Estimation of friction loss under forced flow pulsations in a channel with discrete roughness elements

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Abstract. The pulsating flow in a circular channel with semicircular annular ribs as discrete roughness elements has been studied experimentally. Air flow under atmospheric conditions at the channel inlet has been considered. Steady and pulsating air flow has been studied under different frequencies and amplitudes of forced pulsations generated by periodic blockage of the channel cross section by a rotating flap. Flow resistance in pulsating regimes has been estimated from the average static pressure drop. The resistance values attained twice the steady flow ones.

1. Introduction

The resistance of steady turbulent flow in a smooth round pipe has been studied in detail. But when it comes to unsteady flows, the resistance and pressure cannot be estimated neglecting the effect of forced unsteadiness on the flow parameters.

Daily et al. [1] studied the accelerated and decelerated flow through smooth ducts and orifices. With acceleration, the resistance was slightly but not appreciably greater than for the equivalent steady state. With deceleration, the resistance was appreciably less than for the equivalent steady state. In both unsteady cases, internal flow structure was not markedly different from that for steady states.

It has been shown, both experimentally and numerically, that in a small region of the parameter space the period-averaged wall shear stress may be smaller than the steady flow values. Many authors, e.g. [2], attribute this to a reverse transition generated by the turbulence suppression. Manna and Vacca [3, 4] provide different argument to support the above mentioned resistance reduction. They studied the effect of harmonic pulsations of fixed frequency on the characteristics of a turbulent pipe flow and found that when the ratio of the amplitudes of the oscillating and bulk velocities increased from 1 to 11, the turbulence was affected by the harmonic forcing so much that the near wall coherent structures were substantially modified, although not suppressed through a reverse transition process. This results in an overall space and time averaged resistance reduction which, for the largest amplitude case, adds up to 33% of the non-pulsating flow at the same bulk Reynolds number. Experimental studies of flow resistance in a smooth pipe under periodic air flow rate unsteadiness [5] showed that while steady flow resistance can be estimated from the total or static pressure drop across the channel and roughness elements, the pressure drop in the unsteady flow does not unequivocally yield the flow...
resistance. Pulsating flows with their inherent wave structure require taking the total flow momentum variation into account.

Channels with discrete roughness are used in nuclear engineering, aviation, electronics, etc. However, there is clearly a shortage of both theoretical and empirical relations for estimation of turbulent and laminar flow resistance coefficients in channels in the range of parameters (t/lh, h/D, Re, Pr) that are of critical importance for engineering purposes and allow for the roughness shape. It is well-known that the drag coefficient of a single sharp-edged rib in a fully developed turbulent flow is independent (or weakly dependent) of Re. Generally, the friction factor in the channel with discrete roughness elements depends on the Reynolds number and the turbulators’ height, pitch and shape.

Ahn [6] studied the effects of rib shape geometries and Reynolds numbers on friction factor in a rectangular rib-roughened channel. The local drag coefficient along the rib wall was defined as the ratio of the static-wall pressure drop to the fluid dynamic pressure. Chandra et al. [7] demonstrated that ribs on all four walls of the channel create maximum pressure-drop/friction-factor that is about 12.14 times the friction factor in fully developed smooth pipe turbulent flow for the considered Reynolds number. Cui et al. [8] showed that LES can be used to identify the pressure and frictional components of resistance in a rib-roughened channel and observed that the ribs on the bottom wall influence the resistance on the top wall of the channel suggesting a large-scale interaction between the flow in the roughness layer and the outer flow. Ryu et al. [9] found that a numerical model based on the Reynolds-averaged Navier–Stokes equations coupled with a turbulence model that resolves the near-wall flow is able to successfully capture the essential features of the flow over the surface with two-dimensional ribs and three-dimensional blocks. When the solutions are averaged over appropriate areas, they provide engineering information about the resistance coefficient and its dependence on the geometric and flow parameters.

In general, as it is noted in [10], flows over smooth walls are dominant in the studies of the periodic turbulent flows, whereas, real surfaces in engineering applications are often rough. They also note that the resistance parameter of a corrugated pipe, where particular roughness geometry is applied, cannot be predicted without experimental investigation.

The resistance of unsteady separated flows is almost unexplored. Hvang K.S. et al [11] studied the pulsating laminar flow separating from a blunt-faced flat plate and revealed that the reattachment length in the pulsating flow reduced to a quarter of the steady flow value (at certain frequencies). For the case of an orifice mounted in the channel, the already cited authors [1] showed that with acceleration the resistance is appreciably less than for the equivalent steady state, and vice versa, with deceleration the resistance is appreciably more than for the equivalent steady state. For intense jet action as obtained with small orifice to pipe diameter ratios, it appeared that unsteadiness produces an internal flow structure that is no longer comparable to any steady state condition [1]. Wang et al. [12] investigated the influence of two different amplitudes and two different frequencies of the pulsating laminar flow on the flow resistance in a channel containing a winglet-type longitudinal vortex generator. The overall and local friction factor used to describe the flow resistance characteristics was calculated from the mass-weighted average pressures at inlet and outlet sections. The authors observed the increase in flow resistance for all four considered combinations of unsteadiness parameters, which they attribute to the additional transverse vortex generated by the pulsations, which disturbed the flow field in the channel.

The non-exhaustive yet representative review demonstrates the lack of comprehensive understanding of pulsating turbulent flow hydrodynamics. The prediction of unsteady flow resistance is often hard to estimate. The available experimental data on such flows does not allow wide generalizations in this sphere. The techniques of experimental estimation of flow resistance under forced unsteadiness developed so far are complex and laborious to use in practice.

2. Experimental setup and procedure

The experimental setup is demonstrated in figure 1. The test section (rib-roughened channel) l was a modular ribbed circular pipe with the inner diameter D=105 mm. The rib diameter was d=94 mm
where: $d/D=0.895$. Semicircular ribs were mounted with a streamwise pitch $t=105$ mm ($t/D=1$). Total length of the channel from its inlet to the rotating flap of the pulsator 2 was $L=6.16$ m. The similar channel without ribs was used for test experiments. The first pressure tap 7 was located ~2 m from the inlet, and the second one was ~2.5 m downstream of the first tap. The specified distances were rounded to the integer number of rib pitches since both pressure taps were mounted similarly relative to the rib.

The airflow pulsations were generated by the pulsator whose cross section was periodically blocked by a rotating flap. Adjustment of the window blockage (windows with or without the flap) provided the required air flow rate and the amplitude of velocity pulsations. A receiver tank 3 with the volume of 1.3 m$^3$ was installed between the channel and the compressor 5. It damped the velocity (pressure) pulsations further downstream. The air flow rate was measured using an ultrasonic flowmeter 4 downstream of the receiver. The amplitude of velocity, $U$, pulsations were estimated from velocity measured by the hot-wire anemometer 6. The measurement data were transmitted via ADC 8 and recorded by PC 9.

![experimental setup](image)

**Figure 1.** Experimental setup: 1 – rib-roughened channel; 2 – pulsator; 3 – receiver; 4 – flow meter; 5 – fan; 6 – hot-wire anemometer; 7 – differential pressure gauge; 8 – ADC; 9 – PC.

Flow resistance measurement in the pulsating flow is not a trivial task. First, the gas column in the pressure tapping line has a wave structure. In this case, pressure at the tapping line endpoints is different from the pressure in the measurement section. To mitigate this effect, pressure tapping line was a long capillary duct which was essentially an oscillation damper. Second, flow pulsations are accompanied by waves that are close to the standing waves. Pressure node and velocity antinode are observed at the channel inlet alternating their location every other $1/4$ wavelength further downstream. Waves lead to redistribution of static and dynamic components of the momentum making the pressure drop no longer representative of the flow resistance. Situations are even possible when the static pressure in the channel with the constant cross-section grows downstream, i.e. the flow resistance factor technically estimated from the static pressure drop can be negative [13, 14]. To eliminate such effects, pressure taps were located under similar phases of flow oscillations (close to the standing wave velocity nodes), which imposed additional restrictions on the location of pressure taps and the set of pulsation frequencies considered in experiments. The pressure tapping locations are schematically illustrated in figure 2, where the sine curve shows an acoustic wave (velocity pulsations) in the airflow. When estimating the wave structure of the flow, the channel with the open inlet and blocked outlet (pulsator) was considered a quarter-wave resonator. Due to relatively small rib height, the effect of rib roughness on the wavelength of velocity (pressure) oscillations was neglected.

The experiments were carried out in the Reynolds number range $Re=UD/\nu=(1.1-4.1)\times10^4$. Forced pulsation frequencies were $f=0-190$ Hz, relative velocity pulsation amplitudes $\beta=A_f/U=0.2-0.7$. The corresponding Strouhal number (dimensionless frequency) varied in the range $Sh=fX_p^u/U=0.01-4$.  

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\[ f = \frac{f}{X_p^u} \]

\[ Sh = \frac{f}{X_p^u/U} \]
Here $U$ is the averaged flow velocity; $X_{R}^{st}$ is the reattachment length downstream of the rib in the steady regime.

### 3. Results and discussion

The increase in the flow resistance coefficient due to flow unsteadiness was estimated from the experimental data. The ratio between the flow resistance in unsteady flow and its empirical value in the same rib-roughened channel with steady flow at the same Reynolds number was considered. This ratio appeared to be almost independent of the Reynolds number. Its variation with the flow unsteadiness parameters is shown in figure 3. Here, the ratio between the flow resistance coefficients $\xi=2\Delta P D/(\ell p U^2)$ was estimated from pressure drop measurements across the channel section (with the length $\ell$) in pulsating and steady regimes respectively $\xi/\xi_{st}=\Delta P/\Delta P_{st}$. The symbols represent experimentally obtained $\xi/\xi_{st}$ grouped in a relatively narrow band of relative pulsation amplitudes. It is mainly due to nonidentical values of $\beta$ that data scattering within a single group is observed. The figure shows that the flow resistance curve has a discernible peak around $Sh=0.6$ with abrupt decrease on both sides away from the peak. The data with relative standard deviation of 7% are described by

$$\frac{\xi}{\xi_{st}}=1+0.31\beta^{1.75}+1.9\beta \exp(-1.5 \left|\ln(Sh/0.6)\right|). \tag{1}$$

The values of $\xi/\xi_{st}$ calculated from (1) at five values of $\beta$ are plotted by lines in figure 3. It should be noted that the submitted approximation yields a “sharp” extremum, while the latter is flattened in experiments, but the deviation lies within the data scattering range.

The increase in the resistance of pulsating flow is partly due to non-linear dependence of the velocity head and pressure drop on the flow velocity due to which the mean velocity head under forced pulsations is higher than that under mean velocity. This gain in flow resistance is accounted for by the term $0.31\beta^{1.75}$ obtained from theoretical analysis of pressure drop in the quasisteady ($Sh$ tending to zero) regime of pulsating turbulent channel flow. But the main part of this gain in flow resistance relative to the steady flow is attributed to rearrangement of the pulsating flow pattern around the ribs. Strong “starting” vortices are formed in the rib wake in a certain range of $Sh$ and $\beta$ [15], which substantially enhance the mass transfer between the separation region and the core flow. This results in almost twofold reduction in the reattachment length and increased rarefaction behind the rib. And it is the rarefaction level that determines the rib’s form drag (pressure integral over the area in projection on the channel axis direction).

![Figure 2. Differential pressure measurement in the channel.](image-url)
Conclusions
The experimental study of flow resistance in the rib-roughened channel under forced gas flow pulsations showed that the forced pulsations promote the increase in flow resistance in the channel. In such a case:
- the increase in velocity pulsation amplitude is accompanied by the flow resistance augmentation;
- in a certain range of pulsation frequency (Sh~0.6) the peaks of flow resistance are observed which agree with intense vortex generation in separation regions downstream of the discrete roughness elements.

Acknowledgments
This study was supported by the Russian Science Foundation (Project no.16-19-10336).

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