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Investigation of the Laminar-Turbulent Transition of Boundary Layers Disturbed by Wakes

The boundary layer transition under instationary afflux conditions as present in the stages of turbomachines is investigated. A model for the transition process is introduced by means of time-space distributions of the turbulent spots during transition and schematic drawings of the instantaneous boundary layer thicknesses. To confirm this model, measurements of the transition with zero and favorable pressure gradient are performed.

NOMENCLATURE

d	diameter
i	plate incidence angle
N_A	amplitude parameter of free-stream unsteadiness, $\Delta U/U_\infty$
Re_x	Reynolds number based on streamwise coordinate, $U_\infty \cdot x/\nu$
Re_{NS}	non-steady Reynolds number, see Eq.(3)
Re_{tr}	transition Reynolds number, $U_\infty \cdot x_{tr}/\nu$
s	spacing of cylinder cascade
T	period, s/V_{cyl}
T-S	Tollmien-Schlichting
t	time
t_W	reference time value at half wake depth
U	longitudinal velocity component of mean flow
U_o	mean longitudinal velocity component in afflux
U_∞	mean longitudinal velocity component in external flow
u	longitudinal fluctuation velocity
V_{cyl}	cross velocity of cylinder
v	transverse fluctuation velocity
x	coordinate along surface
y	coordinate normal to surface
δ	boundary layer thickness
ν	kinematic viscosity
ϕ	normalized velocity component in the wake in x-direction
ω	circular frequency

SUBSCRIPTS

f	forced
LE	leading edge
lam	laminar
ns	neutral stability
o	undisturbed
TE	trailing edge
Tr	end of transition
tr	start of transition, i.e. appearance of a turbulent spot
turb	turbulent

INTRODUCTION

In the turbomachine, in which stationary and rotating blade cascades are successively arranged, unsteady flow to the following cascade is produced by the wakes of the previous one. In contrast to oscillating external flows the periodical fluctuations of the mean velocity are superimposed here by the turbulent fluctuations caused by the mixing process in the wake. In this investigation the transition of a laminar boundary

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layer perturbed in this way is observed with the help of boundary layer measurements, in order to show the parameters responsible for the onset of transition.

The measurements were carried out in a low velocity wind tunnel as already described by Pfeil and Herbst [1]. The unsteady flow to a plate is produced by means of a rotating cylinder cascade.

FORMER INVESTIGATIONS OF BOUNDARY LAYER TRANSITION IN INSTATIONARY FLOWS

A fundamental assumption of the linear stability calculation as carried out by Tollmien [2] and Schlichting [3] is that the levels of the perturbations are small in comparison to the values of the basic flow. If the basic flow is superimposed by a periodically changed velocity, one must investigate whether the transition can be understood by means of the linear stability theory. Karlsson [4] performed preliminary experiments in this problem, in which he carried out velocity and boundary layer measurements on a flat plate under oscillating external flow. With his results Karlsson showed that the average value of the local velocity was not influenced by the superimposing of an oscillating component, in either laminar or turbulent boundary layers. The time-averaged velocity profile remains a solution of the Navier-Stokes equation, and the perturbation equations can also be treated as in the stationary case according to Tollmien and Schlichtings theory.

Greenspan and Benney [5] investigated the stability of the Tollmien-Schlichting flow, which is responsible for the high-frequency disturbances and breakdown into turbulence. They superimposed the Blasius profile with a time-dependent periodic shear flow of finite amplitude and established that at favoured locations a continuous production of local instabilities occurred at position and time of the most intense shear layer. The periodic turbulent spots created in this way spread downstream. If the amplitude of the external oscillating velocity is the same as or larger than that of a typical turbulent fluctuation, Miller and Fejer [6] as well as Obremski and Fejer [7] expect an agreement between the transition process within oscillating external flow and Greenspan and Benney's suggested model. The periodically changing external velocity is described by:

$$U(t) = U_\infty \cdot (1 + N_A \cdot \sin \omega t) \tag{1}$$

where N_A represents the amplitude parameter.

$$N_A = \frac{\Delta U}{U_\infty} \tag{2}$$

The evaluation of their measurements shows that with oscillating external flow the start of transition, especially with a zero pressure gradient, depends upon a certain non-steady Re_{NS}-number, Fig. 1.

$$Re_{NS} = \frac{U_\infty}{\nu} \cdot \frac{\Delta U}{\omega} \tag{3}$$

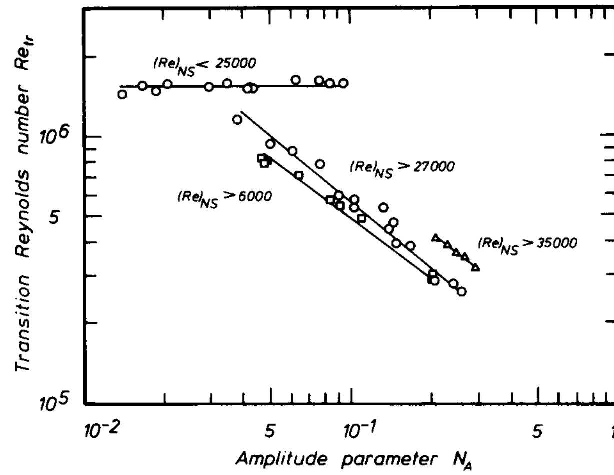

Fig. 1 Transition Reynolds number as a function of the amplitude parameter for three pressure gradients. O, dCp/dx=0.004/ft.; △, dCp/dx=-0.081/ft.; □, dCp/dx=0.045/ft. (Obremski & Fejer [7])

If this Re_{NS}-number ($Re_{NS} \approx 27000$) is exceeded, the transition begins with turbulent spots which are periodically produced with the frequency of the outer flow. The Reynolds number Re_{tr} for the onset of transition is primarily dependent upon the amplitude of the external flow and not on the frequency.

Below a critical value of Re_{NS} ($Re_{NS} \approx 25000$) the transition occurs at a relatively constant Reynolds number, which is not dependent upon the amplitude and frequency of the external flow. In this way the oscillation has lost its dominant role. However Loehrke, Morkovin and Fejer [8] do not find the correlation described above as solely responsible for the correlation of the Re_{NS} number in their review of the transition of oscillating boundary layers. Morkovin et al. [9], [10] do succeed in explaining the above mentioned intermittent behaviour of the boundary layer in the transition region by means of a quasi-steady stability model.

Walker [11] investigated the transition of the boundary layer along the suction side of a stator blade in a single-stage axial-flow compressor. Corresponding to the model from Fejer et al., he regards the influence of the velocity oscillations caused by the wakes of previous rotor blades as responsible for the instability of the boundary layer.

In his considerations the relation of the instability length, i.e. distance between the point of instability and the turbulent breakdown, to local expansion of the wake on the blade surface represents an important parameter. If the instability length is large as a result of small or favourable pressure gradients, the turbulent breakdown can occur in the calmed region between two rotor wake disturbances. That assumes that the perturbations move more slowly than the wakes. When the instability length is small because of adverse pressure gradient the breakdown into turbulence can still take place in a wake area. The result of these considerations is that because of the importance of the instability length and therefore of the pressure gradient large velocity oscillations in the outer flow must not necessarily alter the transition region. However Walker does not make any statement about the influence on the transition of the stochastic turbulence in the wake.

Boundary layer measurements along stationary blades in the turbomachine cause great problems because of the small dimensions and the impossibility to be able to change only one of the various parameters alone which may influence transition in unsteady flow. For example, a variation of the circumferential velocity of the machine alters both disturbance frequency and Reynolds number simultaneously, while changing the throughflow coefficient alters both the disturbance amplitude and the mean streamwise pressure gradient over the transition region.

For this reason Pfeil and Pache [12] carried out boundary layer measurements on a 700 mm long plate. The unsteady flow was, as in [1], realised by a rotating cylinder cascade positioned in front of the plate. This test facility, which provides accurate measurements because of its large dimensions, allows the independent variation of the parameters influencing transition. Their measurements show that the perturbed flow in contrast to the stationary conditions involves large changes in the boundary layer development especially with favourable flows. In the case of undisturbed afflux and favourable basic flow a laminar boundary layer develops along the entire plate length. In perturbed flow a laminar-turbulent transition ocurred.

Comparisons of the transition obtained by measurements cannot be made to agree with Schlichtings stability theory and new empirical transition criteria such as those of Dunham [13], Hall and Gibbings [14] which take the degree of turbulence in the external flow into account. It was presumed that the disturbances which consist of fluctuations and stochastic turbulence were so large that their influence on the transition can no longer be described by the linear stability theory, which is founded on small perturbations. In [12] the question was still open as to the effects of varied perturbation conditions on the temporary development of the instationary boundary layer. For this reason in further investigations by Pfeil and Herbst [1], [15] the number of the cylinders in the rotating cascade was increased from zero upwards. The evaluations of the measurements led to a model which describes the temporary boundary layer development under these special conditions.

MODEL FOR TRANSITION BEHAVIOUR UNDER INSTATIONARY FLOW

Fig. 2 shows according to the test conditions the flow behind a cylinder cascade crossing the flow direction. The wakes, whose slant results from the afflux velocity U_0 and

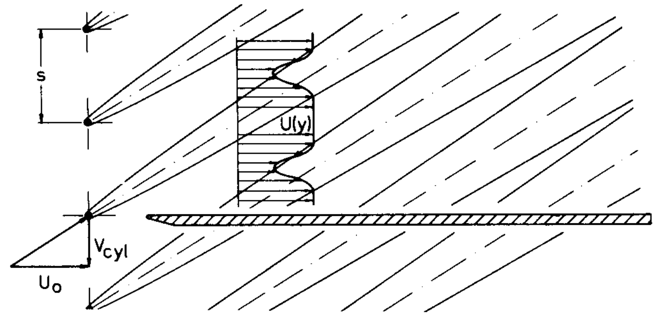

Fig. 2 Scheme of the unsteady flow produced by wakes

the cross velocity of the cylinder V_{cyl}, drift off along the plate surface and influence the boundary layer, and especially its transition behaviour, in a periodical intermittent way.

As an example Fig. 3 presents measured temporal distributions of the ensemble-averaged wake velocities behind a moving cylinder, which crosses the flow with varied velocities V_{cyl}, cf. Pfeil and Schröder [16].

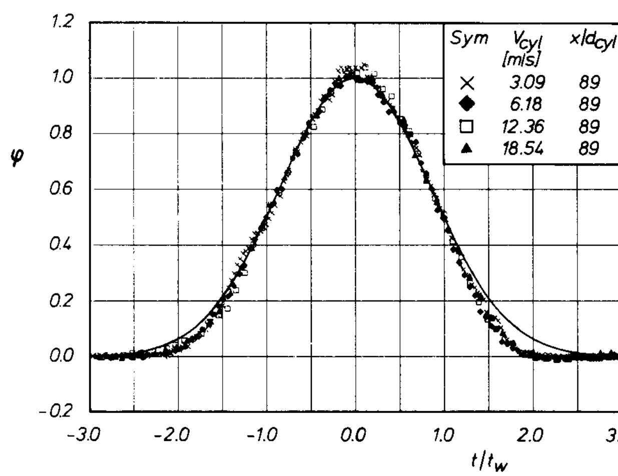

Fig. 3 Profiles of measured normalized velocities in the wake in x-direction compared with the Gaussian distribution curve (Pfeil & Schröder [16])

The time-space distributions, Fig. 4, are suitable to present the transition process, i.e. the formation and propagation of turbulent spots. The parallel lines to the x-axis reproduce the instantaneous flow conditions along the plate, while the vertical lines describe the change of the flow over the time at a fixed place. With undisturbed flow a laminar boundary layer forms along the plate, which undergoes natural transition after a certain flow distance according to the stability criteria from Tollmien and Schlichting, Fig. 4a. The marked positions, the point of neutral stability, x_{ns}, the

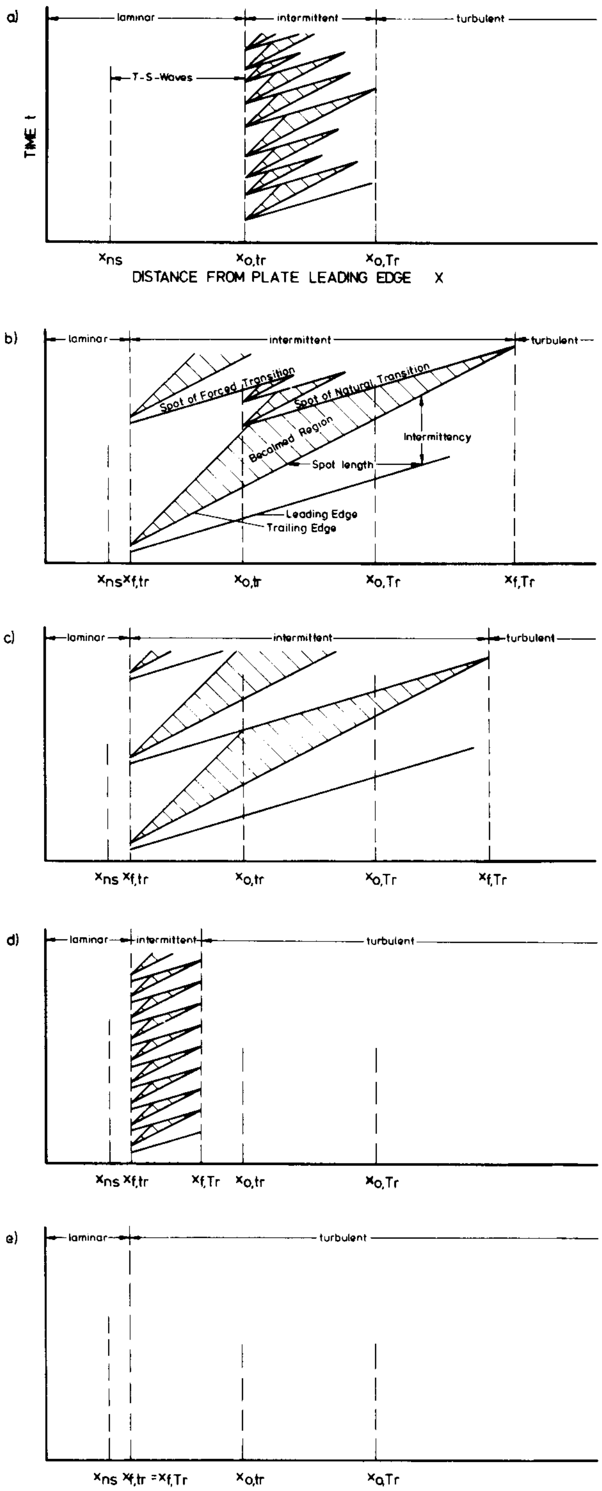

Fig. 4 Time-space distribution of the turbulent spots during transition

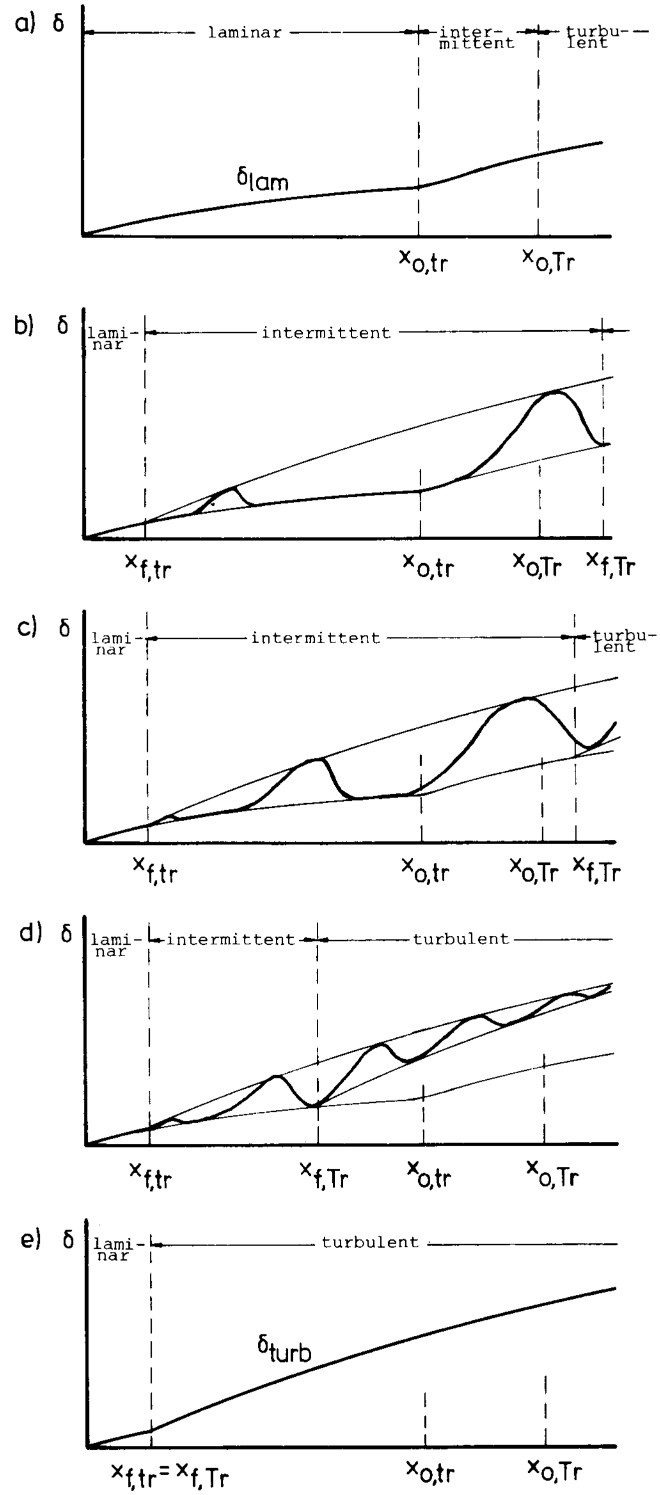

Fig. 5 Schematic drawing of boundary layer development with different cascade spacing

start $x_{o,tr}$ and the end $x_{o,Tr}$, of natural transition describe the transition process. Downstream from x_{ns} small disturbances of a defined area of wave length are stimulated (T-S-waves) and break off from $x_{o,tr}$ upwards in high frequency irregular three-dimensional velocity fluctuations. The turbulent spots, which are formed in this way cause an intermittently turbulent boundary layer. They propagate until they have merged at $x_{o,Tr}$ and the natural transition is ended. As the propagation velocity of two-dimensional waves (T-S-waves) is lower than that of the trailing edge of a turbulent spot (cf. Schubauer & Klebanoff [17]), a so called "becalmed region" is formed at the trailing edge in which no further turbulent spot can arise. In Fig. 4 these regions are marked by hatching.

If a wake with its increased stochastic turbulence moves over the plate surface, the developing laminar boundary layer is already intensely disturbed. The perturbations are however subdued, i.e. are no longer stimulated. At first from the forced start of transition, $x_{f,tr}$, Fig. 4b, the turbulent spots periodically produced by the wakes, spread and form an intermittent laminar-turbulent boundary layer. These turbulent spots are followed by becalmed regions of laminar boundary layer in the same way as the turbulent spots of natural transition. If the spacing of the cylinder cascade is large, the turbulent spots of the natural transition are observed from $x_{o,tr}$ in the undisturbed areas between periodically produced turbulent spots and their becalmed regions. As a consequence of the large spacing and the becalmed regions of the forced turbulent spots the transition is not finished at $x_{o,Tr}$, but subsequently downstream at $x_{f,Tr}$, Fig. 4b.

While other test parameters such as e.g. constant cross velocity of the cylinder cascade V_{cyl}, constant afflux velocity U_o as well as the positioning of the plate remain unchanged, varied spacings show no influence on the position of $x_{f,tr}$. Only the number of periodic produced turbulent spots per unit of time increases inversely proportional to the spacing. With a certain spacing the creation of turbulent spots of natural transition is totally prevented by the becalmed regions of the forced turbulent spots, see Fig. 4c. With this and smaller spacings, Fig. 4d, the transition is only ended by the merging of the periodically produced turbulent spots at $x_{f,Tr}$.

If one reduces the spacing of the cylinder cascade down to a critical value, the wakes already merge in the afflux. Then at the point of the start of transition, $x_{f,tr}$, an almost uniform and still high turbulence level exists. Subsequently the length of transition, $x_{f,Tr} - x_{f,tr}$, of the forced transition tends to zero, Fig. 4e.

As can be seen from Fig. 4 besides the spacing one needs the other important parameters, the instability length and the spot propagation of the natural and the forced transition, in order to describe the entire transition process.

In analogy to Fig. 4 in Fig. 5 the boundary layer development is plotted. The forced turbulent spots of the disturbed flow can be recognized by a local thickening of the boundary layer, which moves downstream rising at the same time, as measured by Pfeil and Herbst [1]. As already shown in Fig. 4b, the end of forced transition, $x_{f,Tr}$, is located downstream of the end of natural transition, Fig. 5b. Smaller spacings affect a displacement of the end of forced transition in direction of the plate leading edge, Figs. 5c and d, until, as in the case of critical small spacing, Fig. 5e, the start and end of forced transition coincide. The then developing turbulent boundary layer δ_{turb} represents a limiting curve for the growth of the thickness of the forced turbulent spots.

The conception described above should be employed as a model for further considerations in boundary layer transition under unsteady flow conditions. As the structure in the wake of a cylinder is almost the same as behind a blade, these relations can also be applied to a rotating blade cascade with the same C_D-value and spacing, placed in front of the testing section. However the influence of the circulation of the previous cascade remains disregarded. It must be mentioned that in this investigation it was assumed that the periodic fluctuations of the static pressure caused by the wakes striking the plate are disregarded.

MEASUREMENT RESULTS

The boundary layer measurements were carried out along a plate with zero pressure gradient, $i = 0^o$, and a weak favourable pressure gradient, $i = -2^o$. Fig. 6 represents a scheme of the test facility.

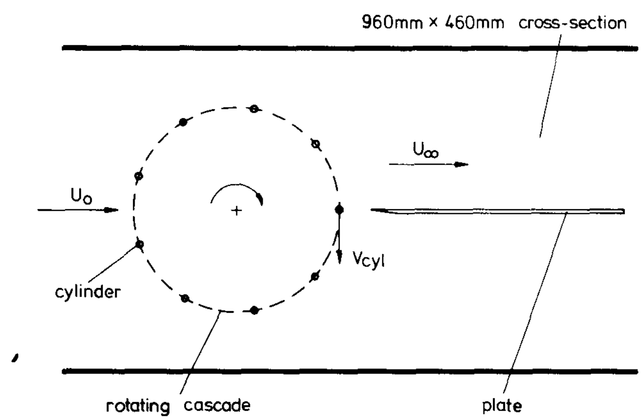

Fig. 6 Scheme of the test facility

The afflux velocity U_o amounted to approximately 20 m/s for all the measurements and the cross velocity V_{cyl} of the moved 2 mm wide cylinders to 12.6 m/s. The spacing of the cylinder cascade, which moves across the flow direction in an orbit with 0.6 m diameter, can be altered.

During the zero pressure gradient measurements three groups of cylinders were mounted in the cascade with an individual displacement of 120 degrees. Each of these groups of cylinders consists of four cylinders closely mounted in distances of 5 mm. In contrast to this during the measurements with favourable pressure gradient the cylinders were placed individually.

The streamwise distributions of the free-stream velocity U_∞, which belong to the two different plate incidences, are shown in Fig. 7.

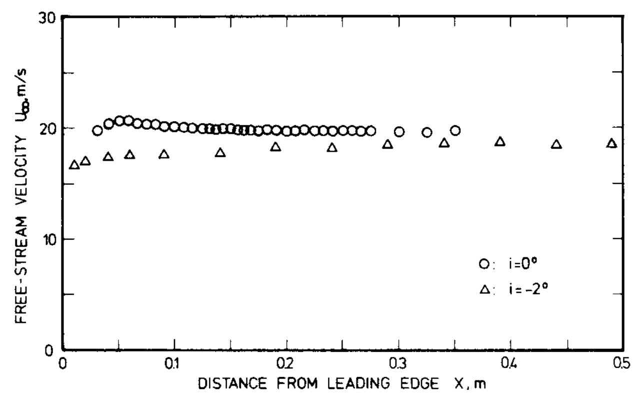

Fig. 7 Distributions of the free-stream velocity

Measurements with Zero Pressure Gradient

Fig. 8 shows oscilloscope traces of the longitudinal velocity fluctuations in the boundary layer at a constant wall distance y. Even from the leading edge of the plate the large perturbations periodically influence the boundary layer flow. As the cylinder twice crosses the middle of the channel in its orbit, in accordance with Fig. 6, two perturbations arise, one of which is weaker, owing to the longer flow distance. It can be seen in Fig. 8a that when x = 31 mm the boundary layer reacts with high frequency changes. The laminar boundary layer is however so stable further downstream that the perturbations are no longer stimulated but are even subdued, as is shown in Fig. 8b by the example of the perturbation of the upward moving cylinder.

After x = 67 mm a definite development also of the width of the periodically produced turbulent spots was established. In accordance with the introduced transition model, Figs. 4 and 5, the onset of forced boundary layer transition $x_{f,tr}$ is found at this x-wise position. The increase of the velocity in the turbulent spot is proof of the fact that the fluctuations of the wake are not carried into the boundary layer, but here a rapid change from the laminar to the turbulent velocity profile takes place in the boundary layer, cf. Pfeil and Herbst [1], Fig. 7. Even further downstream, Fig. 8c, in the undisturbed area between the forced turbulent spots the typical T-S-waves of the natural transition are visible. The amplitude of the T-S-waves is increasingly stimulated until at $x_{o,tr}$, Fig. 8d, the first turbulent

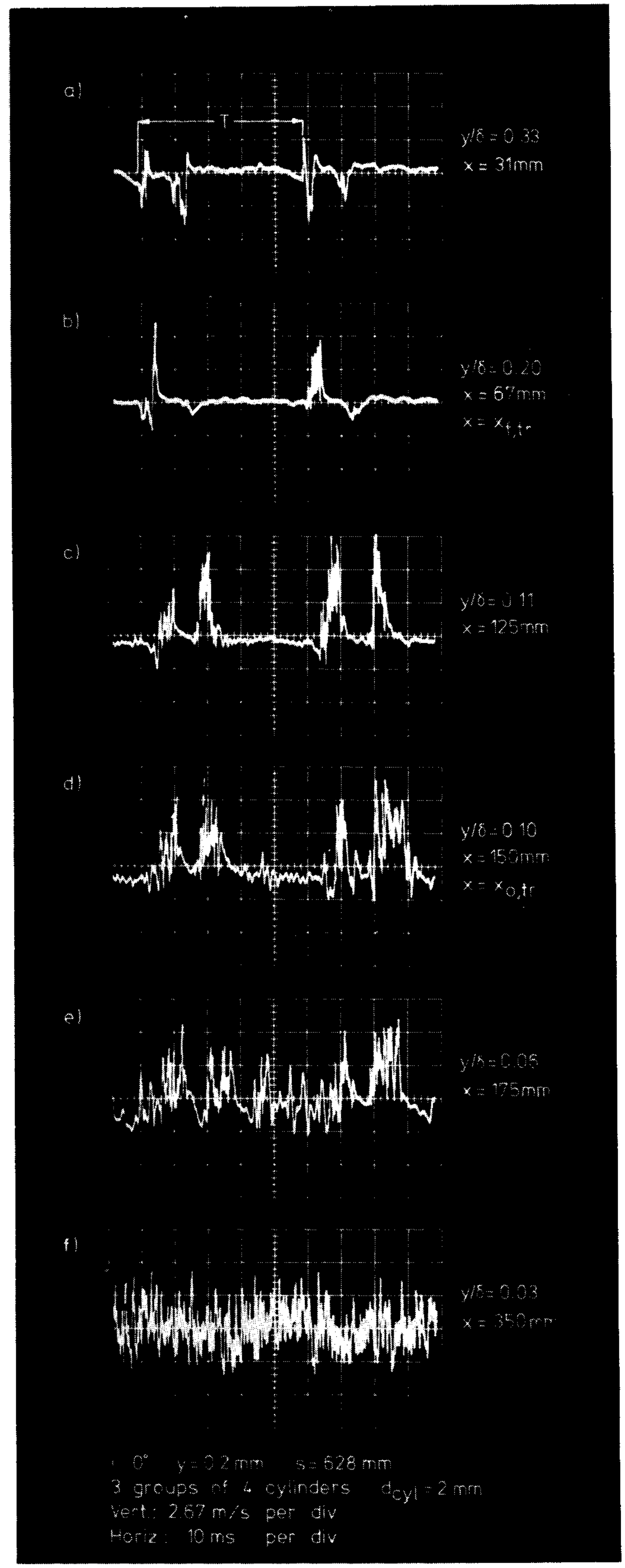

Fig. 8 Oscilloscope traces of the longitudinal velocity fluctuations in the perturbed boundary layer at constant wall distance, recorded at different x-stations

spots of the natural transition appear. Further downstream these turbulent spots fill in the previously undisturbed area even more, Fig. 8e, until, as in Fig. 8f, only turbulent velocity fluctuations can be seen and the transition is ended. As in this record the periodically produced turbulent spots have just merged at their edges, an oscillation of the base flow with the frequency of the perturbation of the moving cylinder cascade is still observed in the turbulent boundary layer.

Due to the chosen spacing the becalmed regions occurring in the environment of turbulent spots are not clearly visible in the oscilloscope traces recorded in Fig. 8. The existence of the becalmed region is evident, if at a x-station downstream of $x_{o,Tr}$ with disturbed afflux an intermittent laminar-turbulent boundary layer is observed. Fig. 9 shows oscilloscope traces of the longitudinal velocity fluctuations in the boundary layer, recorded at x = 350 mm.

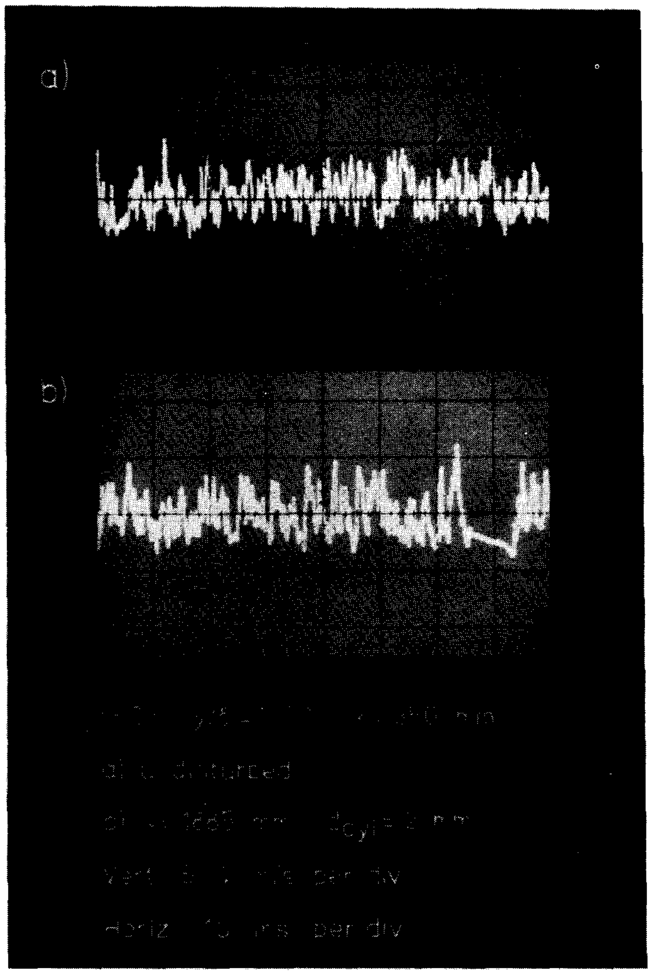

Fig. 9 Oscilloscope traces of the longitudinal velocity fluctuations in the perturbed boundary layer at constant wall distance, recorded at x = 350 mm

Whereas with undisturbed afflux the boundary layer has undergone transition, Fig. 9a, with disturbed afflux caused by a large spacing of the cylinder cascade portions of laminar boundary layer are clearly visible in the record, Fig. 9b. I.e. the end of forced transition $x_{f,Tr}$ is situated downstream of the end of natural transition $x_{o,Tr}$.

The distribution of the fluctuation velocity at constant wall distance in streamwise direction is shown in Fig. 10.

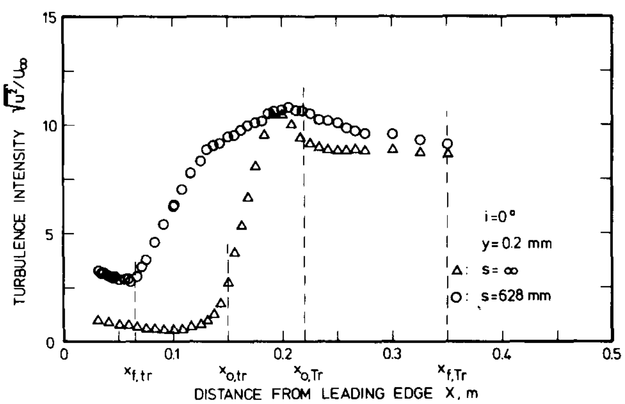

Fig. 10 Distribution of the non-dimensional turbulence intensities along the plate at constant wall distance in undisturbed and disturbed boundary layer

The onset of the natural transition is identified by $x_{o,tr}$ = 150 mm, whereby $x_{o,tr}$ was found with the help of oscilloscope traces. The increase of the fluctuation velocities in front of $x_{o,tr}$ can be explained by the appearance of T-S-waves. As with disturbed afflux the superimposed perturbations in the stable laminar boundary layer are not stimulated, the fluctuation velocities decrease until the onset of transition at $x_{f,tr} \approx 67$ mm appears. The curve increases after $x_{f,tr}$ and bends in the area from $x_{o,tr}$, which could be attributed to the overlapping natural transition. The transition is ended when the turbulence intensity reaches a nearly constant level. The respective positions of the end of transition with undisturbed and disturbed afflux, $x_{o,Tr}$ and $x_{f,Tr}$, are stated in Fig. 10.

In Fig. 11 the distribution of the non-dimensional mean velocity U/U_∞ at constant wall distance was plotted. The alteration of the laminar into the turbulent velocity profile is to be recognized in this graph by an increase of the mean velocity close to the wall.

These measurements show that in the chosen experimental conditions the end of transition is found downstream of the end of natural transition (cf. Fig. 4b); the start of transition caused by large perturbations is located nearer to the plate leading edge, i.e. at smaller Re_x-numbers, as the start of natural transition.

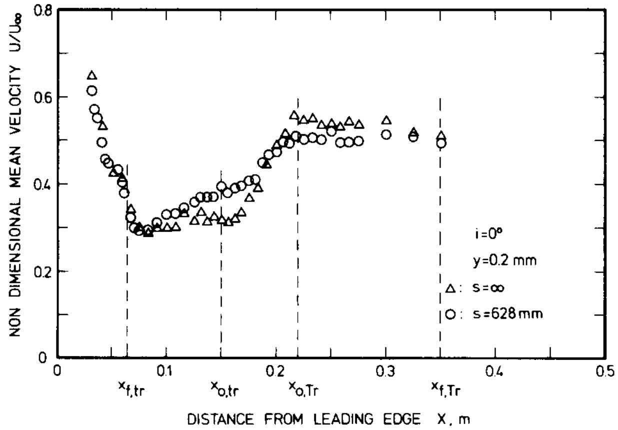

Fig. 11 Distribution of the non-dimensional mean velocity along the plate at constant wall distance in undisturbed and disturbed boundary layer

Measurements with Favorable Pressure Gradient

Like Fig. 8, Fig. 12 shows a series of oscilloscope traces of velocity fluctuations in the boundary layer. In comparison to the measurements at zero pressure gradient, now 9 single cylinders with the spacing of s = 209 mm are mounted in the rotating cascade. One can clearly recognize the turbulent spots, which are created by the wakes, Fig. 12b. The time interval corresponds to the period T of the wakes, which successively strike the plate surface. As for the undisturbed flow the boundary layer is stable laminar along the plate, no T-S-waves are observed in the undisturbed region between two spots in contrast to zero pressure gradient flow. From the oscilloscope traces surprisingly only the start of the forced transition, $x_{f,tr}$, can already be seen after a small distance from the plate leading edge. The turbulent spots merge at $x_{f,Tr}$ = 490 mm as a result of the propagation of their leading and trailing edge and the transition is terminated. It is then shown that the forced transition process was completed within the measured plate region before the natural transition had even begun, cf. Figs. 4d and 5d.

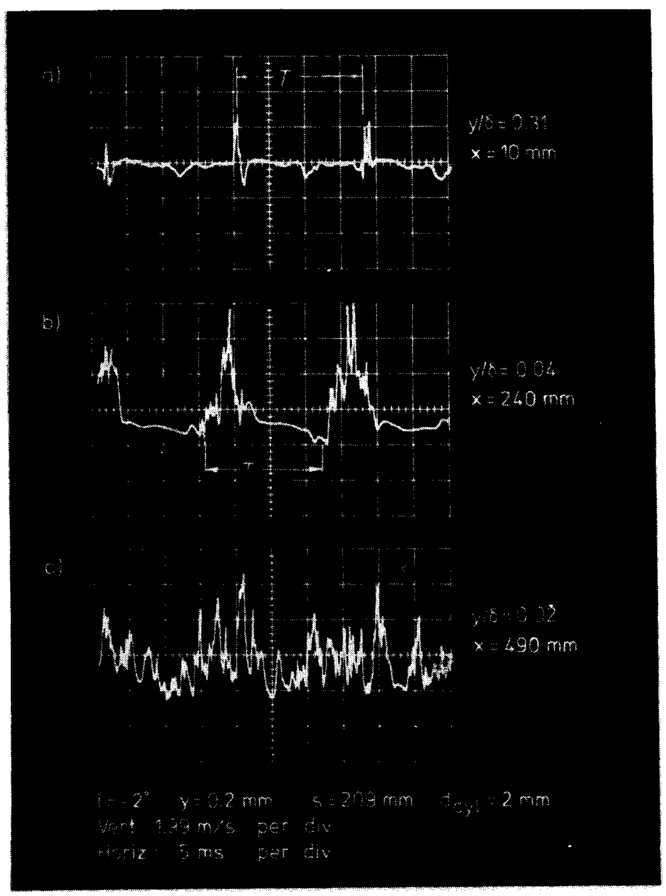

Fig. 12 Oscilloscope traces of the longitudinal velocity fluctuations in the perturbed boundary layer at constant wall distance, recorded at different x-stations

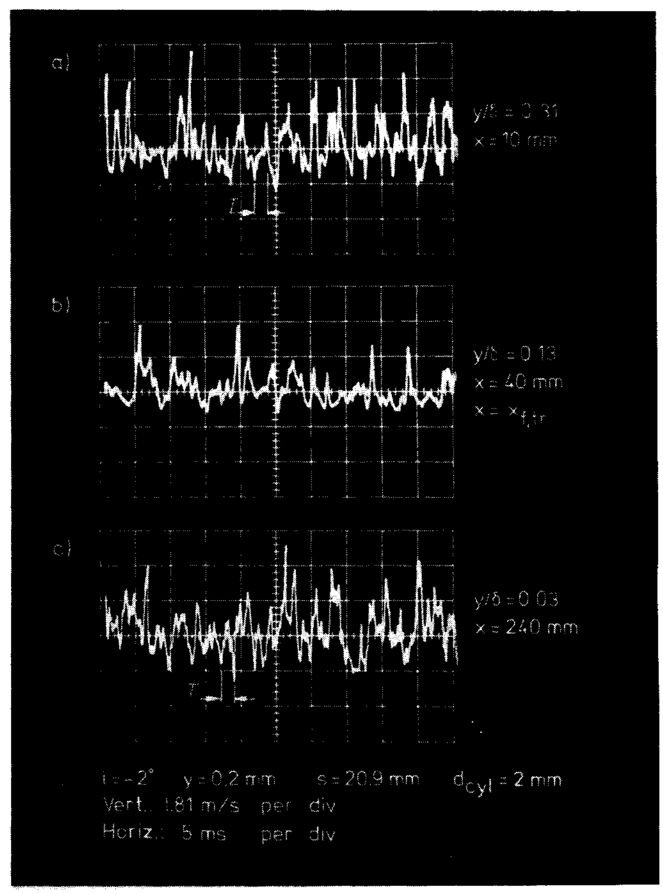

Fig. 13 Oscilloscope traces of the longitudinal velocity fluctuations in the perturbed boundary layer at constant wall distance, recorded at different x-stations

In Fig. 13 the velocity fluctuations in the boundary layer are shown with a cascade spacing of s = 20.9 mm. Due to this critical spacing and to all smaller spacings the wakes have already merged in the afflux. The comparison of the fluctuations where x = 10 mm, Fig. 13a, and x = 40 mm, Fig. 13b, shows that the perturbations, which can no longer be identified in their period are primarily subdued downstream. From x = 40 mm this suppression was no longer to be seen. Therefore the location of the beginning and end of transition was presumed to be in this position. Fig. 5e shows the expected distribution of the turbulent boundary layer δ_{turb}.

Fig. 14 shows the plot of the non-dimensional mean velocity U/U_∞ at various cascade spacings and at constant wall distance.

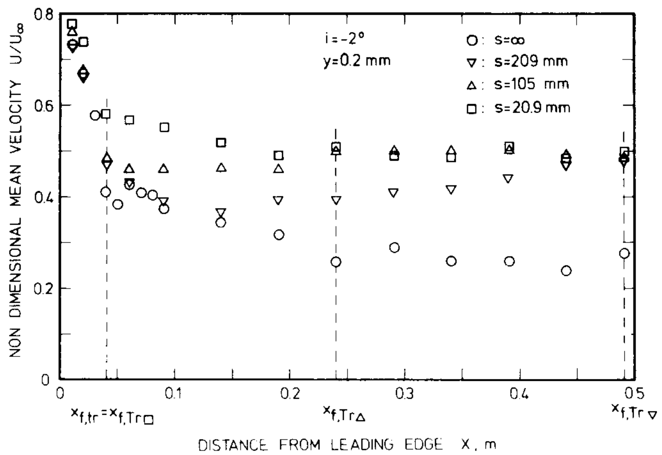

Fig. 14 Distribution of the non-dimensional mean velocity along the plate at constant wall distance and varied cascade spacing

The start of transition can be found at $x_{f,tr}$ = 40 mm for all spacings except for undisturbed afflux (s = ∞). The end of transition, $x_{f,Tr}$, which at s = 20.9 mm is the same as the start of transition, is observed with larger spacing after larger distances from the plate leading edge.

Spot Propagation and Shape

In order to obtain the shape of the turbulent spot and the velocity with which it moves over the plate surface, the running time differences of the spots' leading and trailing edge between two stationary points were measured. The investigations were carried out at an incidence angle of -2° and a spacing of s = 628 mm. This incidence angle was chosen as with favourable pressure gradient no random turbulent spots of the natural transition occurred. The results of the measurements are presented in Fig. 15 as a function of the non-dimensional wall distance y/δ_{turb}. Thus δ_{turb} is the defined boundary layer thickness according to Fig. 5e, which was measured under the chosen test conditions

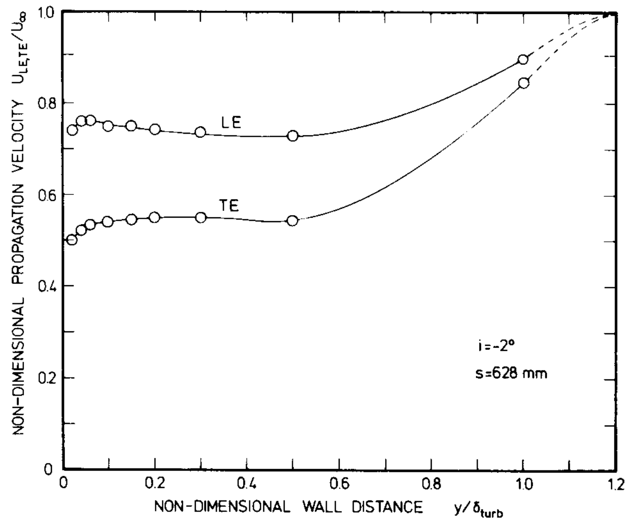

Fig. 15 Spot-velocities at incidence i=-2° as a function of the non-dimensional wall distance

at the critical cascade spacing s = 20.9 mm. As is seen from other authors' measurements, Table 1, which produced the turbulent spots in another way, a relation is determined between the external velocity U_∞ and the velocity of the leading and trailing edge of the spot. Whereas the velocity of the trailing edge agrees with the other results, the measured leading edge velocity deviates to smaller values.

Authors	U_{LE}	U_{TE}	Flow Conditions
Schubauer & Klebanoff [17]	0.88 U_∞	0.5 U_∞	flat plate, spark
Wygnanski, Sokolov & Friedman [18]	0.89 U_∞	0.5 U_∞	flat plate, spark
Obremski & Fejer [7]	0.88 U_∞	0.58 U_∞	flat plate, oscillating external flow
Houdeville, Cousteix & Desopper [19]	0.89 U_∞	0.48 U_∞	flat plate, oscillating external flow
Present results	0.75 U_∞	0.54 U_∞	favourable pressure gradient, i=-2°, wakes

Table 1 Comparison of measured spot-velocities

Fig. 16 represents the shape of the turbulent spots and its change along the plate. The deformation of the turbulent region can be clearly recognized, which particularly close to the wall remains notably behind the wake in the outer flow. The curve of the undisturbed laminar boundary layer δ_{lam} was

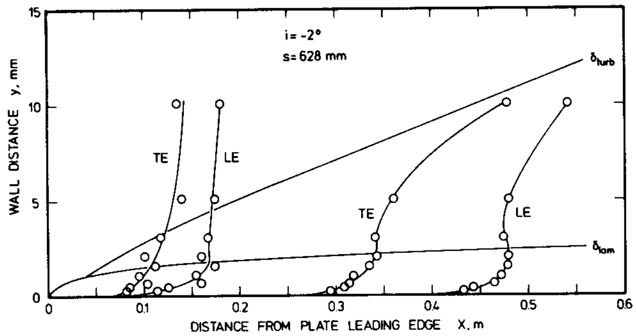

Fig. 16 Development of the turbulent spot along the plate at incidence i=-2°

additionally drawn in the graph. As the laminar boundary layer which surrounds the spot has a subduing influence, the spot has its maximum width in the distance δ_{lam}. At the edge of the boundary layer the turbulent spot must change into the wake of the moving cylinder. This means that the spot velocity, as indicated in Fig. 15, also changes into the velocity of the external flow.

CONCLUSION

The boundary layer transition under instationary afflux conditions is investigated in this paper. In contrast to investigations by other authors [6, 7, 9], who researched the sole influence of the oscillating basic flow, an unsteady flow, as it occurs in the stages of turbomachines, is realised here by a moving cylinder cascade in front of a plate.

A model which describes the transition under these flow conditions is introduced with the aid of time-space distributions of the turbulent spots, Fig. 4, and schematic drawings of the instantaneous boundary layer thicknesses, Fig. 5. The spacing of the cascade in relation to the plate length represents an important parameter for the start and end of the transition. The cascade wakes force the onset of transition after a shorter flow distance than by undisturbed flow. The spacing of the cascade exerts no influence on the position of the forced start of transition. The end of forced transition does not depend on the end of natural transition and can occur due to the spacing downstream or upstream of the end or even upstream of the start of natural transition.

Measurements of the boundary layer transition taken by zero and favourable pressure gradient are referred to in order to confirm the model. Furthermore measurements of the shape and propagation of the turbulent spots in the disturbed boundary layer are introduced.

With the investigations so far carried out it could not be ascertained definitely if the stochastic fluctuations in the wake are responsible for transition. The influence on transition of the periodic fluctuations in the wake also cannot be excluded, as they produce periodic fluctuations of the static pressure on the plate surface. Subsequent investigations shall contribute to a further clarification.

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