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STUDY OF THE DEVELOPMENT OF NATURAL INSTABILITIES IN A LAMINAR BOUNDARY LAYER IN INCOMPRESSIBLE FLOW

Serge Burnel and Pierre Gougat

Translation of "Étude du développement des instabilités naturelles dans la couche limite laminaire en écoulement incompressible". Academie des Sciences (Paris), Comptes Rendus, Serie A - Sciences Mathematiques, Vol. 274, No. 16, April 17, 1972, pp 1251-1254

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16. Abstract

Natural instabilities which are created in a laminar boundary layer consist of intermittent wave trains. The spectral analysis of these fluctuations makes it possible to localize them in terms of frequency and to isolate their spectrum of amplitude modulation. The variation in terms of abscissa value and ordinate value of these instabilities is compared with the results derived from the solution of the Orr-Sommerfeld equation.

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STUDY OF THE DEVELOPMENT OF NATURAL INSTABILITIES IN A LAMINAR BOUNDARY LAYER IN INCOMPRESSIBLE FLOW

Serge Burnel and Pierre Gougat**

1. The first theoretical study on the development /1251*
of two-dimensional perturbations in a laminar boundary layer was performed by Tollmien and Schlichting. These authors considered a perturbation to the velocity components $u'(x,y,t)$ and $v'(x,y,t)$ represented by the stream function $\Psi'(x, y, t) = \Phi(y)\, e^{-\alpha_i x} e^{i(\alpha_r x - \omega t)}$ in which $-\alpha_i$ is the space amplification coefficient, α_r is the wave number, ω is the time pulsation, $\omega/\alpha_r = C_r$ is the phase velocity, where $Re_{\delta_1} = U_e \delta_1/\nu$.

By introducing these values in the system of Navier-Stokes equations, and after eliminating pressure terms, we obtain the Orr-Sommerfeld equation. The solution of this equation leads to curves in the plane (ω, Re_{δ_1}) of curves of equal amplification. These curves show that the instabilities can only develop above a certain critical Reynolds number. The verifications of the stability theory were performed by Schubauer and Skramstad, who injected an harmonic velocity perturbation using a vibrating ribbon. They measured the development of these perturbations as a function of Reynolds number.

The modern calculation techniques allowed Jordinson [1], Obremski and Morkovin [2] to take into account additional factors such as, for example, the longitudinal pressure gradient and the development of the average velocity profile.

*Numbers in margin indicate foreign pagination

**Meeting of March 27, 1972.

The experimental work of Rosse-Barnes-Burn [3] who also used the technique of the vibrating ribbon resulted in the distribution of the spectral power density as a function of y/δ. Also amplification coefficients were measured.

2. The study of *natural instabilities* is carried out with a flat plate having an elliptical leading edge, which is placed in a Eiffel type wind tunnel where the velocity U_e can vary between 4 and 25 m/s [4].

The signals produced by the anemometric chain are processed by a frequency analyzer in real time, which allows one to obtain the frequency range of velocity fluctuations and to measure their spectral power density. /1252

In the laminar boundary layer, and without any excitation, there is a Reynolds number above which *natural instabilities* appear in the instantaneous velocity signal, which is translated into the longitudinal evolution of various spectra due to the existence of a characteristic instability frequency range (Figure 1). For a Reynolds number of $Re_{\delta_1} = 1000$, the central frequency of this range is 1000 Hz, which corresponds to the value determined by Tollmien and Schlichting. This central frequency varies with the abscissa value according to the theory. A visualization of the instantaneous signal after filtering of low frequencies shows that, on the one hand, the instabilities have a relatively pure harmonic character: the frequency corresponds to the central frequency, but the amplitude varies as a function of time. On the other hand, the frequency range between 500 and 1500 Hz does not exist in the instantaneous velocity signal.

This variation in the amplitude of the instability as a function of time motivated a study about the amplitude

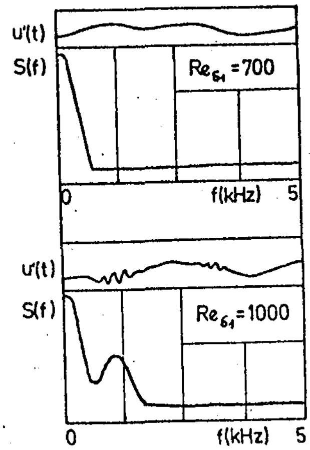

Figure 1

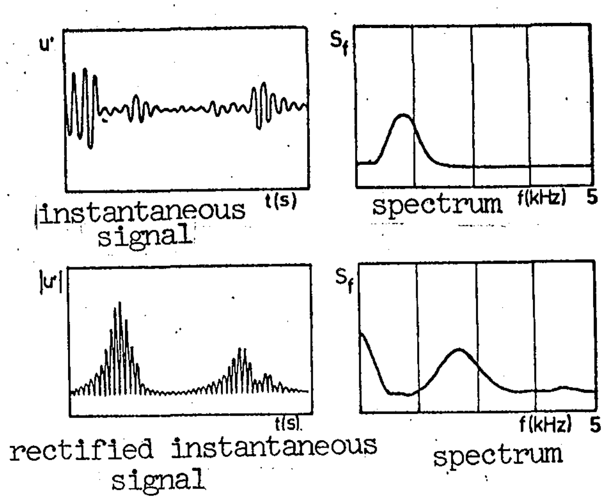

Figure 2

modulation.

If a sinusoid with the pure frequency f_2 is modulated in amplitude by a sinusoid of frequency f_1, the spectrum will include lines at frequencies f_2 and $f_2 \pm f_1$.

A double alternating rectification of this signal gives a spectrum which includes lines at $f_1, 2f_2, 2f_2 \pm f_1, 4f_2, 4f_2 \pm f_1, \ldots$

Alternating double rectification makes it possible to isolate the modulation frequency. This same procedure applied to the physical signal shows that the spectrum has a low frequency zone corresponding to an amplitude modulation spectrum (Figure 2).

The stability theory predicts the existence of a unstable frequency range for a given Reynolds number. On the other hand, the natural instabilities occur at a fixed frequency /1253 and are modulated in amplitude by a continuous spectrum of low frequencies.

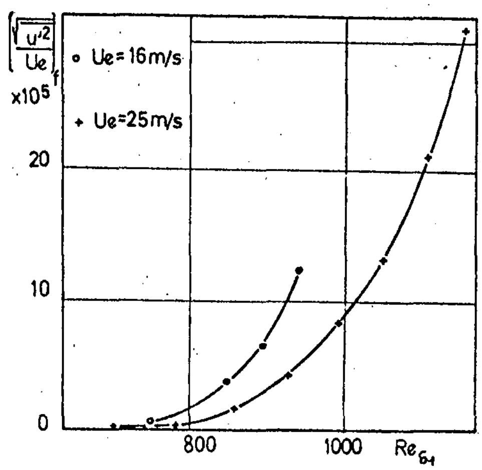

Figure 3

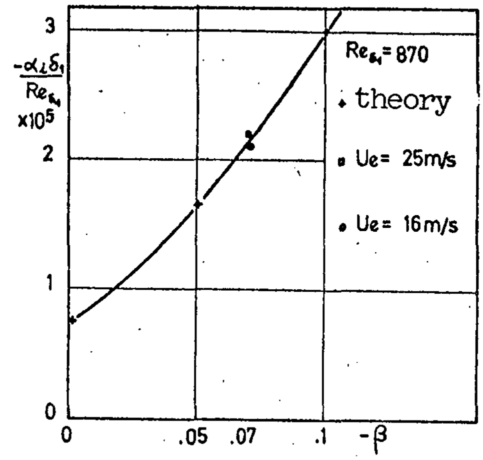

Figure 4

3. In order to characterize the mechanism for the development of the instabilities and to define the amplification coefficient, we measured both the ordinate values and the abscissa values of the variation of the spectral power density of the central frequency.

- The evolution of this power level in a given section passes through a maximum for an ordinate value of $y/\delta \sim 0.35$, which corresponds to an average speed of $U/U_e = 0.4$ which is close to the phase velocity of the instabilities. This result agrees well with the theoretical and experimental works of Jordinson, Ross, Barnes, Burn [1, 3].

- The variation of this level as a function of the abscissa for a reduced ordinate value of $y/\delta = 0.35$ thus translates the space amplification of the instabilities (Figure 3). The slope of these curves represents the amplification factor. For two velocities U_e = 16 and 25 m/s, and for the same Reynolds number $Re_{\delta_1} = 870$, we calculated the non-dimensional amplification coefficients $(\alpha_i \delta_1 / Re_{\delta_1})$ which came out to be $2.1 \cdot 10^{-5}$ and $2.2 \cdot 10^{-5}$ respectively.

The difference between the experimental and theoretical values can be obtained from nomograms of Obremski and Morkovin. On these nomograms, the external velocity gradient is characterized by the value β of the Falkner and Skan parameter. Figure 4 shows for a Reynolds number of $Re_{\delta_1} = 870$ the theoretical variation of $(\alpha_i \delta_1 / Re_{\delta_1})$ as a function of the parameter β. On the same curve, we have plotted the experimental values of the amplification coefficient, taking into account the over-velocity induced by the leading edge, which at the Reynolds number considered corresponds to a value of $\beta = -0.07$. /1254

4. We can see that there is a fundamental difference between the structure of the natural instabilities and that taken into account in the theoretical calculations: for Tollmien and Schlichting, the perturbation consists of a progressive wave. In our case, we are dealing with periodic puffs which have an intermittent character. On the other hand, the amplification coefficients measured are very close to those predicted by theory.

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