FUNCTIONAL PROPERTIES OF THE TURBULENT BOUNDARY LAYER

Arkady Zariankin[1], Tannous Chalhoub[2]
[1]Steam and Gas Turbines Department, Turbo machine laboratory, Moscow Power Institute,
Honored Scientist of Russian Federation
ZariankinAY@mpei.ru
[2]Mechanical Department, Faculty of Engineering - branch 1, Lebanese University
tanchal@ul.edu.lb

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ABSTRACT

A new approach is made to estimate the role of the turbulent boundary layer. On the basis of the results of experiments carried out in the laboratories of the Moscow Power Institute (MEI), complemented by a theoretical analysis, the turbulent boundary layer is regarded as a positive factor protecting the streamed surfaces from external perturbations, and also protecting the external flow from the possible perturbations generated by the vibrating wall. In this way, in the case of non-separated flow, the construction elements of installation passages have a high reliability due to the protective property of the turbulent boundary layer.

Key words: turbulent boundary layer, turbulence, fluctuation, flow separation, vibrating wall, streamed surface, perturbation, boundary layer thickness, viscosity

INTRODUCTION

The theoretical and experimental studies of the boundary layer theory form a particular section of fluid mechanics. They constitute a basis to solve practical problems, related to getting a real physical picture of the fluid flow in different canals in the field of internal fluid mechanics. Much attention is given to the structural investigations of the turbulent boundary layer. Namely, the turbulent layer is developed on the streamlined surfaces of the mostly industrial machines and equipment, and it is extremely inhomogeneous in its structure.

At present, available studies use a two-layer or a three-layered model. In the first case and for smooth streamline a very fine laminar sublayer is formed near the streamlined surface, which will then be close to the turbulent layer. (Zariankin *et al*., 1989)

In the three-layered model some intermediate field is taken between the laminar sublayer and the developed turbulent structure. Despite all its logicality, the three-layered model runs into contradiction with the data on the distribution of the turbulence number across the turbulent layer. For more clarity, the variation of the velocity fluctuation along the normal to the streamlined surface according to the Klebanoff's measurements is shown in Fig. 1. (Klebanoff, 1955).

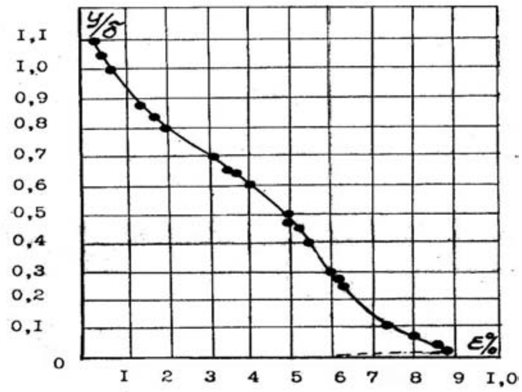

Figure 1. The turbulence number's variation across the boundary layer.

Here, the turbulence number $\varepsilon = \frac{\sqrt{\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)/3}}{\overline{u}}$.

It is obvious that the longitudinal fluctuations attain the greatest values directly on the wall along the border of the laminar undercoat, and then they are damped intensively in the direction of the external border of the boundary layer. In other words, just the wall zone, where a maximal transverse velocity gradient exists, is a great generator of turbulence, and then the dissipative processes essentially surmount the generative one, and the intensity of turbulent fluctuation decreases. In the absence of external turbulence the fluctuations completely degenerate. The generation zone of fluctuations turns out to be sufficiently narrow. In the case of a non gradient flow, this zone does not exceed 10% of the physical thickness of the boundary layer, and the maximal turbulence number attains 7-10%.

Particular attention must be given to this circumstance. In fact, if we examine the numerical values of the flow turbulence number after an artificial static turbulence promoter, we could note that at a short distance from the turbulence promoter rarely we can get a turbulence number more than 5-7%.

Therefore, the turbulent boundary layer is by itself the most powerful, and continuous generator of turbulence.

MATERIALS AND METHODS

To explain the mechanism of this generation, let us examine an elementary volume of fluid in the form of a parallelepiped with a base area $dx.dz$ and a rib height Δ, disposed within the transversal section of the boundary layer (Fig.2). During its motion, the fluid element, unlike a solid, is submitted not only to rotation, but also to deformation. As a result, the center of gravity (point **a** in Fig. 2) is displaced with respect to the centre of rotation (point **b**), and a centrifugal force acts on the particle, whose magnitude is:

$$R_c = \rho.dx.dz.\Delta.\omega^2.e \tag{1}$$

Where:
ω - The angular velocity.
ρ - The density.
e - The eccentricity between the centre of gravity and the centre of rotation.

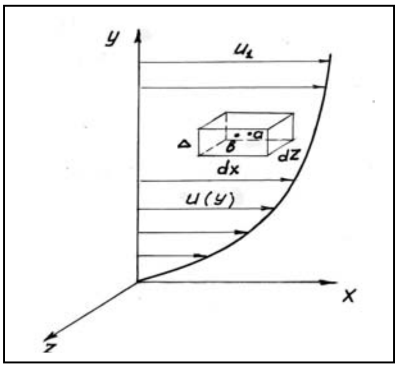

Figure 2.

Dividing the force R_c by the area $d\sigma = dx.dz$ we have the stress τ :

$$\tau = \frac{R_c}{dx.dz} = \Delta.e.\omega^2.\rho \tag{2}$$

The angular velocity ω within the boundary layer may be expressed in terms of the linear velocity $u(y)$ by the known relation: $|\omega| = \frac{1}{2}\frac{\partial u}{\partial y}$.

The eccentricity is also proportional to the transverse gradient of velocity, and taking into consideration the dimension theory, it may be expressed as follows:

$$e = const.\frac{\delta^2}{u_1}.\frac{du}{dy},$$

where:

δ - The physical thickness of the boundary layer.

u_1 - The velocity on the outer border of the layer.

The transverse dimension Δ of the considered particle may be expressed in terms of the layer thickness δ as $\Delta = const.\delta$, and as a result we get from (2):

$$\tau = const.\rho.\frac{\delta^3}{u_1}.\left(\frac{\partial u}{\partial y}\right)^3 \tag{3}$$

In addition to the stress caused by the centrifugal forces on the particle, other stress, caused by the viscosity τ_l acts also on it:

$$\tau_l = \mu \frac{du}{dy} \tag{4}$$

It is obvious that as long as $\tau \leq \tau_l$ the particle of fluid will remain on its stream line, and accordingly there is no fluctuation in the flow. Hence, the loss limit of the flow stability is defined from the following equality:

$$\tau = \tau_l \text{, or,}$$

$$const.\rho.\frac{\delta^3}{u_1}.\left(\frac{\partial u}{\partial y}\right)^3 = \rho.\nu.\frac{du}{dy} \text{ ,}$$

hence:

$$\frac{\nu}{u_1 \delta} = const.\left(\frac{d\overline{u}}{d\overline{y}}\right)^2 \tag{5}$$

and the critical value of the Re number is inversely proportional to the square of the velocity's transverse gradient,

$$\mathrm{Re}_{cr} = const / \left(\frac{d\overline{u}}{d\overline{y}}\right)^2 ,$$

here:

$$\overline{u} = \frac{u}{u_1} \text{ and } \overline{y} = \frac{y}{\delta} \cdot$$

Hence, just the flow peculiarities nearby the wall, where a maximal velocity's transverse gradient exists, determine, on the one hand, the transition from laminar flow to the turbulent one, and on the other hand, they explain the generation mechanism of the velocity fluctuation components. In fact, the initial separation of the particle from its stream line leads to the development of the velocity's transverse gradient, and this causes the disturbance of the equality (5) and the avalanche rise of $d\overline{u} / d\overline{y}$ in the field nearby the wall. The breaking action of the viscosity forces becomes immaterial, and the increasing velocity's transverse gradient leads to the full "unbalance" of the flow.

That is, if the laminar flow may be examined as a balanced one, then, the turbulent flow is a typical example of an "unbalanced" flow with a comparatively narrow zone, generating a high turbulence. Until now, the role of this zone remains practically not studied in the literature, despite the fact, that this zone determines and explains a series of well known experimental data.

This picture is fully expected if taking into consideration the above examined structure of the boundary layer. *The generation zone of the turbulence is a reliable shield, protecting the field nearby the wall from the external influences*. In other words, as long as the level of external turbulence remains less than the turbulence, generated by the boundary layer itself, the flow conditions directly at the wall remain invariable. These conditions start to change only when external perturbations become comparable with the fluctuations in the layer nearby the wall. In practice this situation is rarely realized, since any artificially created turbulence very quickly damps, and its level usually does not exceed (4-5) % at a little distance from the source of turbulence. Therefore, the generation zone of turbulence screens the wall from the external perturbations and reduces the level of dynamic loads.

According to Fig. 1 a sharp increase of the fluctuations is noticed near the wall, where the zone of the intenseist turbulence generation exists. Similar results had been obtained in other works (Baranovsky and Zariankin, 1991; Deitch and Zariankin, 1984). These results allow us to distinguish conditionally two zones in the transverse section of the turbulent boundary layer. The first zone is the zone of an intense turbulence generation, situated near the streamed wall, and occupied up to 30% of the boundary layer thickness, and the second – the external zone, where dissipation processes prevail.

Measurements of the local coefficient of resistance C_f show that if the external turbulence number ε_0 does not exceed 6-8%, this coefficient remains practically invariable on the plate, and only for ε_0>8% it begins to increase (Fig. 3) (Deitch and Zariankin, 1974). However, the generated turbulence number near the wall varies between 6 to 10% (Gribin, 1984). Consequently, if the

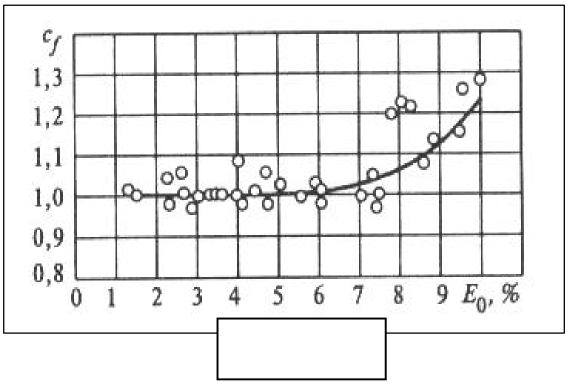

Figure 3.

external turbulence number ε_0 does not exceed this level, then no change may occur in the field below the turbulence generation zone.

The protective properties of the boundary layer must appear not only in hampering the external perturbations, but also in protecting the external flow from the perturbations coming out from the wall (Zariankin and Simonov, 2002).

To prove this statement, let us examine the results obtained from the investigation of the boundary layer structure in vibrating walls.

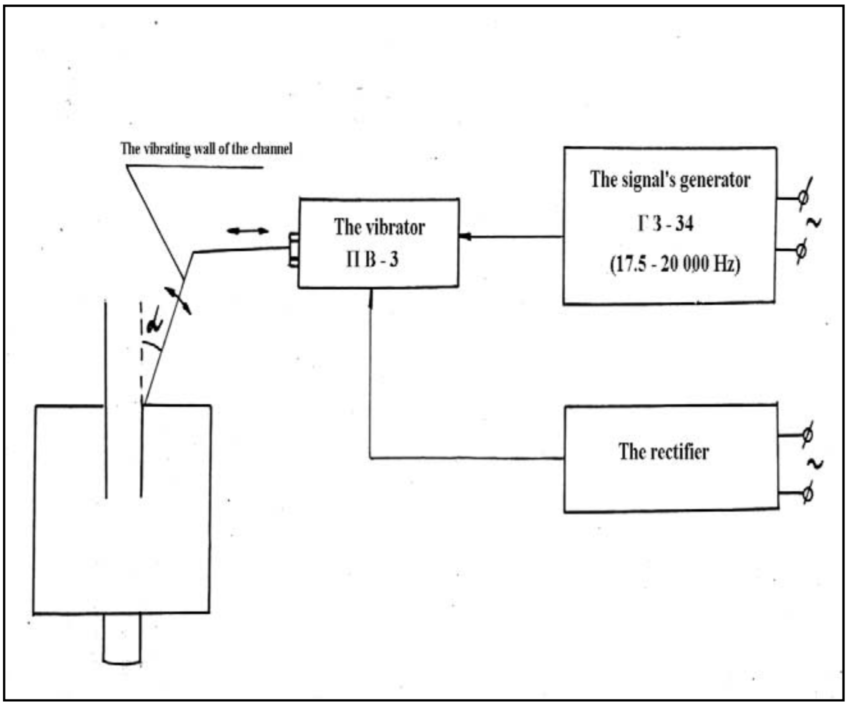

Figure 4. Experimental setup.

The experiments were carried out in an open-type wind tunnel for the subsonic range of velocities ($\lambda = 0.2 \div 0.4$) (λ - the dimensionless velocity, $\lambda = c / c_{cr.}$), which corresponds to the flow in the inlet and the valve diffuser's passages of turbo machines. The air is used as the working fluid. The model was a plane diffuser of relative length $l / b_1 = 3.71$. The degree of divergence varies in the range of $n = 1 \div 2.4$ and $\alpha = 0^o \div 22^o$. This range of geometrical characteristics variations makes it possible to carry out the experiments in the non separated flow, as well as in the separated flow. The error estimation of the dimensionless velocity λ in the boundary layer shows that the maximum value of relative error $\Delta\lambda$ near the wall does not exceed 4%.

To investigate the influence of the wall vibration on the boundary layer characteristics, one of the walls is coupled to a vibrator (П В – 3), which connects it to a sound generator (Г 3 -34) capable of producing vibrations of various frequencies and amplitudes. The frequency can vary over a range from $\omega = 17.5Hz$ to $\omega = 20000Hz$ and the amplitude from 0.5 mm to 0.017 mm respectively (Fig. 4).

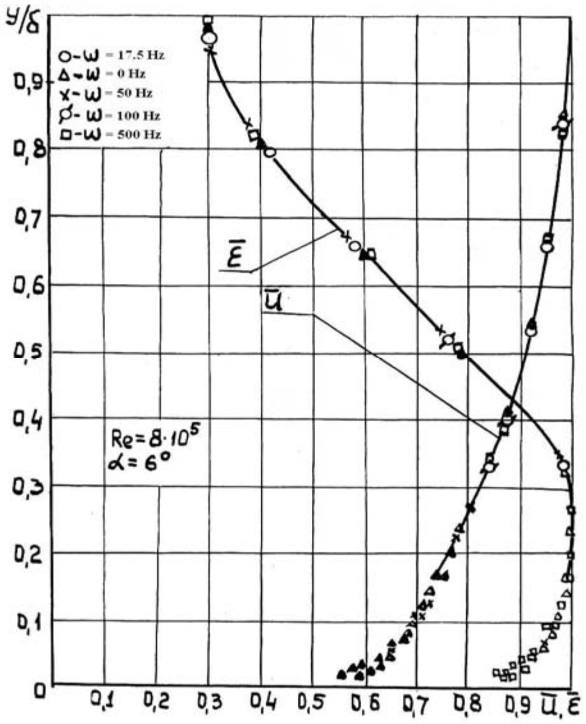

Figure 5. The distribution of the velocity profiles and the relative turbulence number across the boundary layer on a vibrated wall.

The profile of the longitudinal mean velocity is measured by Pitot tube, as well as by a hot-wire anemometer sensor "TSI". The total limiting relative errors are respectively $\delta_{\bar{u}} = 6.1\%$ and $\delta_{\sqrt{\overline{u'^2}}} = 7\%$ for the mean velocity and the root-mean-square values of the fluctuations measured by one wire sensor.

This model is slightly modified in order to reveal the static and dynamic effects of flow on the diffuser's wall. One of the plates that form the plane passage is replaced by a similar plate equipped with a strain gauge, whose signals are sent to a gauge station "TA-5" used for amplification. Amplified signals are transmitted to an oscilloscope "H-115". The evaluation of the apparatus errors shows that the total error dos not exceed 4%. The analysis of the obtained waveforms was carried out by using software, compiled by the authors and based on the Fast Fourier Transforms.

In the first series of experiments, measurements of velocities and turbulences are taken across the boundary layer on a vibrated wall, at a range of frequencies from 0 to 500 Hz. The results of these experiments are shown in Fig. 5. In this figure the velocity profiles, as well as the relative turbulence number across the boundary layer are represented. As a scale of distribution of the turbulence number its maximal value is used for the case when there is no vibration (ω = 0). $\left(\overline{\varepsilon_i} = \varepsilon_i / \varepsilon_{\max.(\omega=0)}\right)$. The absolute velocity of the external flow is 92 m/s and the initial turbulence number is sufficiently high $\left(\varepsilon_0 \approx 3\%\right)$.

It is clear, that the perturbations coming out from the wall change the velocity profile only in a narrow field nearby the wall. The external part of the boundary layer remains invariable for all frequencies of the vibrated wall. Also there was no change in the turbulence number distribution across the boundary layer. Completely similar results were obtained in the reference (Soubrata, 1990), where a boundary layer was investigated on a vibrated wall in a double-phase flow, where the steam is used as the working fluid.

The obtained results give reason to make a new estimation for the role of the boundary layer. If the layer is considered at present as a source of energy loss, and the unique cause of flow separation, then the mentioned results show that its role is not limited to those effects.

A series of experiments were conducted by the authors in the Turbo-machine laboratories of Moscow Power Institute, and they serve also as proof of the many sided characteristics of the turbulent boundary layer.

The next series of experiments are carried out in the modified model (Fig. 6), where a strain gauge was installed in one of the plates, and this enabled the recording of the dynamic loads for different air flow regimes. By rotating the plates, the form of passage could be changed from convergent to divergent (as shown in Fig. 6), and achieve a maximal degree of divergence equal to 3 (n=3).

For the convergent passage (the plates are rotated by an angle of $\alpha = \alpha_1 + \alpha_2 = -1^\circ - 1^\circ = -2^\circ$) the dynamic loads in the plate (in the point of the strain gauge's installation) practically are zero (Fig. 7). The following series of experiments were carried out when one plate (the upper) is fixed at an angle α_1 of about 4.5°, and the lower one was inclined respectively at α_2 = 0°, 3°,5° and 9°. Already for α_2 = 9° a flow separation is observed in the lower plate, and this separation is nearly displaced to the gorge of the passage for α_2 = 12°.

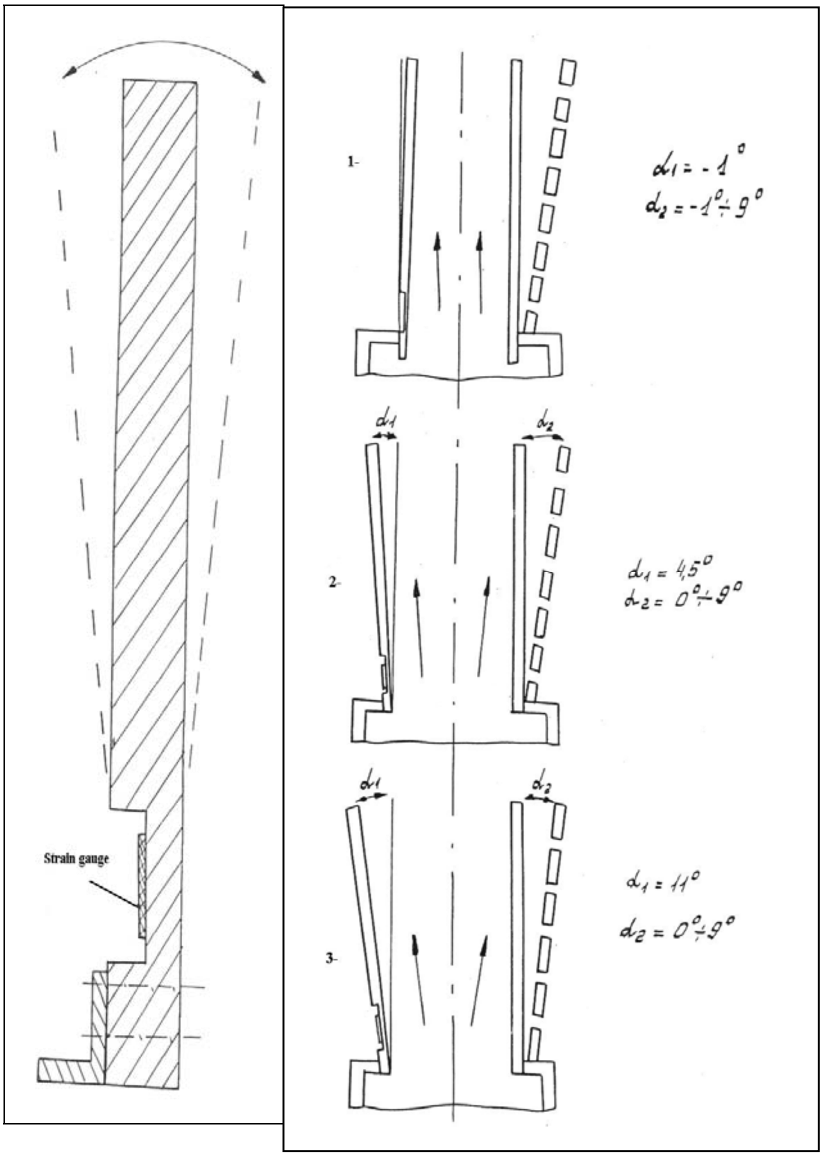

Figure 6. The plane passage in different plate's positions, and the upper plate with a strain gauge to record the dynamic loads.

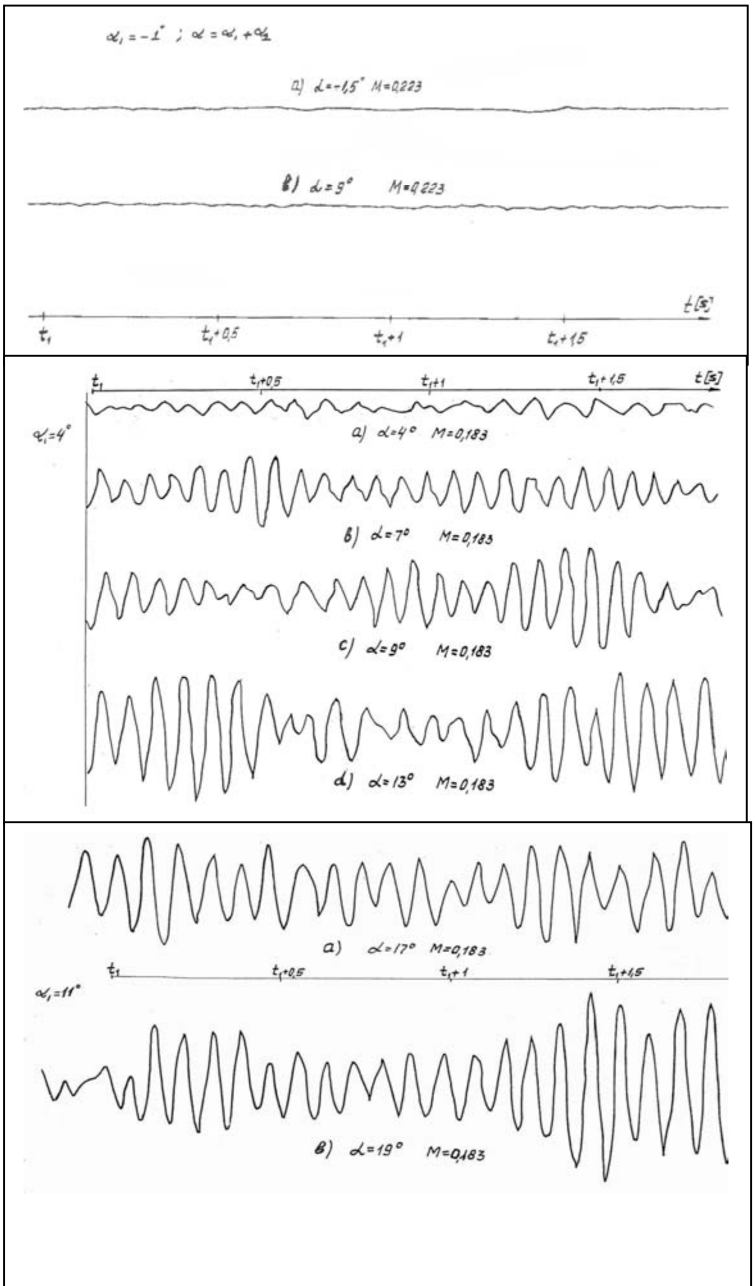

Figure 7- The dynamic load obtained oscillograms for different cases.

RESULTS AND DISCUSSION

The load oscillograms show, that at $\alpha_2 = 9^\circ$ when the flow separation is already observed on the lower plate, there was practically no change in the load, acting on the upper plate in comparison with non separated flow. This is due to the protective characteristic of the boundary layer, which protects the upper plate from the external perturbations, caused by the separated flow from the opposite plate. A completely different picture is observed on this plate in the case of an inclination of about $\alpha_1 = 4.5^\circ$. In this case a development of the dynamic load is noticed, and for $\alpha_2 > 7^\circ$ the plate completely responds to the non-steady flow caused by the flow separation from the opposite wall.

The increase of the plate rigidity will not change the qualitative character of the already described picture even through the absolute values of the loads may change.

In conclusion, the structure of the turbulent boundary layer is principally different from the laminar one. This distinction is due to the turbulence generation zone. In the laminar flow, the boundary layer may be considered as the zone of viscosity dominance. But the turbulent boundary layer is a peculiar protective screen, which protects not only the streamlined surface from the external perturbations, but also the flow from the possible perturbations coming from the vibrating walls. This functional property of the boundary layer ensures, in the case of a non separated flow, a low level of energy loss and a high reliability of the relevant structure.

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