The effect of periodic velocity variation on turbulent characteristics of a channel flow behind a rib

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Abstract The kinematic structure of the flow behind a rib is experimentally investigated for the cases of steady-state and pulsating regimes of air flow. The frequency varies in the range of 0 – 30 Hz, and the normalized amplitude of forced velocity pulsations is 0.5. The profiles of velocity and turbulent characteristics are demonstrated at characteristic coordinates of the separation region.

1. Introduction
Separated flows are often encountered in nature and engineering. They were described in detail in the monograph [1]. Flow separation phenomenon in engineering devices is undesirable when it causes increased hydraulic losses. At the same time, it can be initiated deliberately in many cases in order to enhance heat and mass transfer processes.

Turbulent flows with forced periodic pulsations are among the most complex types of flows. Apart from mean velocity and turbulence intensity, they are characterized by the frequency and amplitude of forced pulsations [2]. Unlike the forcing frequency, the amplitude of forced pulsations varies both in the cross section and along the channel length. Furthermore, the amplitude also depends on the forcing frequency [3].

Thus, the research into complex kinematic structure of pulsating flows requires extensive information on the flow parameters and their variation both in space and time. For this reason, experimental methods employ a large number of sensors and measurement tools, which must meet the requirements for high performance speed [4]. This explains the scarcity of experimental studies of this type of flows. For example, [5] used a phase averaging technique in pulsating flows behind a backward-facing step and observed a discontinuity of the recirculation region with subsequent shedding of large-scale vortices in downstream direction. Additionally, it was mentioned that the location of the instantaneous reattachment point depends on the phase of forced pulsations. Jarosinski [6] performed experimental investigation of heat transfer in channels with discrete roughness elements at low frequencies of pulsation (from 0.2 to 5 Hz). Such low-frequency pulsations (Sh<0.03) appeared to have no effect on heat transfer both in smooth and rough channels if compared to steady flows. Saric et al. [7] employed blowing/suction to periodically disturb the inlet flow at Sh=0.3 and observed that the length of the recirculation region behind the backward-facing step reduced by 28.3% compared to the steady flow case. Lee and Shi [8] simulated turbulent flows past an annular rib in a pipe at the Strouhal number of 0.04. They showed that flow deceleration during the pulsation cycle...
results in the growth of the recirculation region, and this effect is progressively more pronounced with the increasing amplitude of forced pulsations. Pozarlik et al. [9] carried out the simulation of turbulent flows behind a backward-facing step under steady and unsteady boundary conditions at the pulsation frequencies of the inlet axial velocity ranging between 10 and 1000 Hz (the corresponding Strouhal numbers were 0.035–3.5). They reported that forced pulsations did not affect the distribution of the average skin friction coefficient and the Stanton number. The only exception was the regime of minimal frequency Sh=0.035, at which the Strouhal number distribution changed significantly. The location of its maximum moved upstream toward the step reflecting the reduction of the separation region.

Clearly, the pulsating flows with flow separation are currently underexplored despite the fact that their engineering relevance is obvious. The majority of studies in this field deal with numerical simulation of pulsating separated flows.

2. Experimental setup and procedure

Visual study was conducted on the experimental setup shown in Fig.1.

![Figure 1. Schematic of experimental setup: 1 – inlet; 2 – rib; 3 – channel; 4 – pulsator.](image)

The test section 3 of experimental setup had a rectangular cross section of 150×115 mm and the length of 1.2 m. The test section walls were transparent to facilitate visual observation and video recording of flow patterns. The rib 2 was placed at the distance of 100 mm from the smooth inlet 1. The air flow rate was generated by a compressor operating in a suction mode and maintained constant by a set of calibrated critical flow nozzles. Flow pulsations following a close to sinusoidal pattern were generated by the rotating flap of the pulsator 4 at the channel outlet. The pulsator was a device that controlled the frequency and amplitude of forced pulsations of flow. Detailed description of the experimental setup is provided in [10]. The flow was seeded with aerosol droplets of glycerin. Video recording of flow was carried out using a monochrome high-speed camera Fastec HiSpec in a light sheet generated by a continuous laser KLM-532/5000.

Smoke visualization images extracted from the videos were processed using SIV technique, which estimates the dynamics of velocity vector fields from frame-by-frame processing of high-speed video records. SIV obtains the vector fields of velocity estimating the displacement of turbulent structures visualized by smoke in the light sheet over a fixed time interval between the frames. The obtained vector fields were employed to build the profiles of turbulent parameters for characteristic coordinates behind the rib.

3. Results and discussion

Fig. 2 shows typical profiles of time-averaged parameters. They were measured in the region most affected by the forced pulsations in the coordinate range x/e=1.05 – 10. The coordinate x/e=1.05 is located immediately behind the rib. All the demonstrated parameters were normalized by the bulk velocity, U0. The dash lines show the steady flow case, while the solid lines demonstrate the pulsating flow with the forcing frequency f=10 Hz (St=0.176). Coordinates were normalized by the rib height, e.
The measured parameters of steady flows agree well with the data on separated flows available in the literature.

Figure 2. a – Streamwise velocity in the separation region; b – Transverse velocity in the separation region; c – Reynolds stresses in the separation region; d – Transverse velocity in the separation region at x/e=1–3.

The considered pulsating flows exhibit some essential features not observed in the steady flows. E.g., the reattachment point is located much closer to the rib: XR≈3e. Besides, $V$ and $V'$ profiles have a sharp spike which is shown in more detail in Fig. 2d. $V$ and $V'$ are close to zero at x/e=1.05 (immediately behind the rib) in the undisturbed flow region (y/e>1.9). Abrupt change of $V$ and $V'$ is also observed at x/e=2, y/e~2.2. Here, the transverse velocity, $V$, is directed opposite to the one in the previous station, suggesting vortical motion between these coordinates. $V$ has spikes and almost reaches the zero level. The same spike is observed in Vp profile at this coordinate. Further downstream, at x/e=3, y/e~2.5, similar but less pronounced variation is documented. The line connecting these regions can be interpreted as some kind of a boundary between two regions of flow. This boundary is shown by a horizontal dash line in the figures. The flow above this line is essentially
undisturbed and free of vortices. Below this line, the rib disturbs the flow, and large-scale vortices are formed and shed from the rib in pulsating regimes.

Conclusions
The paper elaborates on the experimental study into the kinematic structure of steady and pulsating separated flows past a spanwise rib in the channel. The boundary separating the vortex-free region from the region featuring large-scale vortices is discovered.

It is noteworthy that the term “vortex-free region” is rather artificial, since vortices can exist here at some point in space and time. However, their strength (particularly its time-averaged value) is significantly lower than in the neighboring region.

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References
[1] Chang P K 1970 Separation of Flow (London: Pergamon) 777 p
[2] Yul A J 1983 Turbulent shear flows 2 275–98
[3] Valueva Ye P 2006 Herald of MPEI 5 121–30
[4] M Nabavi, K Siddiqui. 2010 Measurement Sci. Technol. 21(4)
[5] Mullin T, Greated C, Grant I 1980 Physics of Fluids 23 669
[6] Jarosinski W 2003 Journal of KONES Internal Combustion Engines 10(3) 1
[7] Saric S, Jakirlic S 2005 Tropea C Journal of Fluids Engineering 127(5) 879–87
[8] Lee T S, Shi Z D 1999 Int. J. Numer. Meth. Fluids 30 813–30
[9] Pozarlik A K, Panara D, Kok J B, van der Meer T H 2008 Proceedings 5th European Thermal-Sciences Conference
[10] A N Mikheev, V M Molochnikov, N I Mikheev, A E Golsman 2019 Conference Series Earth and Environmental Science 288(1) 012107