Experimental setup for generation and control of sinusoidal pulsatile channel flow

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Abstract. A scheme of an experimental setup for generation and control of sinusoidal pulsatile channel flow has been presented. A pulsator with the shaped rotating flap ensured a cross section area variation by harmonic law is used. Based on the solution of Bernoulli's unsteady equation and the numerical solution of the URANS equations, the effect of inertia forces on the law of average velocity variation over the pulsation phase in the test section of the experimental setup has been estimated.

1. Introduction

According to [1] the term "pulsating flow" is applied to flows, which velocity or pressure law can be written as a sum steady and due to superimposed pulsations of the periodic component. Such types of flow occur in various technical systems and engineering applications [2-4]. The appearance of pulsations and other dynamic changes in liquid flow parameters is usually facilitated by positive-displacement pumps and compressors, the resonant vibrations of pipes and flow-control valves, the flow separations behind obstacles in conduits and certain multiphase flow regimes that are present in industrial flows (energy, chemical, automotive, pharmaceutical, food industry) [5].

Understanding the effects of flow pulsations on the measurement uncertainty of flowmeters and other metering devices is very important [6]. Many years of industrial service showed the sensitivity of measurements by most types of flowmeters to the frequency and amplitude [7] superimposed on the flow of periodic unsteadiness. The resulting uncertainty of measurements leads to significant difficulties in the design and further maintenance of technical systems. The reconstruction of a wide range of pulsating regimes within the framework of a laboratory study makes it possible to estimate the uncertainty of measurements under various operating conditions for metering devices. The results of these studies also allow choosing optimal schemes for the location of meters in real systems and optimizing the principle of their operation, in order to reduce the sensitivity to negative influences of the periodic unsteadiness imposed on the flow [8]. Heat transfer in separated regions behind obstacle in the channel [9] and in transverse flow past the bodies is very sensitive to forced pulsations of the flow [10]. However, the reproduction of sinusoidal pulsatile flow during experimental research is a separate scientific-technical problem [11-14].

The pulsator is the main element of the experimental setup, which determines the frequency-harmonic characteristics of the periodic unsteadiness imposed on the flow. The pulsator design should allow the widest range of pulsatile flow regimes to be realized, which is described by three dynamic similarity numbers: \( \text{Re} = VD/\nu \) is the Reynolds number, \( \beta \) is the relative amplitude of the pulsations, St
\[ fL/V \] is the Strouhal number; for the boundary layer, \( \omega^+ = 2\pi f u_2 / v \) is sometimes used instead of \( St \), \( \omega^+ \) is the dimensionless pulsation frequency (\( V \) is the average velocity, \( D \) is the hydraulic diameter, \( v \) is the kinematic viscosity, \( f \) is the frequency of superimposed unsteadiness, \( L \) is the characteristic dimension, and \( u_2 \) is the dynamic velocity). In carrying out experimental studies, two fundamentally different designs of pulsators are usually used: with a piston or membrane mechanism [8, 13-22], figure 1, and with a rotating flap (ball [23] or butterfly type [9, 10, 24, 25]), figures 2-3.

The principle of the pulsator with a piston or membrane mechanism is to create a local zone with a pressure cycling by the harmonic law. A large gradient of velocity characteristic of this region by means of inertial forces and acoustic disturbances can have a significant effect on the law of variation of flow in the test channel and characteristics of turbulence. Therefore, it is difficult to realize the sinusoidal pulsatile flow with a high relative amplitude and frequency of variation of the average velocity using such pulsator.

The pulsator with a rotating flap provides a pulsatile flow due to the cross section area variation. The main problem of this approach is that the use of standard flap valves in the pulsator designed to regulate the flow rate of steady flow does not provide the cross section area variation by harmonic law. As a result, even with small values of the frequency-harmonic characteristics of the flow, the average flow velocity law deviates significantly from the sinusoidal flow, figure 4. Rotation of the butterfly type flap, as a rule, leads to the emergence of a separated flow with the generation of large-scale eddies of the order of the flap diameter, which creates unfavorable hydrodynamic and acoustic disturbances in the flow and exerts an additional negative influence on the flow law.

In this paper, an experimental setup consisting of a pulsator with a profiled rotating flap and providing the cross section area variation by harmonic law to create and control sinusoidal pulsatile liquid flow in a channel has been considered. The use of the profiled flap also helps to suppress processes that facilitate the separation of the boundary layer from the flap surface. In the authors' opinion, such a pulsator will make it possible to realize pulsatile flow in a wide range of dynamic conditions.
similarity numbers with a slight deviation (due to inertia forces) of the law of average velocity variation from the harmonic law. To estimate the effect of inertial forces on the law of average velocity variation, the Bernoulli’s equation in the unsteady formulation and the method of numerical modeling of the unsteady Reynolds averaged Navier-Stokes equations (URANS) have been used.

2. Experimental setup

The scheme of the experimental setup for generation of pulsatile liquid flow in a vertical channel is shown in figure 5. The flow in the test section 4 is carried out under the action of gravity on a column of liquid of constant height. The level of the liquid in the supply tank 1 is maintained by the constant mass flow to the tank 1 and the system for overflow liquid into the collector 3 through the bypass channels 2. The generation and control of the pulsatile flow regime is carried out using a pulsator 5 installed at the inlet from the test section 4. Such setup can run on the air, if the collector 3 maintains a constant negative pressure relative to the channel inlet. In this case, bypass channels 2 are not needed.

The pulsator with a four-blade profiled flap is presented in figure 6 in detail. The pulsator allows to independently regulate the cross-section area of two supply units 1 and 2 by moving and fixing the flaps 4 and 5 in the direction of their longitudinal axes. The cross-section area of the supply unit 1 varies by the harmonic law due to the rotation of the profiled flap 3. The flap 3 is driven by an alternating-current motor. The motor power is conducted through a frequency converter, which provides the possibility to control the frequency of rotation of the drive output shaft. A significant difference of this pulsator from the works of other authors [23-25], who used a pulsator with a rotating flap, is a profiled shape of the flap, which ensures ensured a cross section area variation by strictly harmonic law.

![Figure 5. Experimental setup](image1)

![Figure 6. Pulsator with four-blade flap](image2)
In the general case, the contour of a flap with an arbitrary number of blades is proposed to be described by the geometrical locus in the polar coordinate system by the relation

\[ r = R - b [1 - \cos(n\alpha)], \quad 0 \leq \alpha \leq 2\pi, \]

where \( r \) and \( \alpha \) - respectively, the module and the argument of the polar function, \( R \) is the radius of the circle circumscribed around the flap, \( b \) is the amplitude of the harmonic crossflow area variation of the flow unit, \( n \) is the number of flap blades, figure 6.

3. Numerical simulation of the experimental setup service and analytical estimation of the average velocity law in the test section

Numerical simulation of the experimental setup service for generation harmonic oscillations of the liquid column was carried out in a two-dimensional formulation in the ANSYS Fluent commercial package using the Euler-Euler Volume Of Fluid (VOF) model [26] based on the solution of unsteady Reynolds-averaged Navier-Stokes equations with the closure of the anisotropic Reynolds stresses turbulence model (RSM).

The calculation zone corresponded to the experimental setup shown in figure 5. However, the bypass channels 2 were excluded from the design model, which functionality was replaced by the boundary condition of the fixed position of the interface in tank 1, on which the total pressure equal to atmospheric and the specific mass of the liquid phase equal to 1. On the side walls of the collector 3, a static pressure equal to atmospheric pressure and a specific mass transfer of the liquid phase equal to 0 (in the case of reverse flow on the boundary). On the solid boundaries of the computational zone, zero values of the flow velocity vector components were set. The motion of the working fluid was provided by a pressure drop caused by the action of gravity on the liquid column. The process of the pulsator flap rotation is realized by means of the use of a dynamic grid with an integral type of adaptation of the grid.

The instantaneous average velocity \( V(t) \) in the test section 4 (figure 5) of the experimental setup taking into account the area \( S^*(t) \) varied by the harmonic law can be estimated as

\[ V(t)S = \mu S^*(t) \sqrt{\frac{2(P^*(t) - P_{out})}{\rho}}, \]

where \( S \) is the cross-sectional area of the test section 4 (figure 5), \( \mu \) is the mass flow rate for the liquid outflow from the hole, \( \rho \) is the density of the liquid, \( P_{out} \) is the pressure behind the pulsator, \( P^* \) is the pressure in front of the pulsator. In view of the fact that the liquid column in front of the pulsator moves with variable acceleration, the numerator of the radicand on the right-hand side of (2) is represented as

\[ P^*(t) - P_{out} = \rho h \left( g - \frac{dV}{dt} \right), \]

where \( h \) is the height of the liquid column in front of the pulsator, \( g \) is the acceleration due to gravity.

4. Results and discussion

For testing, two regimes of pulsatile flow in the channel were taken \( \{ f = 2 \text{ Hz}, \text{Re} = 80000, \omega^* = 0.1, \beta = 0.66 \} \) and \( \{ f = 16 \text{ Hz}, \text{Re} = 80000, \omega^* = 1.02, \beta = 0.66 \} \), which according to [27] belong to the class of fast-oscillating ones. It should be noted that the value of the dimensionless frequency \( \omega^* \) varied from 0.01 to 0.2 in the experimental studies of pulsatile flow [28-32]. Investigation of regimes with a relatively high \( \omega^* \) was necessary to clearly visualize the influence of inertia forces on the law of average velocity variation in the channel and to assess the efficiency of the experimental setup when
reproducing complex from the point of view of the realization of fast-oscillating pulsatile flow with a sinusoidal flow rate at the phase angle.

For both of the considered flow regimes, the estimates of the average velocity variation over the superimposed unsteadiness phase, obtained from (2) and the results of the URANS solution, agree well with each other, figure 7. The results of the estimates for the first regime, which in \( \omega^+ \) corresponds to the limit values of the experimentally investigated regimes in \([28-32]\), show a high degree of reproducibility of sinusoidal fast-oscillating pulsatile flow by an experimental setup. Obviously, with a decrease in \( \omega^+ \) the difference from the sinusoidal distribution of the average velocity law at the pulsation phase will only decrease, and with increasing \( \omega^- \) (mode 2) it will be increased. Such analysis in carrying out experimental studies of pulsatile flow is not usually performed, but as can be seen from figure 7, the true nature of periodic unsteadiness can differ substantially for various regimes of pulsatile flow. In particular, when the periodic unsteadiness is separated from the measured oscillograms, the deviation of the flow pulsations from strictly harmonic law can lead to an increase in the uncertainty of estimates of the turbulent flow characteristics.

![Figure 7. Centerline velocity at the pulsation phase](image)

5. Conclusions
The experimental setup proposed for generation and control of sinusoidal pulsatile fluid flow with a profiled shape of the pulsator flap according to the Bernoulli equation and the results of the numerical solution of URANS allows to realize pulsatile flow with a slight deviation of the average velocity law from a strictly harmonic distribution in the standard for experimental studies range of \( \omega^+ \). The experimental setup makes it possible to realize all known regimes of pulsatile flow in the channel from quasi-steady to fast-oscillating one.

A good agreement of the estimate results based on the solution of the Bernoulli equation with the results of the numerical solution of URANS allows to use only the first approach in the future, which predicts the effect of inertia forces on the law of average velocity variation at pulsatile flow regime more quickly and easily.

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