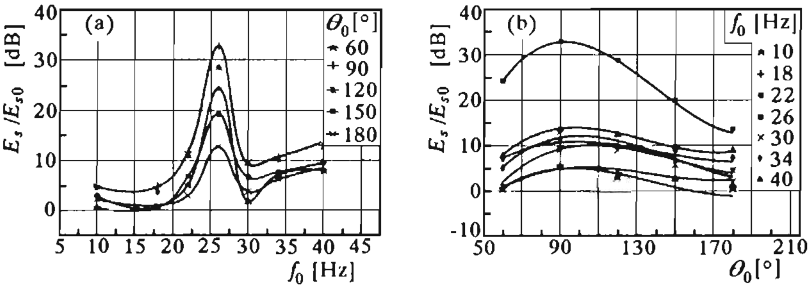

Fig. 8. Reduced amplitudes of the Strouhal peaks in power spectra of the surface pressure versus (a) incident flow frequency, (b) angular location around cylinder

The effects of incident flow oscillations are visible in the form of the vortex shedding peaks amplification. The amplitudes $E_s$ related to the Strouhal peak level $E_{s0}$ in non-disturbed flow are shown in Fig.8. As it can be seen, the zone of lock-on conditions corresponds with the higher amplitudes of the vortex shedding peaks in power spectra of pressure fluctuations. The influence of external flow disturbances is particularly strong near the separation point.

So, the pressure spectra measured on the cylinder surface show differing characteristics depending on whether or not the shedding frequency is captured by the incident flow frequency.

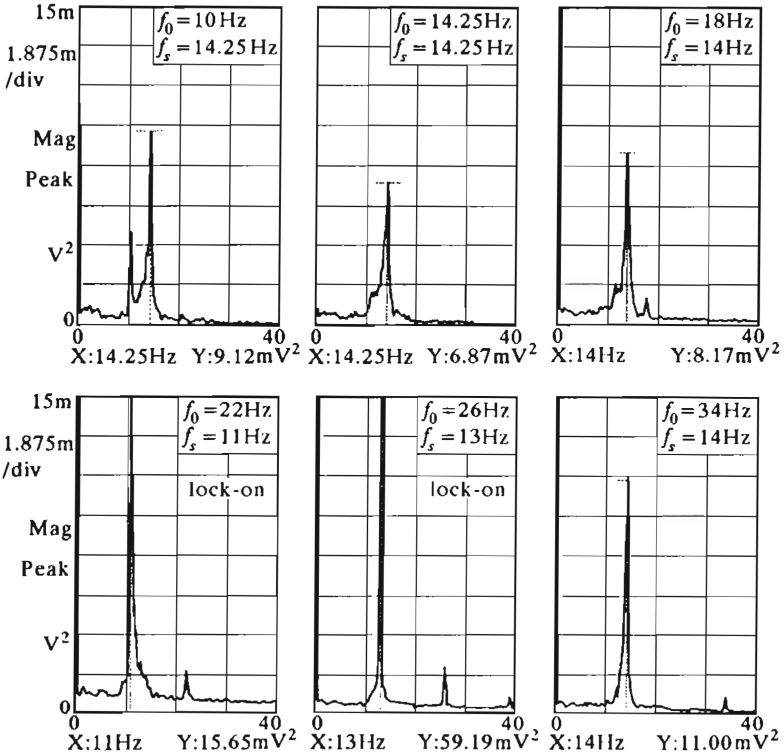

Fig. 9. Power spectra of velocity in the wake for different values of $f_0$

Spectra with similar features were given by hot-wire signals from a probe positioned outside the wake about 3D downstream of the cylinder (Fig.9). They confirm the results presented above and prove the mutually displacement of the two frequencies $f_0$ and $f_s$. One can observe the progressive decrease of $f_s$ as $f_0$ increases. They meet without even any particular changes in the power spectrum, after which $f_s$ continues to decrease. So our findings indicate that the cylinder losses its natural shedding frequency which may vary smoothly with the driving frequency before locking-on its subharmonic.

Surface pressure fluctuations for angular position $\theta = 90$ deg, expressed by the coefficient

$$c_p' = \frac{2p'_{rms}}{\rho U_0^2}$$

are shown in Fig.10 versus the reduced velocity $U_0/f_0D$. As it can be expected, the external periodic flow disturbances bring about more intensive surface pressure fluctuations. The level of pressure coefficient normalized by the value of $c'_{p0}$ corresponding to non-disturbed flow conditions varies in the lock-on range with the local maximum occuring close to the resonance point.

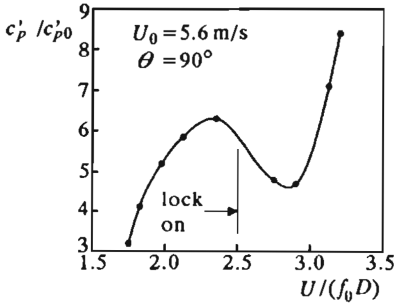

Fig. 10. Effect of inlet flow oscillations on the surface pressure fluctuations at angular position $\theta = 90°$

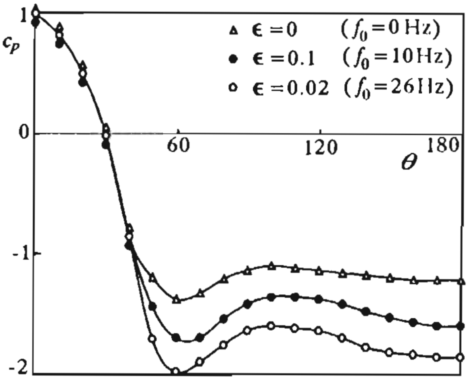

Fig. 11. Comparison of mean pressure coefficients for steady and oscillatory incident flow conditions

Fig.11 shows the selected distributions of mean pressure coefficient obtained by using the central pressure tapping and rotating the cylinder about its axis. The curves compared here were taken in the lock-on region ($f_0 = 26$ Hz), before the locking-on ($f_0 = 10$ Hz) and in steady conditions ($f_0 = 0$), respectively. Inlet flow oscillations were found to have a very small effect on the front-face pressures. The influence of the external flow disturbances appears to be limited to reducing the pressure coefficient at angular positions larger than 60 deg.

The mean drag coefficient, estimated on the base of results presented here, increased from 1.28 for the uniform incident flow to 1.52 in the case of disturbances parameter $\epsilon = 0.02$.

## 6. Conclusions

The analysis of the results presented here gives the possibility to draw the following conclusions:

- The phenomenon of lock-on occurs also in the case of stationary cylinder when the incident mean flow has a periodical component characterized by properly matched frequency and amplitude
- The conditions of lock-on occurence in the case of oscillatory incident flow are in good agreement with the results for in-line forced vibrations of a cylinder in uniform stream
- Shedding frequency varies smoothly with the driving frequency $f_0$ before locking-on its subharmonic. This fact suggests the possibility of active control of the vortex shedding process through the oscillatory inlet flow disturbances
- At lock-on the amplification of the surface pressure fluctuations as well as the higher amplitudes of the vortex shedding peaks in power spectra are observed.

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## Proces schodzenia wirów z cylindra kołowego opływanego strumieniem oscylacyjnym

### Streszczenie

Przedstawione w pracy rezultaty badań eksperymentalnych dotyczą struktury przepływu wokół nieruchomego cylindra o przekroju kołowym umieszczonego w strumieniu powietrza zaburzonym w sposób periodyczny. Wygenerowany napływ oscylacyjny charakteryzował się zespołem cech prowadzących do zjawiska częstotliwościowej synchronizacji typu lock-on i umożliwiał obserwację związanych z tym stanem zjawisk. Eksperymentalnej analizie poddano w szczególności związek między parametrami okresowości strugi dolotowej a fluktuacjami ciśnień na powierzchni cylindra. Stwierdzono m.in., że przejście do stadium lock-on, w którym częstotliwość wirów generowanych przez cylinder osiąga wartość podharmonicznej zaburzeń wlotowych, poprzedzone jest płynnym współzależnym przemieszczaniem się pików spektralnych związanych z okresowością schodzenia wirów oraz oddziaływań zewnętrznych.

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