From Disturbances to Instabilities, to Breakdown to Turbulence: the Physics of Transition in Boundary Layers

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In order to understand the end-stages of boundary layer transition in low as well as high disturbance environments (including bypass transition) it is desirable to establish a unified view of the sequences of physico-mathematical phenomena that lead from laminar flow to self-sustained "bursting" in wall turbulence. The dominant driving disturbances: oncoming free turbulence, unsteady pressure fields (including sound), inhomogeneous density fields, inhomogeneities in wall geometry (including distributed roughness) etc., all force disturbed motions within the boundary layer via multiple competitive receptivity mechanisms. For small disturbances, a sequence of (often linearizable) instabilities then leads to sporadic local bursting very near the wall which can sustain turbulence. The local seeds of turbulence then somehow propagate (as in case of idealized Emmons' spots) to engulf quite rapidly the surrounding disturbed but still laminar regions. The instability sequences differ with basic parameters and with the nature of internalized ("received") boundary-layer disturbances, thus providing highly non-unique roads to turbulence. There may be fewer modes of the final onset of bursting, the criteria for which are not yet clear.

For larger disturbances (even more non-unique) the instabilities will generally bypass the linearizable primary amplified modes (T.S. waves, steady and unsteady cross flow modes, Goertler modes) and amplify nonlinearly and "inviscidly", roughly starting with the secondary instability phenomena. Special attention is called to "algebraically" growing instabilities, which theoretically can grow from rather small disturbances, but must be "environmentally realizable". The final "bursting" breakdown process is likely to be similar to that for the non-bypass cases. In both small and large disturbance cases, the number of governing parameters is large, ten to twenty or more.

In prediction of transition and in modeling of its end stages, idealization and simplification is unavoidable. The purpose of this lecture is to establish a common vocabulary for the various processes and their dominant mechanisms. Then we should be able to compare various theoretic-empirical methods, both in terms of the success in correlating (limited) data and in terms of the essential physics retained in the idealizations (as a guide to its generality).

END STAGES of TRANSITION

Could be for either LOW-DISTURBANCE ROAD involving HIGHER INSTABILITIES

or BYPASSES with STRONG - (S) / WEAK - (W) DISTURBANCES

DEFINITELY NON-LINEAR (non-superposable, NON-UNIQUE)

∴ information primarily from EXPERIMENTS / Direct Numer. Soln → • PARTICULAR SOLUTIONS

↓

GOVERNED by In. Cond + Bound C.

INCREDIBLY RICH PATTERNS OF BEHAVIOR ←

→ CONCEPTUAL GENERALIZATIONS?

via CLASSIFICATIONS

of distinguishable MECHANISMS

of functional CLASSES of DISTURBANCES

$\underbrace{\text{I.C. and B.C.}}$

$\boxed{\text{PRIMARY PARAMETERS}}$

(NON LINEARITY → • CHANGES IN THE BASE FLOW)

• THRESHOLDS

↓

AMPLITUDE - DEPENDENT CHANGES OF FIELDS on the ROADS to TURBULENCE

↓

FOR APPLICATIONS SIMPLIFICATIONS AND IDEALIZATIONS ARE UNAVOIDABLE

CONSISTENCY OF "PHYSICS" "GUARDIAN" of Reliability and Concept generality

illustration: role of EMMONS' SPOTS in highly disturbed environments

illustration:

FINAL BREAKDOWN / Initiation of self-sustained BURSTING → IS LOCAL, SPORADIC, probably caused by EXTREMA of DISTURBANCES

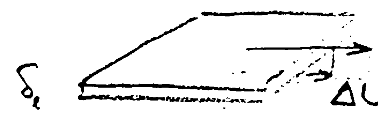
CAN IT BE CORRELADED BY A SINGLE AVERAGE MEASURE : % Tu ?

(S1)

SYSTEMS APPROACH TO

TRANSITION

from



Thin, finite δ_{lam} SLABS or SHEATHS

with LAMINAR VORTICITY $\vec{\Omega}(Y)$ DISTRIBUTION

at lower $Re \sim \frac{\Delta U_\infty \delta_\ell}{\nu}$ QUASI-2D, QUASI STEADY

streamwise L_x
spanwise L_y $\gg \delta_{lam}$

BL's (MIXING L's, JETS, WAKES, etc

SUBJECTED TO ENVIRONMENTAL

weak $|\Delta \vec{v}| \ll \Delta U_\infty$ Free-stream AND Boundary

NONHOMOGENEITIES
in x, z, t

disturbances with characteristic longer scales and times
(except for ROUGHNESS)

INEVITABLY
AS $Re \uparrow$

to

SCALE DISCREPANCIES

finite δ_{tu} SLABS or COLUMNS

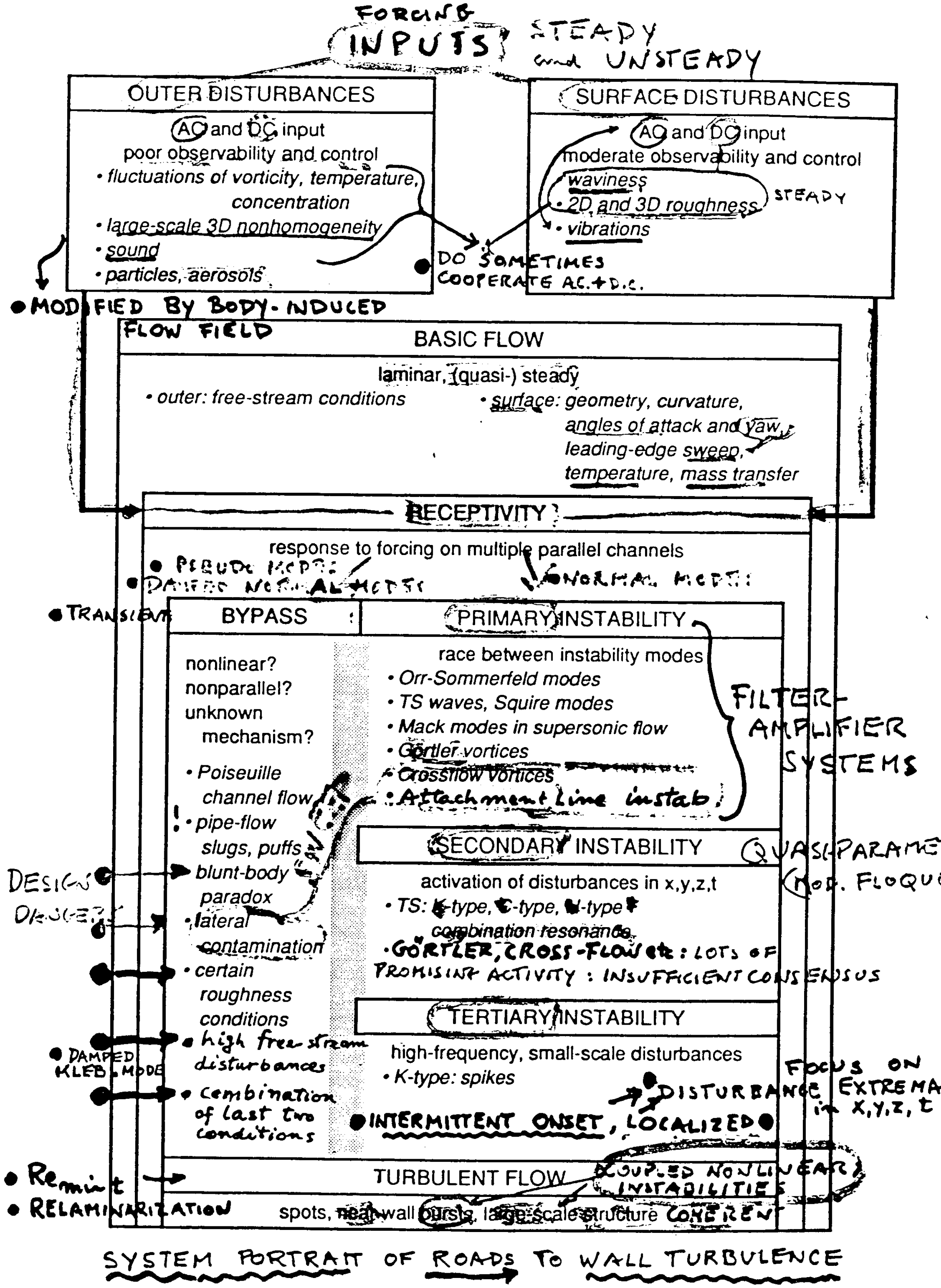
with TURBULENT VORTICITY $\vec{\Omega}(x, Y, z, t)$
DISTRIBUTIONS
with space-time DISORDER (chaos)

(A) with "large coherent eddies" $L_z \sim \delta_{tu}$
$L_x \sim 3\delta_{tu}$

STRONG ω_x role with Z asymmetry

(B) with fine wall-scaled, $\ell^+ \sim 100 \leqslant \delta_{tu}$, NONLINEAR INSTABILITY with a threshold, (Killed in relaminarization!)
referred to as BURSTING for SHORT

See S.K. ROBINSON 1991 Ann. Rev. Fluid Mech. • $Re_{t\,min}$

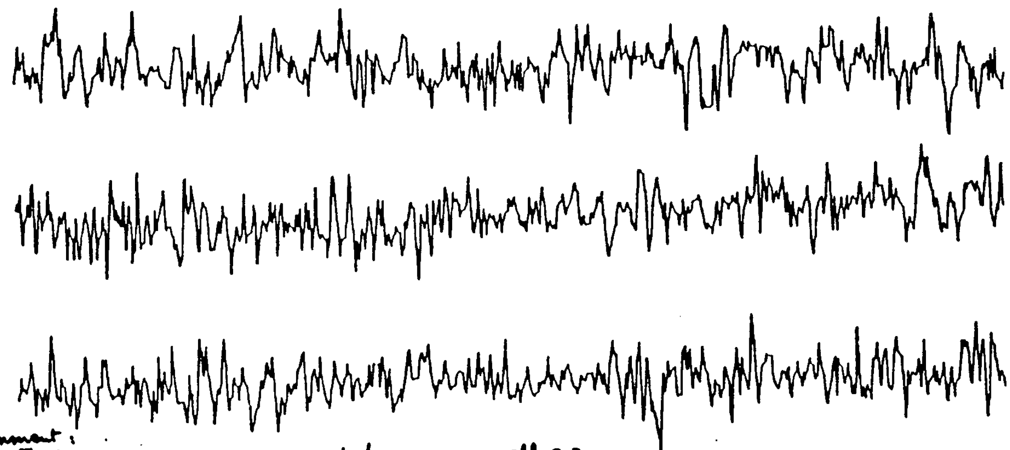

FORCING
INPUTS
STEADY and UNSTEADY
OUTER DISTURBANCES
AC and DC input
poor observability and control
• fluctuations of vorticity, temperature, concentration
• large-scale 3D nonhomogeneity
• sound
• particles, aerosols
SURFACE DISTURBANCES
AC and DC input
moderate observability and control
• waviness
• 2D and 3D roughness
STEADY
• vibrations
DO SOMETIMES COOPERATE AC.+D.C.
• MODIFIED BY BODY-INDUCED FLOW FIELD
BASIC FLOW
laminar, (quasi-) steady
• outer: free-stream conditions
• surface: geometry, curvature, angles of attack and yaw, leading-edge sweep, temperature, mass transfer
RECEPTIVITY
response to forcing on multiple parallel channels
NORMAL MODES
• TRANSIENT
BYPASS
nonlinear?
nonparallel?
unknown mechanism?
• Poiseuille channel flow
• pipe-flow slugs, puffs
• blunt-body paradox
• lateral contamination
• certain roughness conditions
• high free-stream disturbances
• combination of last two conditions
PRIMARY INSTABILITY
race between instability modes
• Orr-Sommerfeld modes
• TS waves, Squire modes
• Mack modes in supersonic flow
• Görtler vortices
• Crossflow vortices
• Attachment line instab.
FILTER-AMPLIFIER SYSTEMS
SECONDARY INSTABILITY
activation of disturbances in x,y,z,t
• TS: K-type, C-type, H-type
combination resonance
• GÖRTLER, CROSS-FLOW etc: LOTS OF PROMISING ACTIVITY: INSUFFICIENT CONSENSUS
DESIGN
TERTIARY INSTABILITY
high-frequency, small-scale disturbances
• K-type: spikes
• DAMPED KLEB. MODE
• INTERMITTENT ONSET, LOCALIZED
DISTURBANCE
FOCUS ON EXTREMA in x,y,z,t
TURBULENT FLOW
COUPLED NONLINEAR INSTABILITIES
spots, near-wall bursts, large-scale structure
COHERENT
• RELAMINARIZATION
SYSTEM PORTRAIT OF ROADS TO WALL TURBULENCE

J. KENDALL '92

FREESTREAM FLUCTUATION RECORDS

Ø.65 SEC DURATION EACH
u'/U_0 = Ø.22 %

STATIONARY INPUT



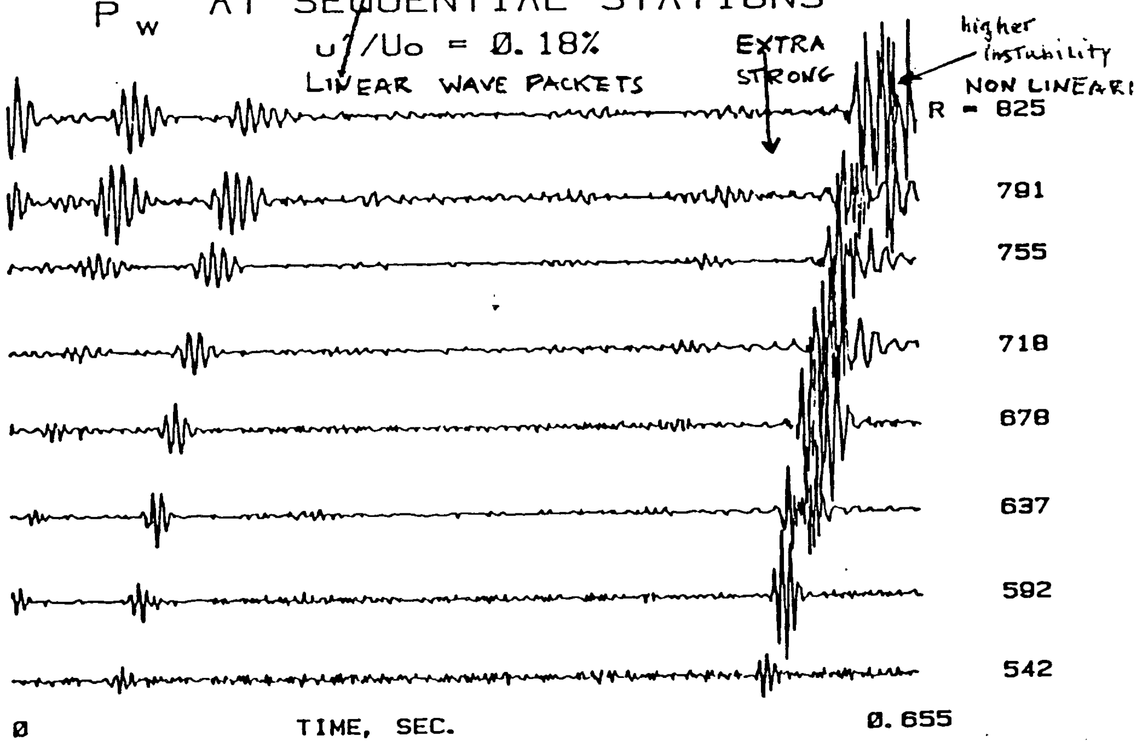
Comment:
Intermittancy appears at large as well as fine scales of Tu – e.g. in dissipation. Fractal nature.

YET DISCRETE OUTPUT

P'_w AT SEQUENTIAL STATIONS

u'/U_0 = Ø. 18%

LINEAR WAVE PACKETS



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FUNCTIONALITY OF DISTURBANCE CLASSES

PROBING DISTURBANCES

To bring mechanism out of NOISE BACKGROUND

(α) PERIODIC
(β) IMPULSIVE + REPETITIVE

R → Regular transition Route

E NHANCING DISTORB.
SHORTEN PATH
(a) WITHOUT CHANGING PRIMARY CHARACTER
(b) THOSE THAT CANNOT BE CLEARLY DISTINGUISHED FROM (a)

S trong
W eak

Bypass routes

MOST DANGEROUS
algebraic growth past THRESHOLD — OFTEN IMPULSIVE
moderate distributed roughness

WE MUST BE SURE THAT THEY ARE

ENVIRONMENTALLY REALIZABLE DISTURB.
DUCT TRANSITION

COOPERATIVE DIST + + RECEPTIVITY

ENVIRONMENT + SURFACE
PROVIDE SIMULTANEOUSLY TIME and LENGTH SCALES
including relatively "impulsive" induction by convected packets of higher intensity freestream TURB.

ROUGHNESS CAN FUNCTION IN ALL THESE CATEGORIES
BUT BEWARE OF —

"A New Direction in Hydrodynamic Stability: Beyond Eigenvalues" " ON PSEUDOSPECTR L. and A. Trefethen
S. Reddy and T. Driscoll, submitted to SCIENCE 12/93; Cornell U. Adv. Comp Res Inst. CTC92TR115

TRANSIENT DISTURBANCES

can lead to substantial "algebraic" growth even when ~~are~~ disturbances
(W) Weak - a property of nonsymmetric PDE operators (for which eigenfunctions are not independent = non normal e.g. Schmid, Henningson, Khorrami & Malik: "A study of eigenvalue sensitivity for hydrodynamic stability operators", Theor. & Comp. Fluid Dyn (in Press 1993). In a system with damped eigenmodes, the growth may be sufficient (before ultimate decay) to modify the system nonlinearly and lead to a bypass (as observed experimentally for most duct and plane Couette flows) For
(S) Stronger disturbances this road to turbulence may be competitive with "REGULAR" paths, based on amplified eigenfunctions and higher-order instabilities.

Obviously, the (W) category represents the larger danger in design. ON THE OTHER HAND, these disturbances are $\boxed{\text{ARTIFICIAL}}$ and question remains whether and how they can be actually induced by a given DISTURBANCE ENVIRONMENT

ONLY THE CLASS OF $\boxed{\text{ENVIRONMENTALLY REALIZABLE}}$ DISTURBANCES is practically relevant. HOWEVER, conceptually it is important to understand the mechanisms - they can even be used as TRIPPERS.

Groups at MIT: Landahl, Breuer, Henningson, Reddy, using pseudospectra Schmid (Gustafson of Swedish KTH) and Lehigh Univ: Charles Smith, Haji-Haidari, J.D.A Walker, B. Taylor ~~etc.~~ have done both experimental and theoretical work. Butler, K. and Farrell, B (1992): "3-dimensional optimal perturbations in viscous flows" Phys. Fl. A, 4(8) used variational theory to find alg. growing flows undoubtedly related to "Klebanoff damped modes" $< Re_{cr}$.

L. TREFETHEN's PSEUDO MODES for NON-NORMAL OPERATORS (Book forthcoming) applied to linearized Navier-Stokes eqs forced by $e^{-i\omega t} v(x,y,z)$ imposed at every point in the shear layer. The response is gauged in terms the resolvent matrix of the system. Its norm $\to \infty$ for v- eigensolutions at ω_{ev} and can be large for complex ω near ω_{ev}. When ω_{ev} is slightly dampe (Im(ω) just below zero) mode-responses with ω near ω_{ev} can be substantially amplified i.e. PSEUDO-RESONANT. ⊙ The forcing functions $v(x,y,z)e^{-i\omega t}$ would have to be induced by the environment. Which of these are environmentally realizable?

J.D. SWEARINGEN, U.So.Cal. Thesis 1985

smoke wire y_{sw} at $x = 21.5$ cm.

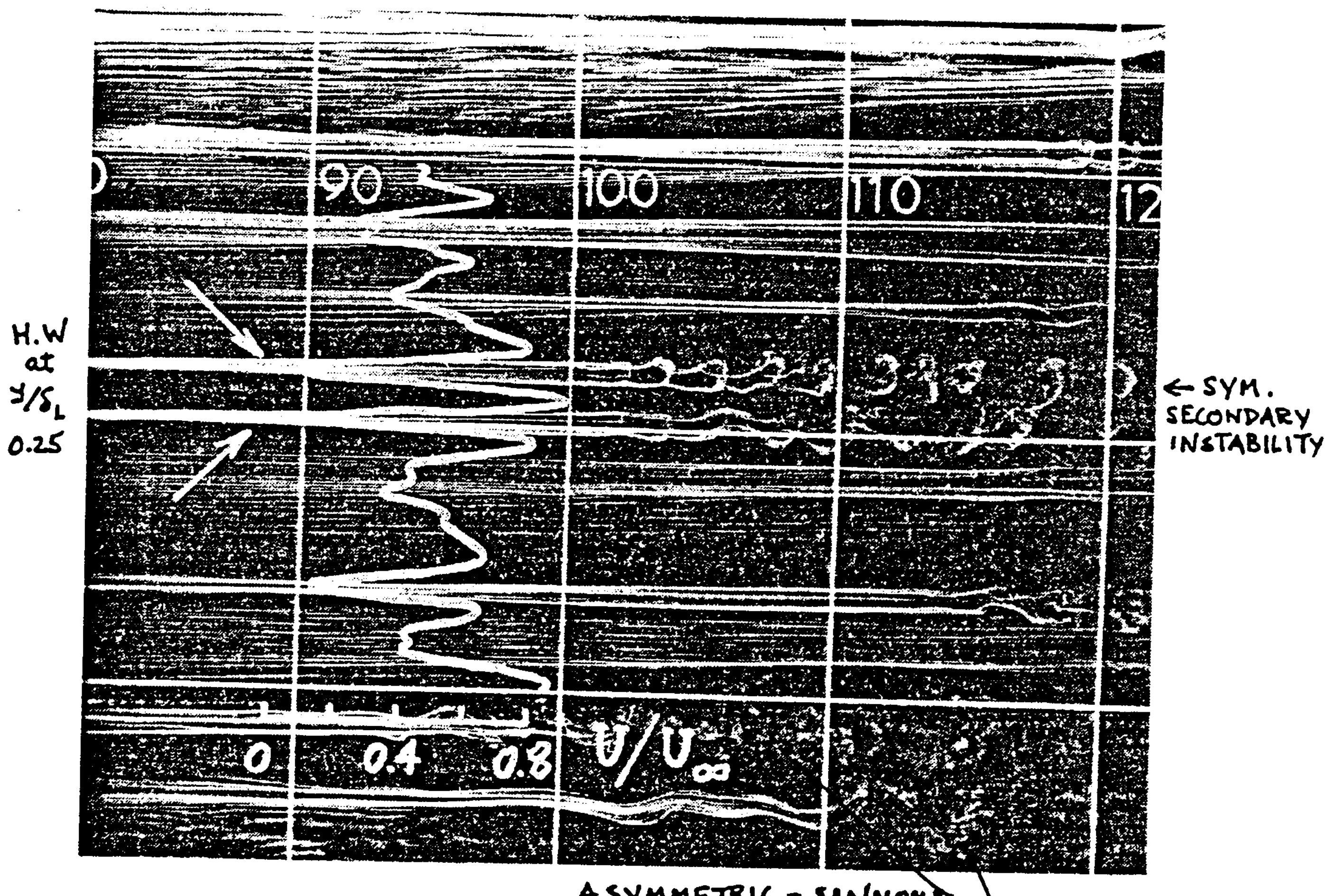
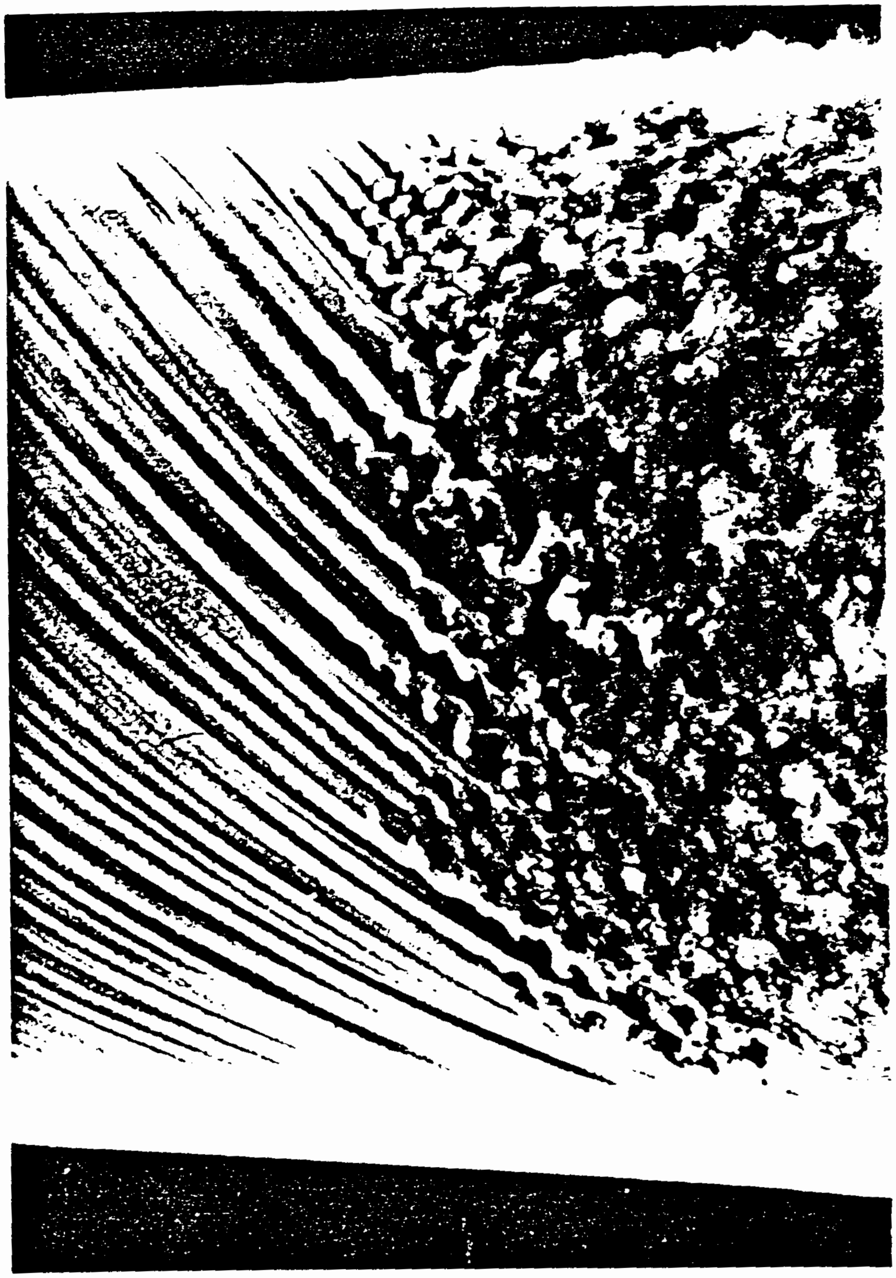


Figure 4.3: Spanwise variation of the mean streamwise velocity at y/δ_L = 0.25 superimposed on the flow visualization of figure 4.2a.

3.21R



J. KEGELMAN

Figure 65: Enlargement of Striations Illustrating Striation Breakdown ($V_s/U_\infty = 0.825$, $Re_L = 0.814 \times 10^6$)

WHAT IS FREE-STREAM TU that gives "NATURAL" TRANSITION ?

{Grid Tu
{Screen Tu
Tu in any WTunnel
Tu in Turbomachinery
Tu in atmospheric flight

- Born in separated shear layers; fed by $v_{tang} \cdot v_{norm} \frac{\partial V_{tang}}{\partial n}$
- wakes from upstream
- $\boxed{\text{decays}}$ in absence of mean flow $\overrightarrow{\text{grad}}\, V$
- and $\boxed{\text{rejuvenates}}$ when comes on
  near stag regions
  in contractions
  over wings and blades

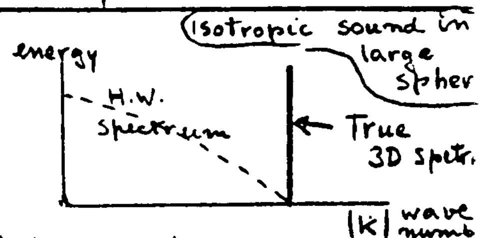
Even when nearly homogeneous and nearly isotropic
it has unknown coherent structures and intermittencies ~ fractals.

BÖTTCHER

masked by the one-dimensional time signals and spectra of hot wires

carry streamwise vorticity Ω
(Klebanoff, Kottke)
↘ direct feeding of Görtler instab. and cross flow Zero f instab.

CORRSIN's EXAMPLE of spectral aliasing



- Hot-wire always projects high wave number on low ones (frequency)
  Scrambles the spectrum

To understand:
Concentrate on the sporadic energetic extremal events
(possibly enhanced by "probing" periodic disturbances)

Then Two-point space-time correlations in free stream
2. one in f-s, one in BL.

Kendall ( ) showed that disturbances associated with the slightly damped {KLEBANOFF MODE RESPONSE} were moving towards the wall.

↓ dominated by Low frequency Streamwise Vortices which generate large u' fluctuations
(with theoretical low v' and w')

agreement with Butler and Farrel 1992 theory

Such disturbed motion then influences Subsequent instabilities especially secondary instabilities