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Characteristic Fields of the Natural Transitional Boundary Layer on the Flat Plate[1]

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1. Introduction

To design flow systems permitting to transform in the shortest way kinetic flow energy into pressure energy at a low loss rate a sufficiently exact calculation of the boundary layer before the diffuser start is generally necessary. This is especially true for such flat blade profiles which, assuming a nominal state, show over a wide range at their suction side a constant velocity and thus a transitional boundary layer, see M. Hackeschmidt (1979) and M. Rößler (1983) [6], [19]. In most cases the turbulence observed in the cascade channel is relatively high. In order to obtain under these conditions a separation-free flow within the outflow space of the cascade channel, the blade cascade has been designed up to now in such a way that the separation criteria, recommended for turbulent boundary layers, were taken as upper bound values. From this follows that the permissible design limit is unknown up to now. This unsatisfactory situation made it necessary to develop calculation methods for transitional bounary layer.

Since the detection of coherent structures in turbulent boundary layers by S. J. Kline in 1967 [14] a thorough investigation of existing flow phenomena began so that the findings known up to now permit already a sufficiently exact calculation of transitional boundary layers. The question was to tackle the following problems:

(i) Determination of free stream turbulence level dependence of the Reynolds number for start and end of laminar-turbulent transition on the flat plate in case of zero pressure gradient.

(ii) Turbulence anisotropy influence of free stream and pressure gradient on start and end of transitional region.

To verify the developed characteristic fields describing the laminar-turbulent transition measuring results of R. Herbst (1980) [11] were taken obtained in case of intermittent inflow of flat plates with pressure gradient by means of the sample method.

For the future it will be necessary to illuminate the flow mechanism leading to the formation of turbulence spots so that it will be possible to formulate hypotheses of its structure which are experimentally founded and then to develop and test mathematical models. W. Albring (1981) [2] and M. T. Landahl (1975 and 1980) [15], [16], for instance, point out promising ways.

2. The start of transition in case of zero pressure gradient

Measuring results of transition starting on the flat plate, positioned in the longitudinal flow direction, obtained by different methods, i. e. hot wire anemometry, heat transfer measurement and soot-oil-petroleum erosion, differ so much that they cover approximately half of the whole transitional region (see M. Hackeschmidt 1982 and 1984) [7], [10]. This applies above all to free stream turbulence level values of 2 % and more. Therefore experimental and theoretical investigations of the flow structure near the wall leading to the formation of turbulence spots have been carried out especially in this incidence area (see M. Rößler 1983 [19] and M. Hackeschmidt 1983 [8]). A result of these investigations is shown in Fig. 1 demonstrating the local skin friction coefficient, i. e. the wall shear stress relating to the dynamic pressure of the undisturbed free stream depending on the streamwise length Reynolds number with the intermittency factor γ as parameter in the transitional boundary layer region. Here we have a mean statistical course obtained according to the measuring results which may be approximated by means of a distribution law passing over the Gaussian distribution in case of turbulence level values less than 0.1 % (see Hackschmidt 1984 [9]). In the present case the free stream turbulence level measured by means of a hot wire anemometer amounts to 4.6 % on the leading edge and is reduced to about 2 % at the end of the transitional region.

The lower part of Fig. 1 gives an insight into the structure of the transitional boundary layer near the wall. It refers to a soot-oil-petroleum erosion, i. e. the bright separation phenomena caused by turbulence spots which can be seen at the right side and in the middle of the figure result from different times of formation and consequently they cannot be a spanwise measure of the intermittency factor. In the first half of the transitional region this factor is very small (see Fig. 1 above).

Above all the matter was

(i) to make a statement on the magnitude of streaks (left side of figure) observed in the unstable laminar boundary layer in front of and immediately after the transition start and

(ii) to fix the transition start as the status nascendi of turbulence spots, i. e. to detect the location ÜA after which first unsteady fluctuations occur.

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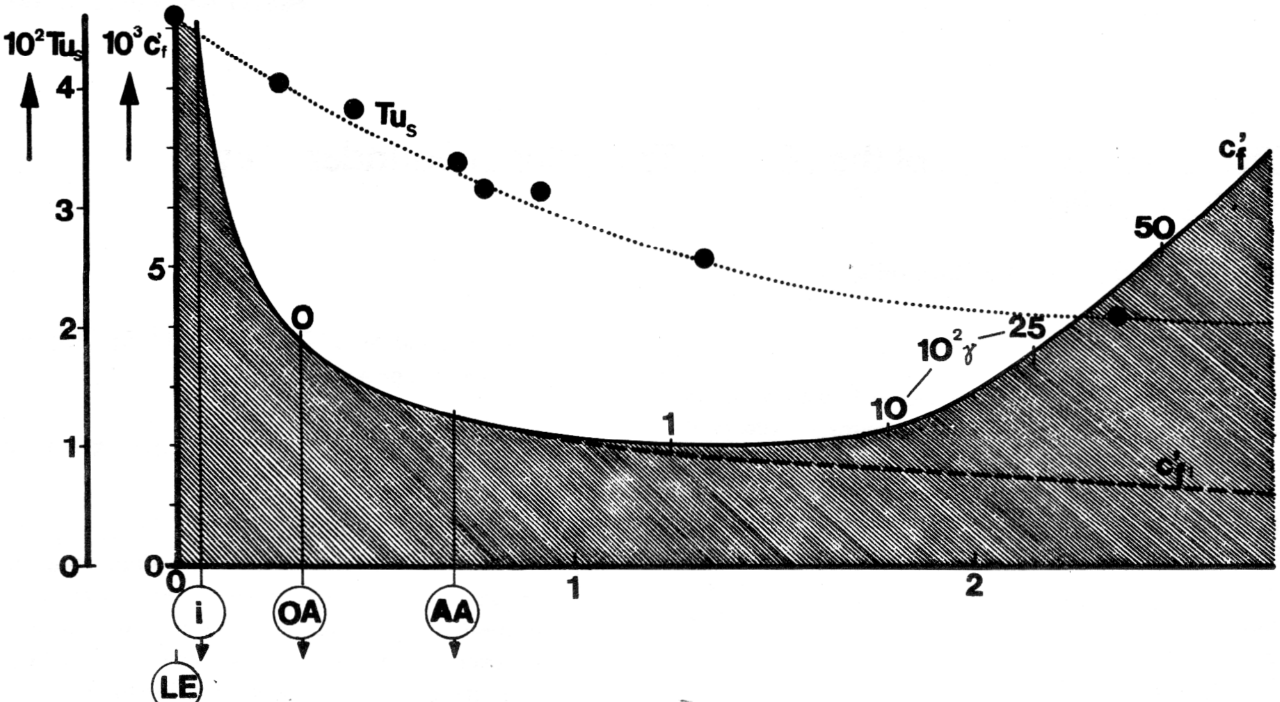


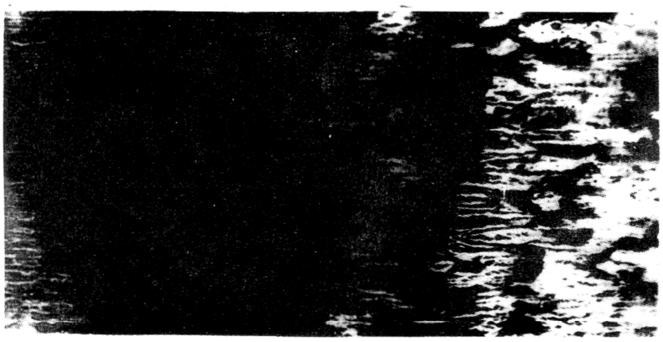


Figure 1 above.
Relationship between local skin friction coefficient c'_f and streamwise length Reynolds number Re_s with intermittency factor γ as parameter on the flat plate for high isotropic free stream turbulence and zero pressure gradient.

LE	**leading edge**	**AA**	**start of spot prints**
ÜA	**start of transition**	**i**	**start of the streaks**

Figure 1 below.
Use of soot-oil-pretroleum erosion to show the streaks (left) in the unstable laminar boundary layer and the turbulent spots (centre of picture and right) in the first half of transitional boundary layer region.

$$Tu_s = \frac{\sqrt{\overline{u'^2}}}{u_\delta}, \quad Re_s = \frac{u_\delta}{\nu} \cdot \quad c'_{fl} = 2\,\frac{d\,\delta_2}{ds}$$

$$c'_{fl} = 0.66412\ Re_s^{-1/2}, \quad c'_{ft} = 0.1\,(Re_s - Re_{s\ddot{U}A})^{-1/5}$$

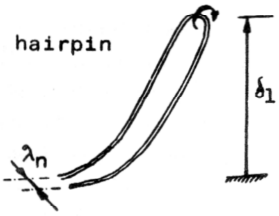
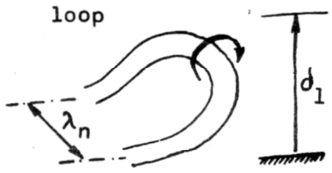
$$c'_f = c'_{fl} + \gamma\,(c'_{ft} - c'_{fl}). \quad \gamma = 1 - \exp\,(-5\,\eta^9)$$

$$\eta = (Re_s \cdot Re_{s\ddot{U}A})/(Re_{s\ddot{U}E} - Re_{s\ddot{U}A})$$

In case of a relatively high free stream turbulence, streaks are formed after a short streamwise length at point (i) of the longitudinal coordinate towards the leading edge of the plate, in this case at $Re_{si} = 5.3 \cdot 10^3$ valid for a local turbulence level of $Tu_s = 4.5\ \%$. At the point ÜA the reciprocal distance of these streaks relating to the boundary layer thickness δ_1 according to Blasius-Howarth differs from the approximate value $\lambda_n/\delta_l = 1$ to become 1.3, see table 1. From this follows that in case of high free stream turbulence the secondary flows in the unstable laminar boundary layer cover the whole boundary layer between the longitudinal coordinate points (i) and ÜA, whereas in case of no and very poor free stream turbulence these secondary flows only cover 1 to 2 % of the boundary layer thickness (see J. T. Stuart, 1980 [20]).

Another hint at this is, according to M. Hackeschmidt (1983) [8], the relative wall distance of 1.6 % in which the one disturbing wave is located which removes the greatest amount of energy from its surrounding and causes the burst of the longitudinal vortex formation near the wall. In case of self-excitation in the laminar boundary layer these vortices take a hairpin shape. In case of foreign excitation they can only form loops because as has been said just now, the longitudinal vortices already occupy the whole boundary layer. In areas of mixed excitation, i. e. in case of free stream turbulence levels of 1 % to 0.1 % and turbulence levels becoming lower and lower, the shape of rising longitudinal vortex pairs changes from the loop to a horseshoe and finally to a hairpin.

Table 1. Characteristic differences of formation of longitudinal vortex systems near the wall at start of transition.

Kind of excitation:	self-excitation	foreign excitation
$10^2\ Tu_s$	< 0.1	> 1
λ_n/δ_1	≈ 0.016	≈ 1 before ÜA ≈ 1.3 after ÜA
$Re_{sÜA}$	= $2.82\cdot10^6$	= $177.1(kTu)^{-1.606}$
Effect of Reynolds number on features of longitudinal vortex pairs at start of transition	hairpin 	loop 

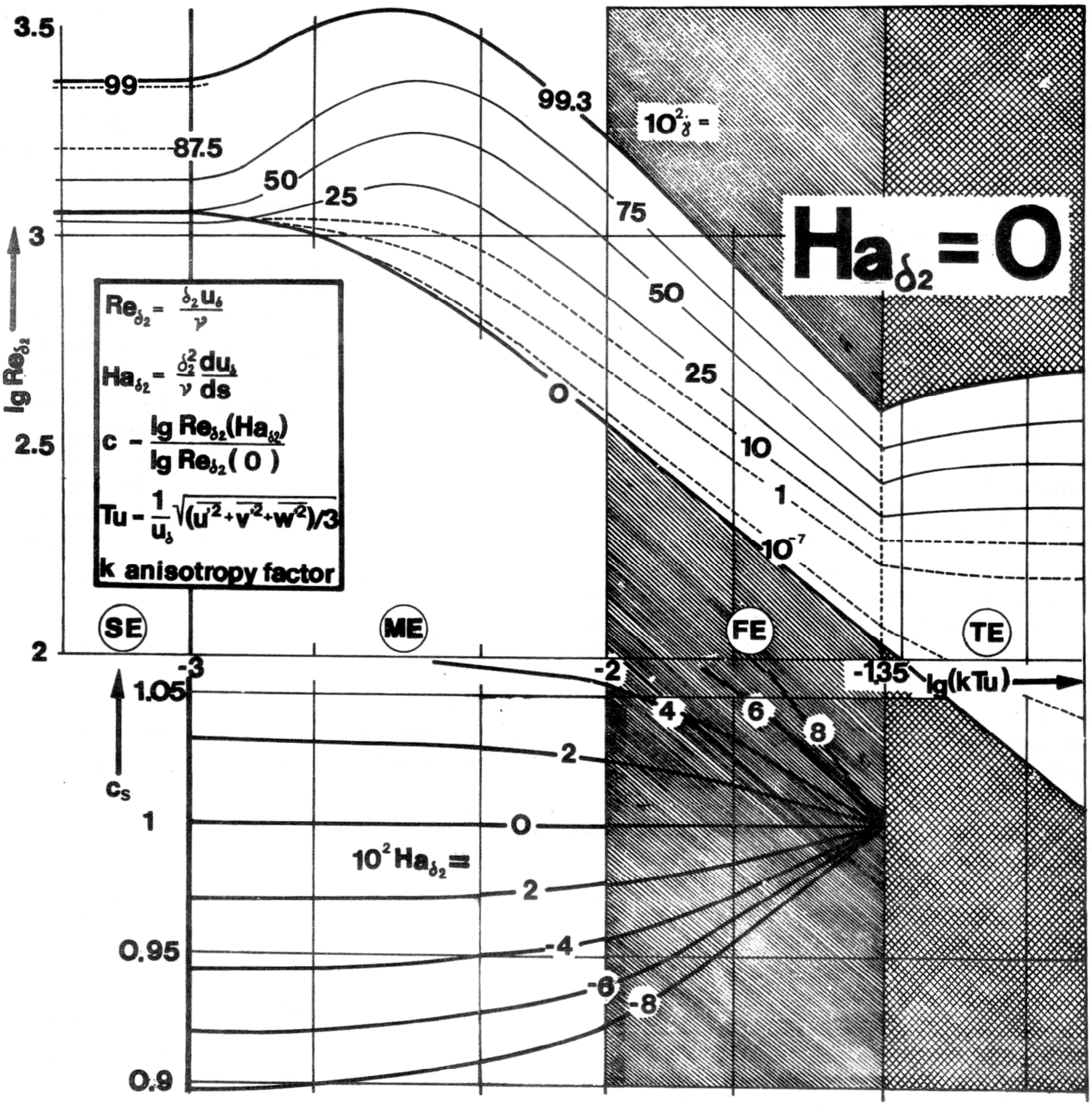


Figure 2 above.
Relationship between momentum thickness Reynolds number and free stream turbulence level for transitional boundary layer in zero pressure gradient with the intermittency factor as parameter.

Figure 2 below.
Effect of pressure gradient for an intermittency factor of 5 %

SE region of self-excitation
ME region of mixed excitation
FE region of foreign excitation
TE turbulence energy in the free stream is greater than or equal to the maximum of turbulence energy in the boundary layer

anisotropy factor: $k = \sqrt{3/(1 + (\overline{v'^2} + \overline{w'^2})/\overline{u'^2})}$

momentum thickness factor: $k_{2t} = \delta_{2t}(0)/\delta_{2t}(k\,Tu)$

The shape of the vortex pairs bursting the layer near the wall depends on the type of excitation, i. e. whether the transition start in case of very low free stream turbulence is induced by self-excitation ($Re_{s\ddot{U}A}$ is relatively large) or in case of high free stream turbulence by foreign excitation ($Re_{s\ddot{U}A}$ is relatively small), see Table 1.

The structural phenomena of fully developed turbulent boundary layers as described by M. R. Head and P. Bandyopadhyay (1981) [21] may in a certain sense be also applied to the status nascendi of turbulence spots, i. e. to the start of transition.

As may be seen in Fig. 1 below there are still other vortex pairs remaining within the immediate wall area, also after the longitudinal coordinate point ÜA. Their burst seems to take place stochastically. The last longitudinal vortex pairs rise when the first ones, i. e. those breaking out in the longitudinal coordinate point ÜA and forming a turbulence spot, have already left their print on the wall: AA in Fig. 1.

Due to the fact that unsteady fluctuation movements occur as soon as the fluid near the wall bursts for the first time in the direction of the boundary layer edge the transition start is fixed although it is not possible to note a marked deviation of the skin friction coefficient behaviour because of the infinitely small intermittency factor, see Fig. 1 above. Exact evaluations of heat transfer measurements carried out by J. Kestin, P. F. Maeder and H. E. Wang (1961) [12] showed, however, that the transition start ÜA may clearly be fixed in the foreign excitation region (see Hackeschmidt, 1982 [7]). The result of this paper is shown in Fig. 2 above by a curve of the transition start at $\gamma = 0$.

3. Transition end of flow in case of zero pressure gradient

At the transition region end the local skin friction coefficient represents a relative maximum (see Fig. 1) so that its determination is comparatively easy. The two following features should be noted:

3.1. The external turbulence deforms the boundary layer velocity profile in such a way that displacement and momentum thicknesses compared with the external turbulence-free state become greater. In the turbulence level region FE (foreign excitation region) the momentum thickness factor is $1/k_{2t} = 1/0.68$, i. e. 1.47 (see Fig. 2, bottom). In the turbulence level region ME of mixed excitation the factor depends on the turbulence level and in region SE of self excitation is equals l according to definition (see Hackeschmidt, 1984, [10]). The corresponding numerical value of displacement thickness in region FE is 1/0.75 = 1.34.

3.2. In case of free stream turbulence level values less than about 4.5 % the maximum turbulence level value in the boundary layer preponderates over that of external turbulence. In case of free stream turbulence levels greater than about 4.5 % the relations are inverted, i. e. within the boundary layer the turbulence is smaller than outside. Hence there is a state of turbulence energy homogeneity dividing the foreign excitation turbulence level region of the transition end according to the diagram in Fig. 2 above in two subareas, i. e. the actual region FE in which the Reynolds number of the transition end depends on the free stream turbulence level and the region TE being independent of the turbulence level due to $Re_{\ddot{U}E} = 9.75 \cdot 10^4$ (see Fig. 2). Accordingly the relative and absolute streamwise transition length relationship were obtained and listed in table 2.

At the transition end the intermittency factor is $\gamma = 0.993$ to 1. For this factor $\gamma = (\overline{F} - F_1)/(\overline{F}_t - F_1)$ is true where F represents the following shape parameters of the transitional boundary layer: displacement thickness, momentum thickness, local skin friction coeffi-

Table 2. Relative length of the transitional region on the flat plate for zero pressure gradient.

Region of	k Tu	$(s_{\ddot{U}E} - s_{\ddot{U}A})/s_{\ddot{U}A}$	$Re_{s\ddot{U}E} - Re_{s\ddot{U}A}$
SE self-excitation	<0.1 %	0.374	$1.072 \cdot 10^6$
ME mixed excitation	0.1 %...	$8.41(kTu)^{0.262} - 1$	
FE foreign excitation	4.45%		
turbulence energy homogeneity	= 4.45 %	2.721	$0.92 \cdot 10^5$
TE	>4.45 %	$550.53(kTu)^{1.606} - 1$	

cient and others, where the subscript t applies to the turbulence spot region and the subscript 1 to the laminar flow surrounding.

4. Turbulence anisotropy and pressure gradient

When entering the test results in the field of characteristics demonstrating the laminar-turbulent transition in case of zero pressure gradient (Fig. 2 above) attention should be paid to two incidences, i. e. external turbulence anisotropy and pressure gradient. In most experimental cases neither turbulence isotropy nor flowing states with zero pressure gradient prevail so that the measuring values must be adjusted to be able to make sufficiently exact statements of the transition region start and end in case of zero pressure gradient.

4.1. The transition field of characteristics shown in Fig. 2 above is due to measuring results made on the flat plate with zero pressure gradient and to considerations of similarity theory and strictly there is only isotropic free stream turbulence (produced by screens). In case of external turbulence not excessively anisotropic, i. e. nearly isotropic, this field of characteristics may, however, also be applied if the product of turbulence energy level Tu and an anisotropy factor k is used as a independent quantity instead of the turbulence level which only regards to the longitudinal fluctuation component (see Hackeschmidt, 1984, [9]). Although this product corresponds formally to the usual turbulence level, i. e. that which is only formed by means of the longitudinal fluctuation component, the factor k gives a practicable measure of accuracy which must be reckoned with if this transition field of characteristics is applied to anisotropic external turbulence.

4.2. As similarity number describing the pressure force-to-viscous-force ratio within the fluid, the Hagen number $Ha_{\delta 2}$ introduced 1961 by W. Albring must be taken. Relatively reliable measuring results regarding this Hagen number influence may be obtained for region SE of the low-turbulence free stream (see Fig. 2 bottom left). As dependent quantity the exponent c appears by which the momentum thickness Reynolds number of a flow without zero pressure gradient may be reduced to that number describing a flow state with zero pressure gradient.

Furthermore, the relevant test results suggest that in region TE in which the turbulence of the boundary layer is less than that of the free stream the pressure gradient is of no influence. In case of the equivalent turbulence level k Tu = 4.45% the field of characteristics of the exponent c has a pole. The asymptotes of the lines $Ha_{\delta 2}$ = const in this pole and in region SE intersect approximately at the boundary of turbulence level regions ME and FE, i. e. in case of an equivalent turbulence level of about k Tu = 1 %. The field of characteristics shown in Fig. 2 was plotted on the basis of measuring results gained by means of an intermittency factor of $\gamma = 5$ % (index S) (see Hackeschmidt 1984 [10]), i. e. according to Fig. 1 this field is approximately true for the transition region centre. With increasing intermittency factor the expression /c-1/ becomes smaller. At the transition end the exponent c is less than $c_S = c\ (\gamma = 5\ \%)$ by about a power of ten so that by way of approximation the relative difference may be set $(c - c_{ÜA})/(c_{ÜE} - c_{ÜA}) := \gamma$ with $c_{ÜE} \approx 1$.

5. Verification by means of sample technique

For reliability tests of the characteristic transition start line shown in Fig. 2 measuring results of R. Herbst (1980) were taken obtained on the flat plate by means of the sample technique independently of the tests made by R. Rößler (1980 to 1983) (Fig. 1 below). In this respect the averaging technique of variable interval times (VITA technique, i. e. variable-intervall-time-averaging technique) according to R. F. Blackwelder and R. E. Kaplan (1976) may be compared. With reference to the unsteady flow into cascade direction located in multi-stage flow machines R. Herbst generated, by means of a spoked roll, an unsteady flow into the direction of the flat plate having different pressure gradients (the angles being between -2° and -10°) so that accelerated transitional boundary layers were able to form. In our case the wakes behind the 90 spokes of the fluctuation generator are of interest having already grown together at the transition start so that there was a continuous turbulence field in the free stream.

The Hagen number varied from $Ha_{\delta 2} = 0.01$ to 0.03, the momentum thickness Reynolds number at the transition start from $Re_{\delta 2}\ (Ha_{\delta 2}) = 110$ to 150 and the free stream turbulence level was $Tu_s = 3$ to 4 % (see Appendix 1). This turbulence level $Tu_s = \sqrt{u'^2}/u_\delta$ only covers the fluctuation velocity u' which seems to vary irregularly.

After revaluation of the momentum thickness Reynolds number to get the flow state of zero pressure gradient $Re_{\delta 2}\ (0)$ equals 107 to 140 according to the field of characteristics shown in Fig. 2 and the free stream turbulence levels at $Tu_s\ (0)$ amount to 5.8 % to 4.1 %. In the field of characteristics the three values determined in this way nearly lie on a line of constant intermittency factor which on its part is very small. By means of the sample technique it is not possible to find the transition start ÜA with an intermittency factor $\gamma = 0$ exactly, but obviously it is possible if the value is rather small.

Although the external turbulence, according to A. C. Ginevski et al. (1979), tends to show isotropy already after a shorter streamwise length behind non-stationary cylindrical bars compared with the same bars in a stationary state an eventual turbulence anisotropy at the transition start should not be excluded (see Hackeschmidt 1984 [9] and Appendix 2).

6. Conclusions an prospects

As a result of these investigations the following conclusions may be drawn:

1. The Transition fields of characteristics shown in Fig. 2 apply to isotropic and nearly isotropic free stream turbulences.
2. As nearly isotropic turbulence both an anisotropic turbulence in a steady free stream and in an intermit-

tent-unsteady free stream may be taken in case of a coherent turbulence field.

3. As a measure of nearly isotropic turbulence the anisotropy factor k is suitable.
4. In case of distinct anisotropic free stream turbulence anisotropy ratios of each of the three coordinate directions (see F. Klatt, 1976 [13]) must be introduced as independent quantity instead of the anisotropy factor k.
5. In case of intermittent non-stationary free stream the relative amplitude of velocity change Δu_δ and the Strouhal number of periodically arranged wakes must be introduced as further influential parameters. According to H. H. Obremski & A. A. Fejer (1967) [17] there is a critical non-steady number value $(\Delta u_\delta\, u_\delta)/(\omega\, \gamma)$ of amplitude and frequency relationships below which no relationship of such a kind exists and turbulent spots are formed in a aperiodic way. Above this number turbulence spots are formed periodically with the free stream frequency; but the Reynolds number $Re_{\delta\ddot{U}A}$ describing the transition start is not dependent on the Strouhal number but only on the relative amplitude of velocity change $\Delta u_\delta/\bar{u}_\delta$.

Summary

For the development of a method to calculate transitional boundary layers various measuring results served to design fields of characteristics of the laminar-turbulent transition on the flat plate with/without pressure gradient. These fields were obtained by means of hot wire anemometry, heat transfer measurements and according to the soot-oil-petroleum erosion method and similarity-theoretical considerations.

Accordingly the transition start ÜA may be determined as a location where the first longitudinal vortex pairs near the wall separate (see Fig. 1). The last longitudinal vortex pairs only separate from the wall after the first turbulence spots have already left their prints on the wall. The dimensions of these longitudinal vortex pairs formed in the unstable laminar boundary layer are dependent on the type of excitation (see table 1). Accordingly different turbulence level regions may be differentiated in the fields of transition characteristics (see Fig. 2):

(1) In region SE of turbulence level, transition is exclusicely initiated by self-excitation in the unstable laminar boundary layer,

(ii) while in region FE it is initiated by external flow turbulence (foreign excitation).

(iii) Region ME is considered to be a transition region.

(iv) In region TE external flow turbulence is greater than that of the boundary layer and there is no pressure gradient influence. In this region one has to reckon with a distinct influence anisotropy so that here further influential parameters will be required in addition to the factor of anisotropy k.

In the course of growing free stream turbulence level the absolute length of the transition region becomes smaller, but its relative length increases (see Table 2).

The start of transition is defined by the intermittency factor $\gamma = 0$. Presupposing foreign excitation and a Reynolds number also increasing this factor will increase at the beginning, i. e. when bursting vortex loops are formed, only in a very slight manner. As is generally known it is only in the middle of the transition region that it increases rapidly (see Fig. 1). In case of foreign excitation, however, the development of the intermittency factor is balanced due to hairpin vortex formation.

The intermittency factor appears as parameter between the lines ÜA and ÜE in figure 1 being dependent on the momentum thickness Reynolds number. It may be written in the standardized form as follows: $\gamma = (\overline{F} - F_1)/(\overline{F}_t - F_1)$ where F are the following shape factors of the transtional boundary layer: displacement thickness, momentum thickness or local skin friction coefficient (relative wall shear stress). In this formula the changed turbulent velocity profile shape, resulting from the external flow turbulence in the region where turbulent spots are observed, is taken into account by means of the coefficients k_1 and k_2 being themselves dependent, in the turbulence region of mixed excitation (ME), on the momentum thickness Reynolds number. The pressure gradient influence may be shown separately (see Fig. 2 below). As dependent quantity the exponent c appears by which the momentum thickness Reynolds number may be reduced, in case of a flow of nonzero pressure gradient, to that which represents the flow state of zero pressure gradient. For the latter the correlation $\gamma \approx (c - c_{\ddot{U}A})/(1 - c_{\ddot{U}A})$ was found.

For all correlations there are heuristic formulae serving as a basis of electronic data processing programs. The calculation technique for transitional boundary layers is designed in such a way that it may be easily modified by using the latest pertinent findings, as for instance heat transfer, Mach number, wall roughness incidences.

APPENDIX 1:

Revaluation of field data of transition characteristics with regard to pressure gradient.

The data of transition start on the flat plate with different pressure gradient given by R. Herbst are stated in the columns 1 and 2 of Table 3. For a revaluation to get a flow state with zero pressure gradient the 4 equations are taken shown in this table. Equation (4) is only true for the turbulence level region of foreign excitation. The free stream turbulence level values obtained for the flow state of zero pressure gradient (0) listed in column 8 of Table 3 are taken to plot the dotted line in Fig. 3. This line seems to be a rather probable extrapolation of the measured values of R. Herbst from $Ha_{\delta 2} > 0$ to $= 0$.

APPENDIX 2:

The anisotropy factor k behind non-stationary and stationary round bar cascades

The change of the turbulence level and of the anisotropy factor k in the wake depends very much on the type of turbulence generator. If round bar cascades are taken there are two excellent values of the relative streamwise length $(s/t)_T$, being marked by (H) and (I) in Fig. 4. In line 1 of Table 4 these values indicate the ranges of validity concerning the inherent laws of turbulence level re-

Table 3. Revaluation of transition start data given by R.Herbst in case of accelerated flow ($Ha_{\delta_2} > 0$) to get state values of zero pressure gradient ($Ha_{\delta_2}=0$).

$\lambda \equiv Ha_{\delta_2}$	Re_{δ_2}	c_S	$c_{ÜA}$	$Re_{\delta_2}(0)$	$10^{-4}Re_s$	10^2Tu_{s*}	$10^2kTu(0)$
1	2	3	4	5	6	7	8
0.01	110	1.005	1.005	107	1.734	4.1	5.8
0.027	130	1.012	1.013	122	2.252		4.6
0.03	150	1.013	1.014	140	2.957	3.0	4.1
R.Herbst		Fig.2	eq.(1)	eq.(2)	eq.(3)	R.Herbst	eq.(4)

(1) $c_{ÜA} = 1.05(c_S - 0.05c_S^{-1})$

(2) $c = \lg Re_{\delta_2}(Ha_{\delta_2})/\lg Re_{\delta_2}(0)$

(3) $Re_{\delta_2} = 0.66412\sqrt{Re_s}$

(4) $Re_{sÜA}\Big|_{FE,TE} = 177.1(kTu)^{-1.606}$

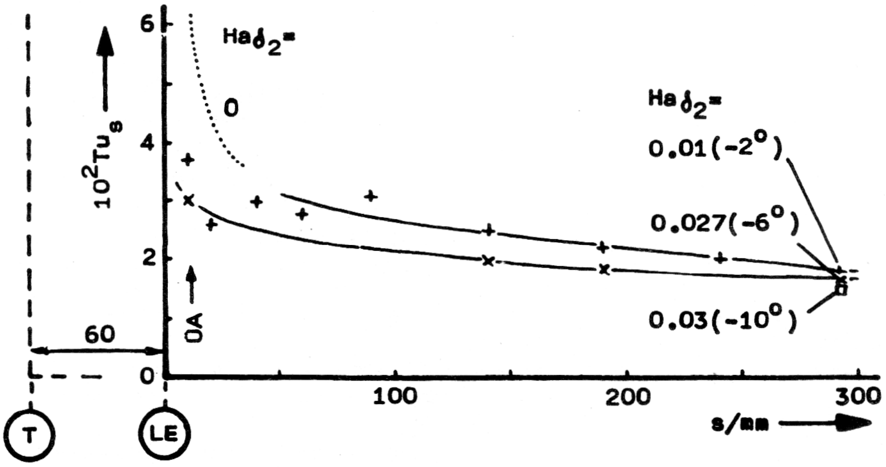


Figure 3.
Turbulence level above the flat plate with pressure gradient behind a fluctuation generator T in the form of a wheel having a pitch diameter of 0.6 m on which 90 nylon strings of 2 mm in diameter are arranged according to R. Herbst (rotational frequency: 400 min^{-1}).
Hagen number as parameter (in parantheses the plate angle with pressure gradient). LE leading edge of the plate

lationship. According to F. Klatt [13] the point H of the individual stationary round bar cascade separated the region of inhomogeneous turbulence from that of homogeneous turbulence. Behind the nonstationary round bar chain the region of apparently isotropic turbulence k = 1 begins in this point H according to measurements made by A. S. Ginevski et al. [5]. In case of a stationary round bar chain, i. e. if 2 stationary round bar cascades are arranged one after the other, anisotropic turbulence can be observed up to the point (I) at which a changed regularity of the turbulence level relationship may be observed behind the non-stationary round bar chain (see lines 2 and 3 in Table 4). As regards the exponent k_2 the non-stationary round bar chains differ substantielly from the stationary round bar chain, the screen and the individual stationary round bar cascade. For the letter, however, the anisotropy factor k increases degressively with the streamwise length (see Fig. 4). With regard to the inflow conditions found in flow machines the round bar chain device described by W. H. Gibson [4] is representative.

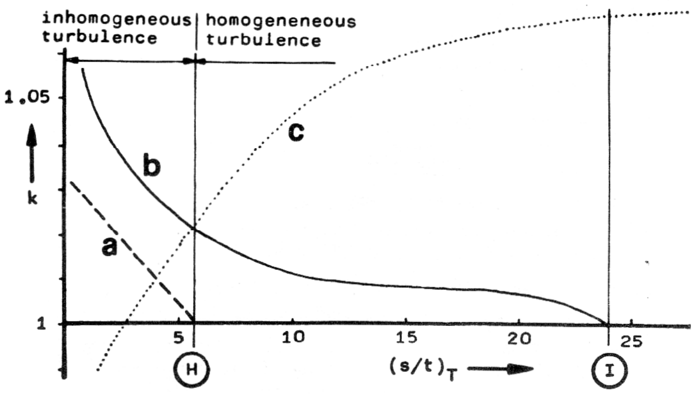


Figure 4.
Correlation between anisotropy factor k and relative streamwise length behind the turbulence generator being an
a) non-stationary round bar chain
b) stationary round bar chain = 2 stationary round bar screens
c) individual stationary round bar cascade

Here the object to be studied is exposed to turbulence behind a single non-stationary round bar cascade so that thinkable interference phenomena of the wakes behind two round bar cascades moving counter-moving are excluded. The spoked wheel used by R. Herbst [11] will presumably approach turbulent conditions of the indi-

Table 4. Correlation between turbulence level and relative streamwise length with its beginning at the turbulence generator (T) representing non-stationary and stationary round bar chains compared with the screen and the individual round bar screen.

1	$Tu_s = k_1(s/t)_T^{-k_2}$		k_1	k_2	according to measuring results made by
2	non-stationary round bar chain	$3<(s/t)_T \leqq 24$	0.269	0.240	A.S.Ginevskij et al.
3		$24 \leqq (s/t)_T$	0.158	0.075	
4	stationary chain = 2 round bar screens one after the other	$3<(s/t)_T \leqq 48$	0.232	0.642	
5	screen		0.3	0.63	
6	1 round bar screen	$5.7<((s/t)_T + 0.9)$	0.42	0.71	F.Klatt

vidual non-stationary round bar cascade, but it does not exclude, either the existence of interference phenomena of low intensity so that here an external turbulence anisotropy up to the point (I) of Fig. 4 should be regarded as probable.

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