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DETERMINATION OF THE TRANSITION POINT IN A BOUNDARY LAYER BY THE MEASUREMENT OF PRESSURE FLUCTUATION

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16. Abstract

A method is developed for determining the laminar-to-turbulent transition point in a boundary layer. The method involves the measurement of pressure on the surface of the body and the computation of pressure fluctuations. This method of determining the transition point is suitable when visualization methods cannot be used.

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DETERMINATION OF THE TRANSITION POINT IN A BOUNDARY LAYER BY THE MEASUREMENT OF PRESSURE FLUCTUATION

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A brief review is given of studies determining the laminar-to-turbulent transition point in a boundary layer. The described method involves measuring pressure on the surface of a body and computing pressure fluctuations. This method of determining the transition point is useful in conjunction with measurements of pressure distribution. It is suitable particularly when visualization methods cannot be used. /201**

INTRODUCTION

Several methods were developed for determination of the laminar-to-turbulent transition point in boundary layers. The majority of these methods can be used at high air velocities. These methods can be classified into four basic groups characterized by a varying utilization of the transition phenomena.

(1) Methods utilizing ribbons glued to the body surface and methods utilizing streams of colored gasses or liquids [1], [2]. The main disadvantage of these methods is that the ribbons act as sources of turbulence on the body surface; the colored gases of liquids require elaborate generators; moreover, the colored streams dissipate rapidly at high velocities.

(2) Methods based on wet layers [3], [4] utilize differences

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between evaporation rates of volatile substances in laminar and turbulent flow. Surfaces coated with such substance remain wet for a longer time in laminar boundary layer regions. On the other hand, the liquid dries more rapidly in the turbulent regions. This phenomenon can be made visible when china-clay powder or a fluorescent substance is used. The wet surface can be also sprinkled with a dye. The main disadvantages are that these methods require experienced experimentators and they are lengthy.

(3) Methods utilizing detection of changes of the refractive index; these methods detect streaks or shadows observed when light propagates parallel to the object's surface. However, they can be employed only in studies of two-dimensional flow [5]; moreover, the resolution is rather low [6]. They are particularly suitable in conjunction with other methods.

(4) Methods based on detection of fluctuations in the boundary layers. These methods are the most reliable ones and experimentally suitable. Fluctuations can be detected by the use of hot wires [7] or by the use of films on a probe which is moved in the anticipated boundary layer. However, the disadvantage is that a probe may cause disturbances in the boundary layer; the coordination of the movement of the probe during measurement is difficult.

Another method is used, based on subjective detection of the boundary layer. It can be classified together with the fourth group methods. Fluctuations of the velocity create a hissing noise which propagates from the pressure probe location through the conduit. If a listening device is attached to the end of the conduit, a noticeable increase of the hissing intensity can be detected in the transition point in the boundary layer, as compared to the areas of the laminar flow. The method is based on subjective evaluation of the intensity of hissing.

CHARACTERISTICS OF THE BOUNDARY LAYER

A large number of papers deal with the theorectical and experimental study of the boundary layer and of the transition point. The following characteristics of the boundary layer and its transition point can be described:

(1) Flow of a real fluid media becomes turbulent above a certain value of Reynolds number.

(2) Laminar flow has a very low degree of turbulence.

(3) Turbulent flow has a high degree of turbulence.

(4) Turbulence increases dramatically at transition points.

(5) Turbulence in the boundary layer increases in the direction perpendicular to the object's surface.

(6) Transition from laminar flow to turbulent flow in the boundary layer occurs either in the continuous line alongside of the transition vortex or in "turbulent spots" in the critical region.

(7) Turbulent flow can dissipate and undergo a transition to laminar flow in the boundary layer.

(8) The turbulence develops from a macrostructure to a microstructure; it dissipates there.

These characteristics are sufficient for a qualitative determination of a turbulent or laminar flow. Both flow regions must be experimentally characterized at the same time.

The degree of turbulence is an important experimental /202 variable. It is expressed as a mean value of fluctuations (or as a square root of the mean kinetic energy of fluctuations) of the mean flow velocity. The velocity of the layer boundary (in "non-viscous flow") is also used.

Let us designate the velocity of the fluid as v. The mean velocity during a time interval T can be expressed as:

$$U = \frac{1}{T} \int_0^T v dt \quad (1)$$

and the velocity fluctuation is:

$$u = v - U \quad (2)$$

and the mean value of fluctuations during the time interval T is:

$$\bar{u} = \sqrt{\frac{1}{T} \int_0^T u^2 dt} \quad (3)$$

The mean velocity U and the mean fluctuation are statistical variables.

The velocity and its fluctuation are vectors. For the sake of accuracy, they should be expressed by all vector components (using a selected system of coordinates).

PRESSURE DISTURBANCES

The flow instability and the friction over the object cause vorteces in the boundary layers of a variable intensity. They cause pressure disturbances which propagate into the surrounding space; they are known as the aerodynamic noise. The intensity of the noise disturbances in the given point depends on the distance from the noise sources. The level of these disturbances can be expressed by formulas which are similar to those used for expressing velocity. Lighthill described a model of the radiation field of the aerodynamic noise (e.g., ref. 8). Two noise sources are described: (1) the aerodynamic hiss at a large distance from the source; (2) the so-called "pseudo-noise" which is characterized by pressure fluctuations directly on the surface of the object. The causes of both kinds of noise are identical; the main difference between them is the mode of propagation to the surrounding space. The first kind of noise is "pure" and the magnitude of the pressure fluctuation (amplitude of the noise wave) is indirectly proportional to the distance from the source. The second kind of noise is manifested as the location of the origin as a strong pressure disturbance. The intensity of the disturbance is indirectly proportional to the square of the distance. Lighthill distinguishes the near field by its predominant pseudo-noise pressure disturbance and the distance field in which the noise propagation is governed by acoustic laws.

Dipole noise sources predominate in the turbulent boundary layer. The axes of the dipoles are predominantly perpendicular to the surface of the object. The fluctuating moment of the dipole strongly affects the surrounding flow. In other words, it is in equilibrium with the acceleration of the surrounding flow. This results in local compression of the media which is transferred depending on the propagation vector and the dipole moment. The magnitude of the pressure disturbance decreases in the direction of propagation as a function of the reciprocal square of the distance (path of propagation of the pressure wave). It is clear that the decrease of the intensity is rapid. The pressure disturbance becomes negligible at a larger distance.

It is useful to give some estimate of distances in question for the purpose of this analysis. The distance at which the pressure fluctuation is manifested can be estimated from the data given in [8]. Results of correlations between the pressures at the object's surface were obtained by NASA's W.W. Willmarth. The autocorrelation function of the pressure signal registered at one location on the object's surface with a turbulent boundary layer was obtained. It was established that the signal correlates well up to the time delay $1.5\delta_1/U$. The typically gaussian distribution of the correlation function drops off rapidly at the sides of the curve. The signal is virtually uncorrelated at higher time delay (δ_1 is the thickness of the boundary layer). These measurements also proved the transfer of the pressure fluctuation by the flow. Thus, at a distance equal to double the thickness of the boundary layer ($17\delta_1$) in the direction of the flow, the correlation was 0.5. At a distance equal to five times the thickness of the boundary layer ($41\delta_1$), the correlation was 0.2.

Lighthill used these measurements to determine the magnitude of the correlation radius of the studied pressure sample. The value is about $1.2\delta_1$. The magnitude of vorteces in the turbulent boundary layer is about one sixth of the thickness of the boundary layer. We can assume that the propagation of the pressure fluctuation in other directions (different from the direction of convection of the pressure disturbance) is characterized by a much more rapid drop of magnitude. Moreover, it can be expected that the phase change is more rapid. /203

The above results can be used to estimate the regions which are affected by pressure fluctuations in the vicinity of the surface of a given object.

Sources which are closer than twice the thickness of the boundary layer contribute significantly to the total magnitude of pressure disturbances in a given location of the turbulent boundary layer. This conclusion is very important for experimental measurements. It further can be concluded that the pressure fluctuation monitored by a pressure probe located on the surface of the object contains fluctuations propagating from the distant field. In addition it reflects phenomena taking place in the immediate vicinity of the probe in the boundary layer. The level of disturbances from the distant field depends on the location of the probe only to a small degree. On the other hand, the level or disturbances originating in the immediate vicinity of the probe depends strongly on the location of the probe. However, the pressure signal in the location of the probe can reflect additional non-stationary states which propagate through the boundary layer from the surrounding media. Such non-stationary states are usually manifested as shallow waves which propagate longitudinally (e.g., in the direction of the flow outside of the boundary layer); they can also assume the shape of cylindrical waves. The intensity of such disturbances is usually considerable. It changes very little with the distances from the source; it may be indirectly proportional to the distance. The fluctuation modes can be distinguished from each other only on the basis of frequency analysis.

MEASUREMENT OF PRESSURE DISTURBANCES

Examination of the transition point by this method assumes placing pressure probes on the surface of the objects. This method can be used without problems in cases when the objective of the measurement is to determine the pressure distribution on the object's surface. The pressure probes and the manometer must be capable to determine pressure changes of very low amplitudes while the level of the mean pressure is high. The frequency range is at least 1 kHz. Moreover, the overall signal reaching the manometer must be separated into static and dynamic components which must be precessed separately. The dynamic component is processed by statistical methods or the periodic non-random signals. The hiss level is identified in the signal. Both variables are used to determine the transition point in the boundary layer.

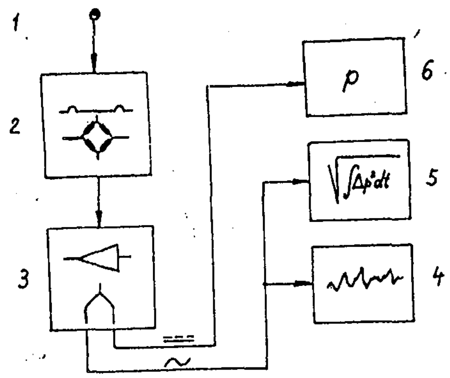

Figure 1. Schematic representation of the measurement apparatus. 1 -- Pressure probe; 2 -- transducer; 3 -- amplifier and signal analyzer; 4 -- oscilloscope; 5 -- apparatus for determination of the mean quadratic deviation; 6 -- voltmeter.

The device described in Figure 1 was used for this purpose at the VZLU Laboratory of High Velocity Aerodynamics. This device is used to measure pressure on a cylinder first. A single probe on the surface of the cylinder is connected to the pressure gauge. The cylinder can be turned around its axis to achieve a desirable position of the probe relative to the air flow. Figure 2 shows the mean quadratic pressure deviation as a function of cylinder rotation. The transition of the flow type in the boundary layer is manifested by a sharp bend in this plot. The pressure fluctuations increased dramatically.

The apparatus shown schematically in Figure 1 can be characterized as follows:

The pressure probe (1 in Fig. 1) on the surface of the cylinder is an opening of diameter 0.3 mm. It is connected by a 17 mm duct to the SiTT, transducer (2 in Fig. 1) (manufactured by ZPA Prague). The range of the transducer is 0-100 kPa. The pressure signal is linearly converted to an electrical signal at a sensitivity of

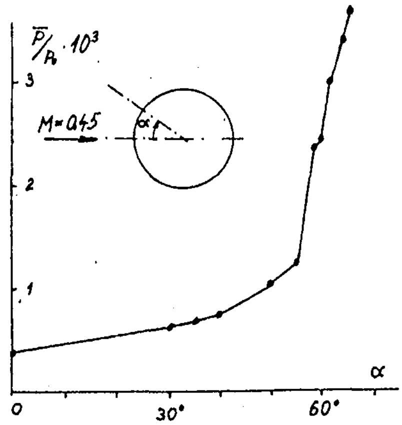

Figure 2. Pressure fluctuation on the cylinder surface.

0.6963 mV/kPa. The transducer is a semiconducting membrane with /204 vapor-deposited resistors connected in a bridge. The resistors are thermally compensated. The amplifier (3 in Fig. 1) and the analyzer were manufactured in VZLU according to ZN 49/76. Filters are used in the analyzer to separate components with frequencies below 5 Hz and those with higher frequencies. Each of the signals thus separate is independently amplified to the level which is suitable for further processing. Direct observation of fluctuations is done on a slow-scan Tesla OBP oscilloscope (4 in Fig. 1). The deviations (mean quadratic deviations) of the pressure fluctuations are determined in the DISA 55 A 06 correlator (4 in Fig. 1). The digital Solarton LM 1420 voltmeter (6 in Fig. 1) is used to measure the signal of the mean pressure. The magnitude of the signal is virtually time-independent.

An identical apparatus, in which the instrument 1 (Fig. 1) was replaced by a pressure change-over switch connected to probes located at various locations on a blade, was used for detection of the transition point on the blade surface in a casade blade. The result of the measurement is shown in Figure 3. The transition

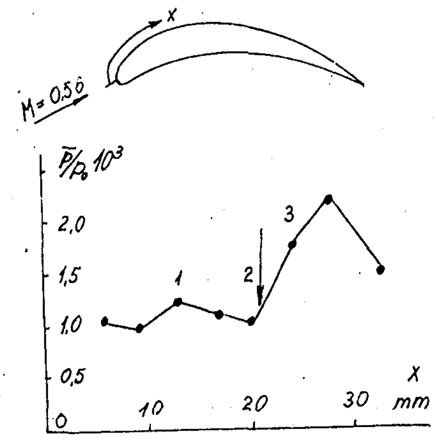

Figure 3. Pressure fluctuation on a profile in a cascade blade. The transition point is marked by an arrow.

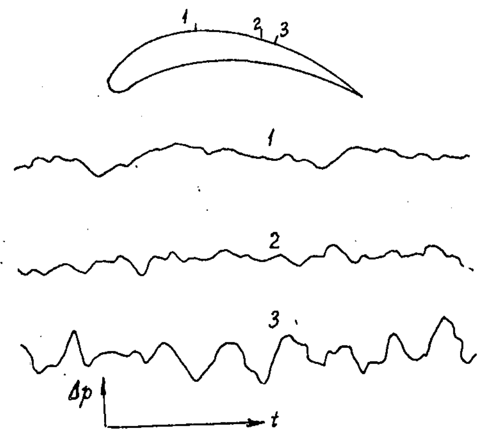

Figure 4. Time distribution of pressure fluctuations on the blade surfaces for probes located at points 1,2,3; cf., Figure 3.

is not manifested by such a distinct change of direction in the plot of the mean quadratic value of pressure fluctuations. Pressure was measured at probe locations which were placed at large distances from the blade surface. Consequently, the transition point was determined as a point in which lines representing laminar and turbulent regions cross. A more reliable determination of the transition point was obtained from the picture of the signal on the oscilloscope. The signal obtained for three locations of the probe on the surface of the blade is shown in Figure 4.

CONCLUSION

Determination of the transition point in the boundary layer based on measurement of pressure fluctuation distribution can be used in cases when the examined surface can not be visually observed. This measurement is particularly suitable for determination of the static pressure.

Pressure monitoring reflects particularly the disturbances originating in the direct vicinity of the probe and the disturbances propagated from sources beyond the boundary layer. The transition point can be determined with a sufficient accuracy from the commonly used distribution of pressure probes used in measurements of static pressures on various aerodynamic profiles.

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