STUDIES ON THE INFLUENCE ON FLEXURAL WALL DEFORMATIONS ON THE DEVELOPMENT OF THE FLOW BOUNDARY LAYER

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16. Abstract
Flexural wave-like deformations can be used to excite boundary layer waves which in turn lead to the onset of turbulence in the boundary layer. The investigations were performed with flow velocities between 5 m/s and 40 m/s. With four different flexural wave transmissions a frequency range from 0.2 kc/s to 1.5 kc/s and a phase velocity range from 3.5 m/s to 12 m/s was covered. The excitation of boundary layer waves becomes most effective if the phase velocity of the flexural wave coincides with the phase velocity region of unstable boundary layer waves.

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STUDIES ON THE INFLUENCE ON FLEXURAL WALL DEFORMATIONS ON THE DEVELOPMENT OF THE FLOW BOUNDARY LAYER

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SUMMARY /7**

Flexural wave-like deformations can be used to excite boundary layer waves which in turn lead to the onset of turbulence in the boundary layer. The investigations were performed with flow velocities between 5 m/s and 40 m/s. With four different flexural wave transmissions a frequency range from 0.2 kc/s to 1.5 kc/s and a phase velocity range from 3.5 m/s to 12 m/s was covered. The excitation of boundary layer waves becomes most effective if the phase velocity of the flexural wave coincides with the phase velocity region of unstable boundary layer waves.

SYMBOLS

x local coordinate in the wind direction

A amplitude of the oscillator normal to wall

A_s amplitude of the excitation threshold

λ wavelength

λ_o wavelength of the flexural wave

δ^* displacement thickness

f frequency

f_s signal frequency

f_c coincidence frequency

U_∞ wind velocity in the middle of the tunnel

c_r phase velocity of the boundary layer waves

α amplitude coefficient of the boundary layer waves in dB/cm

c_r/U_∞ nondimensional phase velocity

$2\pi f\delta^*/U_\infty$ nondimensional frequency

Re Reynolds coefficient

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**Numbers in margin indicate pagination in foreign text.

φ phase angle
Tu degree of turbulence.

1. Test Assembly

1.1 Wind Tunnel

The influence of a flat wall deformed by a propagated wave on the flow boundary layer at this wall has already been studied on a theoretical basis several times [1, 2, 3]. The present experimental studies treat this problem with regard to the excitation of boundary layer disturbances due to this type of wall deformations.

The wind tunnel used for the studies has a cross-section of 10 cm x 10 cm and permits measurement in the velocity range from 5 m/s to 40 m/s. The degree of turbulence in the middle of the tunnel is $Tu < 4 \times 10^{-4}$. In this tunnel there is a flat plate employed with its sharp edge parallel to the directionof flow. The middle section of this plate can be replaced by different sound generators or flexural wave transmissions.

Without introducing an artificial disturbance, the boundary layer is laminar along the entire test section (ca. 50 cm); the displacement thickness δ^* is between 0.3 mm and 0.5 mm.

To measure the boundary layer deformations, two hot wire anemometers are used; these can be moved in a horizontal or a vertical direction. The amplitude of the wall deformation is measured by a capacitive sonde (carrier frequency procedure).

1.2 Flexural Wave Transmissions

Different preliminary studies which used a piston oscillator set into the wall as a sound generator have shown that even at very small amplitudes ($A \approx 10^{-3}$ mm), a continuous excitation of boundary layer disturbances can occur. For a more accurate study of the disturbance excitation, a wall deformation shall be induced which corresponds to a flexural wave. The phase velocity of this flexural wave must be in the range of phase velocity of the free boundary layer wave, so that coincidence of both waves can be achieved over a longer path length. The phase velocities and frequencies of unstable boundary layer waves along a flat wall are determined by the Reynolds coefficient according to the theory of Tollmien and Schlichting [4]. There thus results a frequency range of ca. 0.2 kHz to 1.5 kHz and a wave-length range from ca. 5 mm to 30 mm, for the flexural wave transmission under consideration of the data of the wind tunnel. The phase velocity of the flexural wave should therefore be varied between 1 m/s and 20 m/s. These low velocities cannot be attained in a homogeneous material which simultaneously has sufficient static strength and small damping values.

Therefore, an arrangement was selected for which the flexural wave could be modeled by two support points per wavelength[1]. It consists of a plate with a number of parallel slits covered on the windward side with an easily bent foil. The resultant chambers are driven by two pneumatic loudspeakers so that they oscillate in pairs in counterphase. Figure 1 shows this type of flexural wave transmitter. It has a constant wavelength which is equal to twice the slit separation. Four transmitters with wavelengths λ = 9, 14, 20, and 28 mm were used. This type of linear arrangement of oscillators radiates practically no sound since it consists of a number of elements oscillating in counterphase; the separation of these elements is very small compared to the sound wavelength; accordingly, the field decreases rapidly with increasing distance from the oscillators. In the direction of the target, a field decrease of 20 dB/cm was measured.

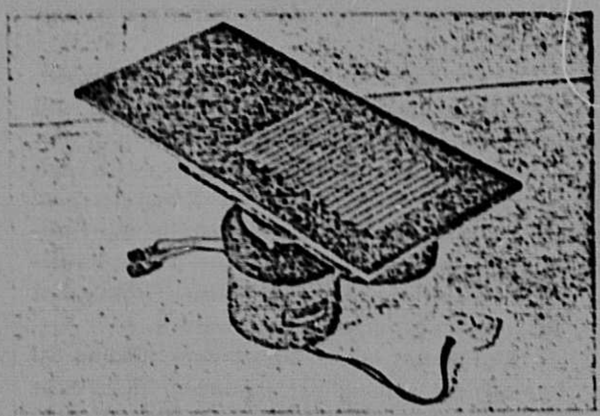

Figure 1: View of the flexural wave transmitter λ_o = 14 mm.

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[1] An expansion of the apparatus was planned so that the flexural wave could be imaged with a maximum of twelve support points. Thus, a significantly improved realization of the flexural wave is ensured.

2. Results

The amplitude and phase sequence of this special, periodic, surface oscillation corresponds to a standing wave. Measurements of the alternating speed caused by the oscillation in the boundary layer show that with increasing wind velocity, a propagating wave in the direction of flow becomes more and more pronounced. Figure 2 shows the phase sequence measured at 0.5 mm distance from the plate at various wind velocities. The signal frequency f_s is 543 Hz, the wind velocity increases from 7 m/s to 20 m/s. We clearly see the transition from a standing to a moving wave.

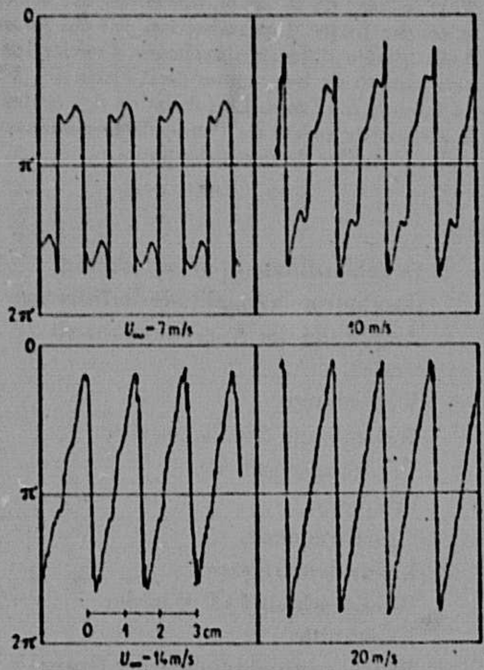


Figure 2: Measuring phase curve of the alternating speed in the boundary layer along the flexural wave transmission at different wind velocities f_s = 543 Hz.

Figure 3 shows the course of the alternating speed in the boundary layer measured above the oscillator for two wind velocities. The phase position of the individual oscillator is sketched along the abscissa.

At small wind velocities (U_∞ = 7 m/s, upper section of the figure) the air flows between the elements vibrating in counterphase corresponding to the short-range field of a group of oscillators whose periods are very small compared to the sound wavelengths.. The phase jump of the alternating speed in the boundary layer is accordingly above the

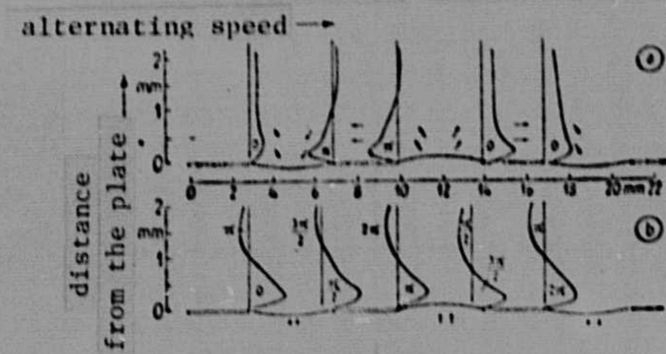


Figure 3: Course of the alternating speed in the boundary layer at various points of the flexural wave transmission.

a) U_∞ = 7 m/s, "standing wave"

b) U_∞ = 15 m/s, propagating wave. The alternating speeds are relative values f_s = 500 Hz.

middle of each oscillator.

At greater wind velocities (U_∞ = 15 m/s, the lower section of the figure), a propagating wave has formed; this wave is guided by the boundary layer and kept in motion by the wall deformation; here the shape of the wall deformation remains unchanged, the transition to a moving wave lies in the range of critical Reynolds coefficient of plate flow.

The studies have shown that this surface deformation leads to excitations of unstable boundary layer waves, even at small amplitudes; these waves cause a turbulence in the boundary layer. These boundary layer waves have the frquency of the flexural waves. Figure 4 shows the increase of this type of sine-shaped boundary layer wave from the spatial periodic field of the transmission. The alternating speed measured at 0.5 mm from the plate surface is plotted. At x = 12 cm, the exponential rise stops, the boundary layer wave is transformed into turbulence. This excitation of boundary layer waves occurs at the given wind velocity U_∞ especially at a frequency equal to the coincidence frequency f_c. Outside of this frequency a continuous excitation of disturbances can only be attained by large increases in flexural wave amplitudes. For each of the flexural wave transmissions studied, the coincidence frequencies measured as a function of wind velocity all lie on a straight line. The measured results are shown in Figure 5. For the transmission λ_o = 28 mm the measured values designated as $\lambda_o/3$ are also plotted; these will be discussed below.

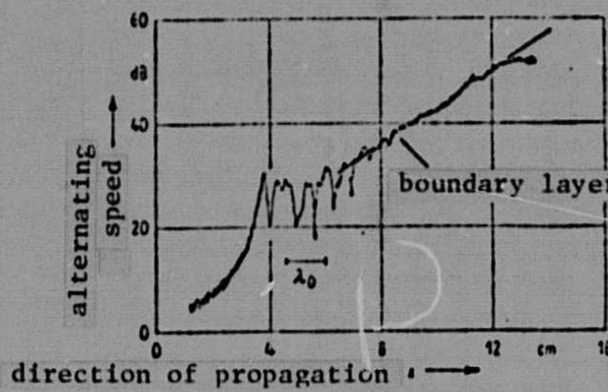


Figure 4: Excitation of a boundary layer wave due to the reflection wave. The ordinate is plotted logarithmically.

U_∞ = 15 m/s, f_c = 400 Hz, λ_o = 14 mm, $\lambda_o f/U_\infty$ = 0.374

α = 3.37 dB/cm, $Re_{\delta}*$ = 470, A ≈ 2 x 10^{-3} mm.

At coincidence, the wavelength of the boundary layer wave radiated by the transmission is independent of the wind velocities and equal to the wave length of the bending wave λ_o. Accordingly, its phase velocity C_r increases linearly with the wind velocity U_∞. For all transmissions, the quotient of phase velocity and wind velocity c_r/U_∞ = $\lambda_o f/U_\infty$ is between 0.325 and 0.45 at coincidence. A comparison with stability theory of plate flow [4] shows that the measured c_r/U_∞ -values lie within a range of phase velocities of unstable boundary layer waves. In Figure 6, all measured values and the theoretical indifference curves are plotted. From this it is visible that the flexural wave always excites boundary layer waves when the phase velocity of the flexural wave lies in the instability range of phase velocities of the boundary layer waves.

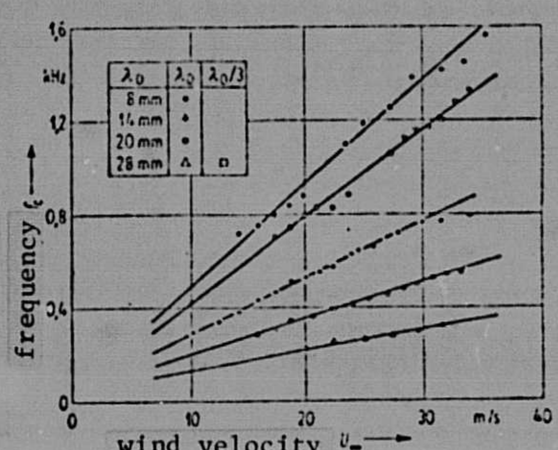


Figure 5: Measured coincidence frequencies of the various reflection wave transmissions as a function of the wind velocity.

The stability theory together with the phase velocity conditions still requires a frequency condition; that is, only boundary layer waves of certain frequency and phase velocity are unstable.

For the type of boundary layer wave excitation studied here, the wavelengths of the disturbance are predetermined. Therefore, a simultaneous fulfilment of the theoretical frequency and phase velocity condition is not always possible. In these cases, a boundary layer wave is excited when the phase velocity condition is met, although a coincidence of wave length of boundary layer wave and reflection would be possible at the unstable frequencies. However, the reflection rate amplitude needed for excitation becomes smaller, the closer the coincidence frequency is to the instability region.

In order to perform a comparison of excitation amplitudes, those reflection wave amplitudes at which a transition from laminar to turbulent flow takes place were determined at a given location downstream from the reflection wave transmission at the various frequencies and wind velocities. This amplitude value is called the threshold value.

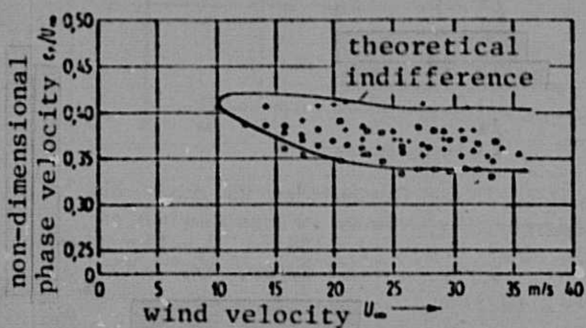


Figure 6: Comparison of the measured, non-dimensional phase velocities with the theoretical instability range.

Δ λ_o = 8 mm

O λ_o = 14 mm

□ λ_o = 20 mm

\+ λ_o = 28 mm

As already noted in Figure 5, a boundary layer wave of wavelength $\lambda_c/3$ is excited for the 28-mm transmission in addition to the base wave λ_o (for uneven fractions of the base wave, coincidence over the entire passage is possible as a result of the point-shaped imaging of the reflection wave). Figure 7 shows that the base wave of the 28-mm transmission is far below the instability range, whereas the second harmonic vibration runs in the interior of the instability range. Accordingly, the measured threshold values of the base wave are more than 12 dB greater. The other curves entered in Figure 7 illustrate the course of coincidence frequencies of the other transmissions. They are both within as well as outside the instability range. As ordinate, the non-dimensional frequency $2\pi f\delta^*/U_\infty$ was selected in Figure 7 in order to

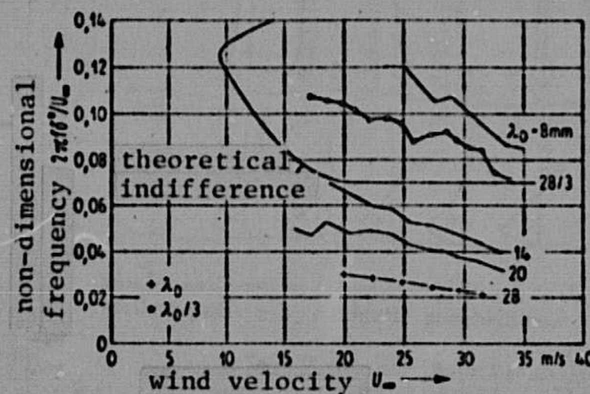
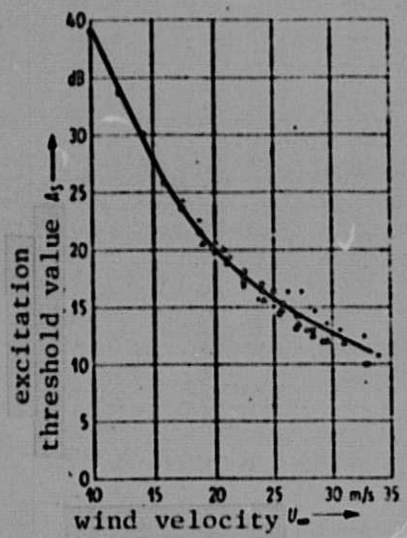


Figure 7: Comparison of coincidence frequencies of the base waves and the second harmonic vibration of the 28-mm transmission with the theoretical instability range. Also plotted; coincidence frequencies of the other reflection wave transmissions.

to implement and improve comparisons with the theoretical neutral curves.

A quantitative comparison of the measured threshold values of the various transmissions could not be performed. Therefore, in Figure 8 the threshold values of the individual transmissions are standardized so that the curves at U_∞ = 20 m/s coincide. As a result of this standardization all values fall on one section of a curve, the threshold values decrease greatly with increasing wind velocity because of the linear relationship between wind velocity and phase velocity; the phase velocity is obtained by multiplication of the dimensional coefficients of the abscissa by 0.375. The ordinate in Figure 8 is plotted logarithmically. For the threshold value of the 14-mm transmission we have 0 dB $\triangleq 10^{-4}$ mm.

The course of the excitation threshold value and of the phase velocity of the excited boundary layer waves was also studied in the range of the coincidence frequency. The results confirm the state of affairs discussed above. The excitation threshold value was measured at constant



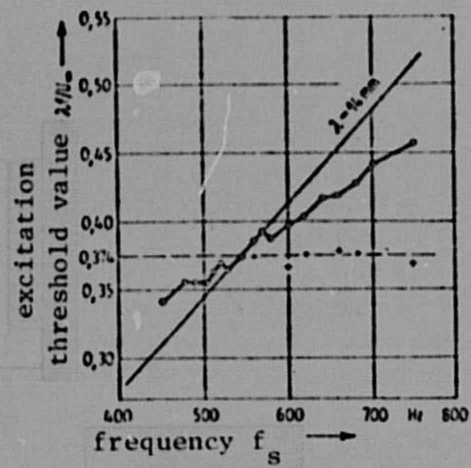


Figure 8: Course of the relative excitation threshold value at coincidence as a function of the wind velocity. The curves are standardized at U_∞ = 20 m/s to the same threshold value. 0 dB $\underline{\Delta}$ 10^{-4} mm (λ = 14 mm).

O λ_o = 14 mm

Δ λ_o = 20 mm

\+ λ_o = 28 mm

Figure 9: Course of the excitation threshold value as a function of frequency at constant wind velocity U_∞ = 20 m/s.

wind velocity U_∞ = 20 m/s as a function of the frequency and it shows a pronounced minimum (Figure 9) at coincidence. The coincidence frequency is 543 Hz. Figure 10 shows the non-dimensional phase velocities c_r/U_∞ belonging to it. The straight line c_r/U_∞ = 0.374 denotes the middle of the instability range. At coincidence, the curves of the measured phase velocities intersect this line. Outside the coincidence range the wavelength of the induced disturbance is not exactly equal to the wavelength of the reflection wave which is given by the straight line λ = 14, rather it lies nearer the instability range. The guide through the reflection wave is not complete.

Downstream from the reflection wave transmission where the guide stops, the wavelength of the excited boundary layer waves changes so that its phase velocity ends up within the instability range. The phase velocities measured along the transmission as well as downstream from the transmission are plotted in Figure 10, for several frequencies

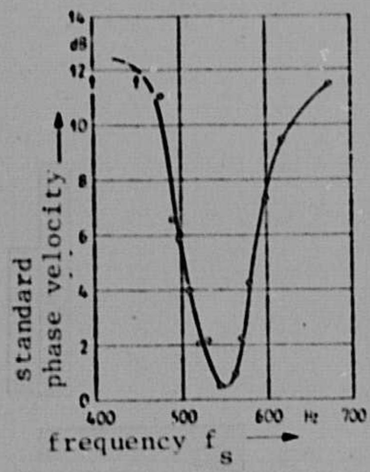


Figure 10: Phase velocity of the excited boundary layer wave along and downstream from the reflection wave transmission plotted as a function of frequency at constant wind velocity U_∞ = 20 m/s. O $\lambda f/U_\infty$ in front of the transmission
+ $\lambda f/U_\infty$ behind the transmission

$f > f_c$.

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LITERATURE

1. Becker, E.: The laminar incompressible boundary layer at a flat wall deformed by moving waves. DVL Report 132.

2. Benjamin, T. B.: Shear Flow over a Wavy Boundary. J. Fluid Mech., 6, (1959), 161.

3. Benjamin, T. B.: Effects of a Flexible Boundary on Hydrodynamic stability. J. Fluid Mech., 9, (1960), 513.

4. Schlichting, H.: Grenzchichttheorie (Boundary Layer Theory); Pub. by G. Braun, Karlsruhe, 1958.