# BRIEF OVERVIEW OF PUBLICATIONS CONSIDERING QUESTIONS OF CLASSIFICATION OF UNSTEADY TURBULENT FLOWS

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Abstract: This article provides a brief overview of the results of studies of turbulent flows. The classification methods for unsteady turbulent flows developed by domestic and foreign scientists are considered, taking into account the complexity and variety of factors affecting the unsteadiness on the kinematic flow structure. It is shown that there are no reliable methods for predicting both the conditions for the occurrence of unsteady flow regimes and estimating the parameters of an unsteady flow at present. These circumstances lead to the need for a detailed study of the spatio-temporal structure of the turbulent flow under unsteady conditions. The most complete classifications are given by Ramporyan and Tu, Grigoryev and Fafurin. They distinguish five groups of unsteady flows in their works. The classification is based on the turbulence "transmission" mechanism, and the boundaries between groups are defined in the space with respect to the frequency and amplitude of superimposed pulsations.

Key words: unsteadiness, flow structure, turbulent Stokes number, "quasi-stationary" flows, velocity profile.

### 1 Introduction

Turbulent flow is the main frm of continuum. The liquid and gas flows, as a rule, have a periodic nature and are complicated by the significant dependence of the profiles of hydrodynamic parameters on the frequency and amplitude of superimposed pulsations in practice. Such flows are called unsteady. Unsteadiness is understood as the time change of a particular flow characteristic

Unsteadiness is quite often manifested during the operation of modern technical products used in aircraft and rocket engineering, energy, shipbuilding and other areas, can also occur in transient operation modes of the products, having a significant impact on the equipment performance. Thus, the studies of unsteady thermal and hydrodynamic processes become relevant when developing new products.

To date, the most studied is the kinematic structure of unsteady turbulent boundary layers. The experimental studies of domestic and foreign scientists - Bukreev and Shakhin, Grigoriev, Fafurin, Dreitzer, Kraev, Mikheev, Ramaprian, Tu, Parikh P.G., Reynolds, Jaraman, Karlsson, Mizushina et al. - are known in this area.

The results obtained by researchers do not give a complete picture of the influence of unsteady factors on hydrodynamic and other flow parameters and do not allow, today, formulating a clear idea of the physical mechanisms of influence on the equipment performance. Many of the effects identified in experiments have not received a reliable physical explanation. It should be admitted that there is a problem of the classification of unsteady flows, which would take into account the complexity and variety of effects of the unsteadiness impact on the kinematic flow structure.

### 2 Methods

To process the results of experiments, the researchers used dimensionless numbers - similarity criteria. In fluid and gas mechanics, the similarity criterion is defined as a dimensionless quantity made up of dimensional physical parameters representing the studied physical phenomenon.

The Strouhal number was used as the dimensionless frequency in most works. The Strouhal number is a dimensionless quantity, one of the similarity criteria for unsteady flows of liquids and gases, characterizing the process constancy in time:

$$Sh = fL/U,$$

where $f$ – vortex frequency
$L$ – inherent length
$U$ – flow velocity.

To estimate the velocity of turbulent flows, the authors used the "turbulent Stokes number", which determines the relationship between the kinetic energy of suspended particles and the energy of their interaction with the flow

$$S = {}^{D}/_{2}\sqrt{{}^{\omega}/_{2\nu_{T}}},$$

where ω – cyclic frequency,
$\nu_T$ – turbulent viscosity,
$D$ – pipe diameter.
The next parameter is dimensionless frequency -
$\omega' = R^3\omega/\nu$ $\omega' = R^3\omega/\nu$,
where $\omega = 2\pi f$ – circular frequency,
ν – kinematic viscosity.

### 3 Results And Discussion

Given the complexity and diversity of the unsteadiness impact on the kinematic flow structure, a number of attempts have been made to classify the unsteady flows.

In their work, the authors attempted to generalize theoretical and experimental methods for studying the unsteady flows (Galitsky et al, 1977). The authors used the parameter fluctuations as the basis for classifying the hydrodynamic vibrations:

- pressure;
- density;
- speed;
- body.

The distribution of the flow parameters along the channel length significantly depends on the ratio of the channel length and the oscillation wave.

The disadvantage of the proposed classification is that all these parameters are interconnected and, therefore, the oscillations of one parameter will lead to the oscillations of others. Nevertheless, the classification proposed by the authors can be used in the study of boundary conditions or oscillation source(Galitsky et al, 1977).

In his work, Carr L.W. proposed to classify turbulent flows by the nature and degree of manifestation of dynamic effects (Carr, 1981). The relative amplitude of velocity pulsations β = AU/U and the frequency ratio of superimposed pulsations to the inherent "frequency of explosions" were selected as parameters describing the manifestation degree of unsteady impact.

Three flow patterns were identified:

1) the unsteadiness impact is absent;
2) the influence is limited near the wall;
3) the influence spreads over the entire cross section of the channel.

The boundaries between the groups were determined by frequency $Sh_\delta$ (dimensionless Strouhal number) and the amplitude of superimposed pulsations $\beta$.

In this case, the area of parameters that determine the flows of the first and second modes is set fairly accurately, but a clear boundary is not established between the second and third modes of pulsating turbulent flows.

The main disadvantage of this classification method is that this approach does not fully disclose the physical nature of the impact of superimposed pulsations on the flow microstructure.

In their work, Ramaprian B.R. and Tu S.W, when calculating the unsteady turbulent flows in a pipe, took the dependence of turbulence penetration distance on the turbulent viscosity $\nu_T$ and its transmission time *t* as the basis (Ramaprian & Tu, 1983).

To estimate the transmission velocity of turbulent flows, the authors used the "turbulent Stokes number" - *S*.

According to the turbulence "transmission" principle , the authors identified five flow regimes:

1. “Quasi-stationary” flows - hydrodynamic unsteadiness does not affect the kinematic flow structure. This group is dominated by quasi-stationary laws - the unsteady flow of a liquid or gas at small Strouhal numbers Sh = D/(Vt) << 1).
2. Low-frequency "flows - the unsteadiness impact on the component profiles of the flow velocity averaged over the implementation phases manifests itself over the entire channel cross section. But at the same time, the unsteadiness impact does not extend to the profiles of the phase-averaged mean-square value of velocity pulsations and to the profiles of the time-averaged flow velocity. The boundary between the flow regimes is specified by the condition (Mizushina & Maruyama, 1975):

$$\frac{\omega D}{U_*} = 0.1,$$

where $U_*$ – average over the period of superimposed pulsations, dynamic speed.

3. "Mid-frequency" flows - with a pronounced interaction of turbulence with superimposed pulsations. In addition, the mean-square velocity profiles are distorted near the wall; as a result, the turbulent structure of such flows will noticeably differ from quasi-stationary one with the entire pipe section. The time-average flow will still remain quasi-stationary.

The lower boundary is described by a curve

$$\frac{\omega_{\text{ВН}}\, D}{U_*} = 166 Re_m^{0,54},$$

and upper -

$$\frac{\omega_{\text{В}} D}{U_*} = 1,58 Re_m^{1/8}.$$

4. “High-frequency” flows are characterized by a strong interaction of turbulence with superimposed flow pulsations. The unsteadiness impact is limited by the layer y/R ≤ 0.1. Outside this layer, the flow oscillates like a solid body, or in other words, the turbulence will be “frozen”. Unsteadiness is expressed by deformation on the profiles of the time-average flow velocity at which an inflection point may occur.

The upper limit of this mode is defined by a curve

$$\frac{\omega_{BB} D}{U_*} 31 Re_m^{0,215} \left[10^{-(3,32-0,667 Re_m)}\right],$$

where $\omega_{\text{ВВ}}$ – upper boundary for the emergence of turbulent “bursts”.

5. "Fast-oscillating" flow regimes. The boundary is determined from the condition $\omega > \omega_{\text{ВВ}}$. The flows of this regime are characterized by a rather strong interaction of the turbulent structure with superimposed pulsations, however, all the influence is concentrated in the layer y/R ≤ 0.01. The transverse size of the region of “frozen” turbulence is much larger than in the fourth group. This flow regime has been little studied.

The advantage of classification proposed by the authors is represented by its systematic nature, because it takes into account the complex mechanisms of the emergence and propagation of turbulence (Mizushina & Maruyama, 1975).

The main drawback of the classification considered is that it did not take into account the impact of amplitude of superimposed pulsations on the averaged and pulsating features of turbulence.

In their work, M.M. Grigoriev, V.V. Kuzmin and A.V. Fafurin proposed a classification option for turbulent pulsating flows depending on the impact mechanism of superimposed pulsations on the flow microstructure (Figure 1). The authors used the dimensionless frequency Sh as the Strouhal number and the relative amplitude of flow rate fluctuations β = AU/U as classifying complexes (Grigoriev et al, 1990).

The authors established 5 flow patterns:

1. "Quasi-stationary" flows. Unsteady flows are represented as successive stationary turbulent flows. In this case, the influence of the flow history is completely excluded. Changes in the values of the flow parameters occur without a phase shift. When calculating the actual values of the features concerning the parameters of such flows, stationary calculation methods can be used.
2. "Low-frequency" flows. Unsteadiness makes impact on the turbulent kinetic energy, the parameters of which are obtained by averaging over implementation ensembles. The impact is reduced to the appearance of a phase delay in the fluctuations in the intensities of turbulent pulsations, which leads to a deviation of the profiles of ensemble-averaged turbulent energy values from quasi-stationary analogues. At the same time, the profiles of ensemble-averaged velocities remain quasi-stationary. For this flow regime, quasi-stationary turbulence models can be used, but it is necessary to solve unsteady transport equations.
3. "Mid-frequency" flows. Unsteadiness makes impact on the profiles of turbulent kinetic energy and the profiles of ensemble average flow velocities over the entire channel radius or the boundary layer. Moreover, with increasing parameters $f \cdot D/U_*$ or vibration amplitude β, the unsteadiness impact increases. With the use of quasi-stationary turbulence models, some discrepancies with experimental data are possible, moreover, the discrepancy increases with increasing *Sh* or *β*.

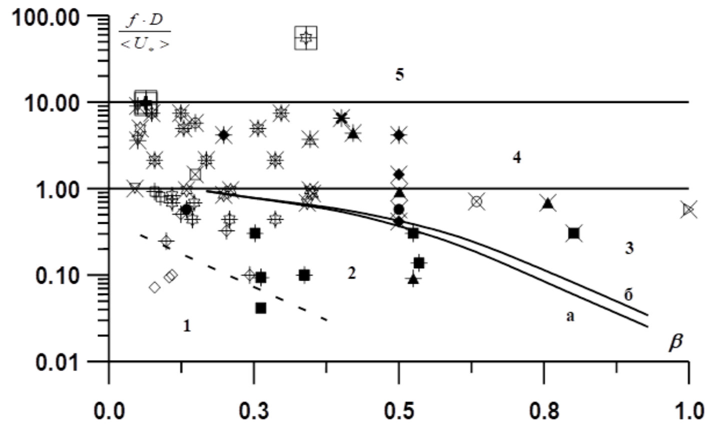


Figure 1. Classification of unsteady turbulent flows (Grigoriev et al, 1990).

Flow in the pipe: ○ – (Tu & Ramaprian, 1983), Δ - (Ramaprian & Tu, 1983), □ – (Hartner, 1984), ▲ - (Mizushina & Maruyama, 1975), ◊ - (Shemer et al, 1985). ♦ -, ■ - (Iguchi et al, 1985), ● – (Grigoriev, 1987).

4. "High-frequency" flows. A significant unsteadiness impact on the structure of a turbulent flow is recorded. An inflection point appears in the profiles of the time-averaged flow velocity. The high-frequency flow regime is limited by the region of dimensionless parameters $1 \leq (f \cdot D/U_*) \leq 10$. The unsteadiness impact is concentrated in the layer $0 \leq y/R \leq (U_*/f \cdot D)$. Beyond the boundaries of this layer, the effect of "frozen" turbulence is observed, and the oscillations of the velocities averaged over the ensemble occur according to the solid body laws. In the layer where the influence of unsteadiness is concentrated, quasi-stationary calculation methods diverge from the experimental data, and the same calculation methods are in good agreement with the experimental data in the frozen turbulence area.
5. "Fast-oscillating" flows. The regime scope is limited to $10 \leq (f \cdot D/U_*) \leq 100$. The unsteadiness impact is concentrated in the region $0<y/R<0.1$. Researchers studying unsteady turbulent flows discovered the "memory" effect, which consisted in the fact that the turbulent flow "remembered" its previous state. It is noticed that the flow continued to behave as slowed down for some time in the acceleration phase after changing the derivative velocity sign on the channel axis with respect to time, and as accelerated - in the slowing phase.

In this article, the problem of determining the boundary between quasi-stationary and low-frequency flow regimes was discovered due to the lack of specific estimates of their separation (Grigoriev et al, 1990). In this case, the boundaries are limited to a conditionally drawn line (Figure 1).

The boundary between the "low-frequency" and "mid-frequency" regimes is set by a conditionally drawn line and is determined from relation

$$\frac{fD}{U_*} = \frac{(1+\beta Cos(\omega\tau)_{max})^2 (\varsigma/8)^{3/2}}{0{,}005\pi\beta Sin(\omega\tau)_{max}\sqrt{\varsigma/8}},$$

where

$$(\omega\tau)_{max} = arccos\left(\frac{1-\sqrt{1+8\beta^2}}{2\beta}\right),$$

where ξ – hydraulic resistance coefficient.

The advantage of the classification option proposed by the authors is the ability to more accurately determine the boundaries of the regimes of unsteady turbulent flows by the degree of influence of the frequency and amplitude of superimposed velocity pulsations on the kinematic flow structure (Grigoriev et al, 1990).

The main disadvantage of this classification is its locality, associated with a change in the amplitude of the velocity fluctuations along the channel length; classification can be carried out only in a limited way - for a certain section. And as a result, different fragments of the same stream can appear in different classification modes for a given current.

## 4 Summary

When analyzing the literature on unsteady turbulent flows, it is noteworthy that simultaneous measurements of only one parameter and only in one section of the channel were performed in the considered experimental works. It was established in (Feoktistova, 2005; Rzaeva et al, 2018) that the intensity of pulsations of the flow parameters is determined not only by the frequency and amplitude of the superimposed flow pulsations, but also (at resonant frequencies) by the position of the corresponding section relative to the velocity (pressure) node (antinode). Thus, the spatio-temporal structure of the flow is not taken into account. The researchers implicitly accepted the assumption that, like the stationary case, the flow parameters remain unchanged in all sections at the same time. However, this assumption at least requires experimental confirmation.

## 5 Conclusions

Based on the foregoing, it can be argued that today the problem of classification of unsteady flows is not completely solved and needs to identify the characteristic features of such flows, to develop the reasoned criteria for unsteadiness.

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