THE MANY WORLDS OF TRANSITION RESEARCH

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The transition from laminar to turbulent flow in a boundary layer is a complex phenomenon that may take different routes, each involving distinct stages governed by different, often not-yet unraveled dynamical principles. There are, surprisingly, questions concerning virtually every stage in the process, beginning with receptivity to external disturbances, the linear stability of spatially developing flows, different possible nonlinear end games, the formation and propagation of turbulent spots and the emergence of fully developed turbulent flow. There seems no doubt that the flow has to be seen as a forced, nonlinear spatio-temporal system, but the system is so complex that to extract simple insights is still very difficult.

There is evidence that there is no transition in the boundary layer if there is no forcing; and further that different kinds of forcing may select different routes to turbulence - an issue that we shall shortly return to. A proper specification of the disturbance environment is therefore essential, although what is 'proper' is not clear. In controlled wind tunnel experiments, the disturbance has often been created by wavemakers of some kind - 2D vibrating ribbons (following Schubauer & Skramstad), point sources (as Gaster has done, using small surface-mounted loudspeakers), oblique waves (Corke, with surface films) etc. In such experiments the disturbance is often harmonic in time, but does not have to be; some interesting results have been obtained by Gaster using white noise forcing. The transition scenario obtained in these cases is not in general the same: while what we may call the "canonical" route charted by Klebanoff and others in a low-disturbance environment involves 2D TS waves, peak-valley splitting in the spanwise direction, appearance of spikes and the formation and growth of turbulent spots. Morkovin has emphasized how in high-disturbance environments the canonical route may be by-passed, and the flow may proceed "directly" to the transition zone consisting of spots short-circuiting the slow build-up on a viscous time scale that is so characteristic of the canonical route. I believe it is still to be established whether the TS mechanism is necessarily irrelevant on a by-pass route; waves may not actually be "visible", but the response of the flow to the disturbance environment might still be describable through TS transfer functions. A genuine by-pass would occur when the disturbance level is so high that significant mean flow distortion may be expected to occur, as for example when roughness may induce local inflexion points in the velocity profile that lead to turbulence on a short inviscid time-scale. Meanwhile the existence of a "spot-less" route, involving a gradual filling up of the spectrum rather than a catastrophic collapse into a turbulent spot, has been demonstrated by the Novosibirsk group, and investigated by Corke at Illinois, although the disturbance environment required to 'select' spot-less transition may have to be specially contrived.

We thus broadly distinguish between three classes of routes: the canonical (slow-build-up, rapid collapse into spots), the by-pass (short road to spots/turbulence), and what we may call the "scenic" (long spot-less road involving spikes in the velocity signal that may behave like solitary waves, followed by gradual spectral filling). Many variations on these routes are possible (there are bylanes everywhere), and some of these have been described elaborately by Morokvin.

The emergence of three-dimensionality from 2D TS waves can be described by a weakly nonlinear theory that accounts for parametric resonance when the basic flow is modulated by finite amplitude 2D TS waves, by the application of Floquet techniques, as Herbert has shown. But is the emergence of stochasticity from the waves characterizing instability, in the later non-linear stage, a form of dynamical chaos? Some physical models describe the gross features of the transition process in the framework of nonlinear dynamical-system theory (e.g. Bhat, Narasimha & Wiggins; interestingly, their equations have some commonality with a set proposed by Herbert, and some crucial differences as well: see Appendix). Gaster's experimental investigations sketch the way that a continuous spectrum may arise in boundary layers excited in different ways, in particular by combinations of harmonic and stochastic forcing. One promising method of identifying a low-dimensional dynamical system underlying observations of transition has been recently proposed by Healey. My own personal view is that it would be surprising if there were no connection between dynamical chaos and boundary layer transition. One way to find out would be an experiment in which some easily-recognized milestone on the route to turbulence, such as e.g. the first appearance of turbulent spots, is determined for different levels of stochastic forcing <u>keeping the deterministic (say harmonic) forcing always of the same amplitude</u> (see Figure 1). If say the Reynolds number at onset is independent of the stochastic forcing as it is diminished while the harmonic forcing is unchanged, we should be able to attribute the stochasticity at onset to nonlinear mechanisms alone, rather than to the stochasticity of the forcing itself. If the end-stage in transition were to be describable in terms of a low-dimensional nonlinear system there would be a considerable conceptual simplification in understanding the process, possibly with many benefits in applications. However, it must be admitted that as of today nonlinear system theory has made no significant contribution to our ability to predict any feature of the transition process.

Once spots are generated they grow and fill the boundary layer, taking it asymptotically to a fully turbulent state. The growth of intermittency in this transition zone, and the development of various boundary layer properties, has been studied extensively on flat plates. However, even here there have been various questions. The hypothesis of concentrated breakdown (Narasimha), postulating that turbulent spots are born in a relatively narrow band around a suitably defined onset location, has worked well in a variety of flows, although there is no direct observational evidence of the region over which breakdowns do occur in actual practice. It seems clear, especially if the disturbance environment is not violent, that no breakdowns can occur over the slow build-up phase in the canonical route; equally there would not be many breakdowns once the intermittency is substantially different from zero, and there can be none when the flow is fully turbulent. So a hypothesis that most breakdowns should occur over a relatively restricted region should be reasonable. It is in fact surprising how closely measurements obey the resulting intermittency distribution, as Gostelow and Fraser have recently found. However we are in no position yet to explain <u>why</u> spots are born where they actually are.

There are also unresolved questions about spot propagation, especially possible interference from other spots in the neighbourhood, and about the possibility of each spot giving birth to offspring in pockets of the neighbourhood (e.g. the wing tips) that the spot excites (as in Wygananski's observations). Are the offspring autonomous spots, or do they eventually merge with the parent to make it grow bigger? There are also issues concerning the propagation of spots in pressure gradients (studied by Wygnanski, Narasimha and Gostelow), in skew and diverging flows (Jahanmiri et al.), etc. Very few studies have been made here, and surprises may be in store. In our study of spots in a distorted duct (no pressure gradient but streamlines diverging on plate), it was found that the spot does not necessarily propagate across streamlines always, and can have a highly unsymmetrical structure (fatter on the outside of the bend as the spot traces a curved trajectory).

In turbomachinery, where the free-stream disturbance levels are not only high but may involve travelling wakes from upstream rotor stages hitting stator blades, transition is a major feature of the boundary layer flow, as Reynolds numbers tend to be in the awkward range of $5x10^5$ to $2x10^6$. In addition the flow is rendered complex by the possible presence of separation bubbles, reverse transition etc. Wake-hitting induces a transition zone that is also intermittent, but this time due to the propagation and growth of "slabs" of turbulence stretching across the span of the blade (rather than arrow-headed Schubauer-Klebanoff spots). There has however been some evidence that there are S-K spots concealed in the turbulent slabs induced by the wakes. What precisely such slabs and concealed spots do to the flow remains to be investigated.

Finally, does the emerging turbulent boundary layer remember its origins? Does it differ depending on the route taken to turbulence? If the "standard" boundary layer defined by Coles is to have any meaning, there must be an asymptotic state independent of the route by which it is reached. It must then necessarily have a well-defined virtual origin that can be obtained by extrapolation backwards, helping to determine an onset location, irrespective of how dispersed breakdown is and indeed of which of the three classes of routes to turbulence is selected by the disturbance environment. This question has not been directly addressed either.

What is striking after so many years of transition research is that there is not a single investigation which traverses the whole route from fully laminar to fully turbulent flow: we each seem to live in our own world, and look at stability or breakdown or spot propagation or solitary waves or intermittency or turbulent boundary layer or whatever, to the exclusion of the other aspects of the transition process. The time has come to make a few grand experiments that go the whole way and traverse the different major routes. This is not going to be a simple task, but transition is not a simple problem. Such experiments may even require new facilities (long test sections, wide control over disturbance environment, etc.).

The existence of multiple paths to turbulence raises an obvious question: what selects the route? Clearly the disturbance environment (in which we include not only free-stream turbulence but noise, vibration, roughness etc.) must be the major determinant. That suggests that we ought to start delineating what nonlinear scientists call the "basin of attraction" for each of the "attractors" (strange or otherwise) that dot the transition landscape (Figure 2). Morkovin estimates that, given the numerous factors that can induce transition, the space of disturbances may have something of the order of 10 to 20 dimensions. To map things in such a high-dimensional space seems hopeless, and (even if feasible) will certainly be an expensive and tedious task; but it would be interesting even to sketch sections or projections of the basins of attraction in subspaces of fewer dimensions: e.g. it should not be difficult (Figure 3) to determine the location of transition onset as a function of the characteristics of 2D and spanwise-periodic components of the disturbance made by a wave maker (which one can conceive of as consisting of appropriate strips of thin film on a flat plate, programmed to produce both spanwise uniform and periodic disturbances). I do not think we have a clue yet on what the boundaries of the different regimes will be: aligned or staggered lambda vortices, spots or spotless transitions, etc.

Clearly, there is still a great deal of interesting work to be done before one can say that the transition problem is understood. I hope this meeting can chart the course of future investigations.

APPENDIX

LOW-DIMENSIONAL NONLINEAR SYSTEMS

Herbert 1988:

$$\frac{d\hat{A}}{dt} = a_o\hat{A} + a_1\hat{A}^2 + a_2B^2$$

$$\frac{dB}{dt} = b_oB + b_1\hat{A}\,B$$

where $\hat{A} = A - A^*$

— amplitude of basic periodic flow

~ amplitude of 2D secondary instability

B ~ amplitude of 3D subharmonic or fundamental instability

Narasimha & Bhat (1988), Bhat, Narasimha & Wiggins (1990)

$$\frac{dU}{dt} = a_oU + \underset{(*)}{a_1U^3} + \underset{(*)}{a_2u|u|}$$

$$\frac{du}{dt} = b_ou + \underset{(*)}{b_1\,U\,|u|}$$

Note differences in starred terms.

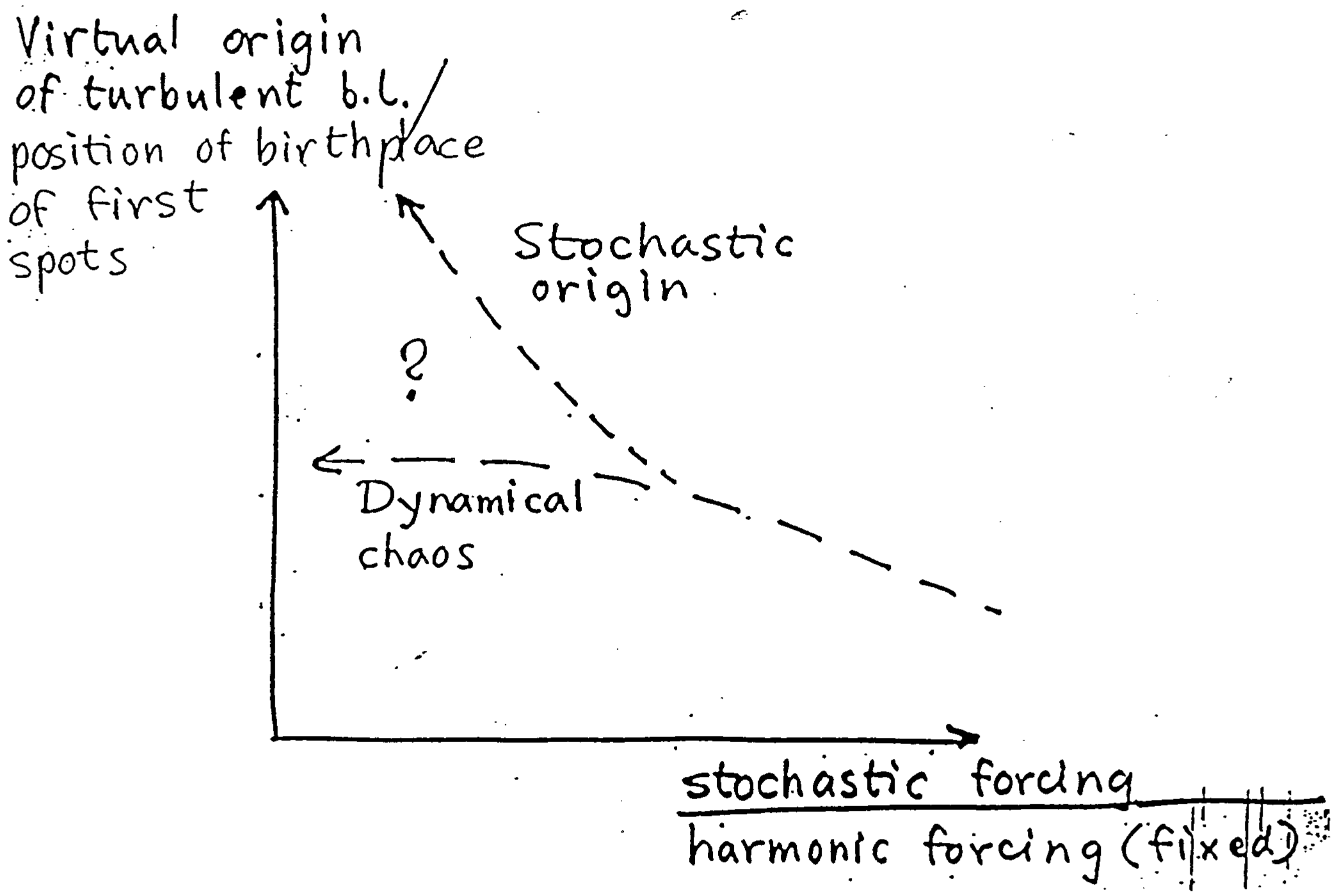
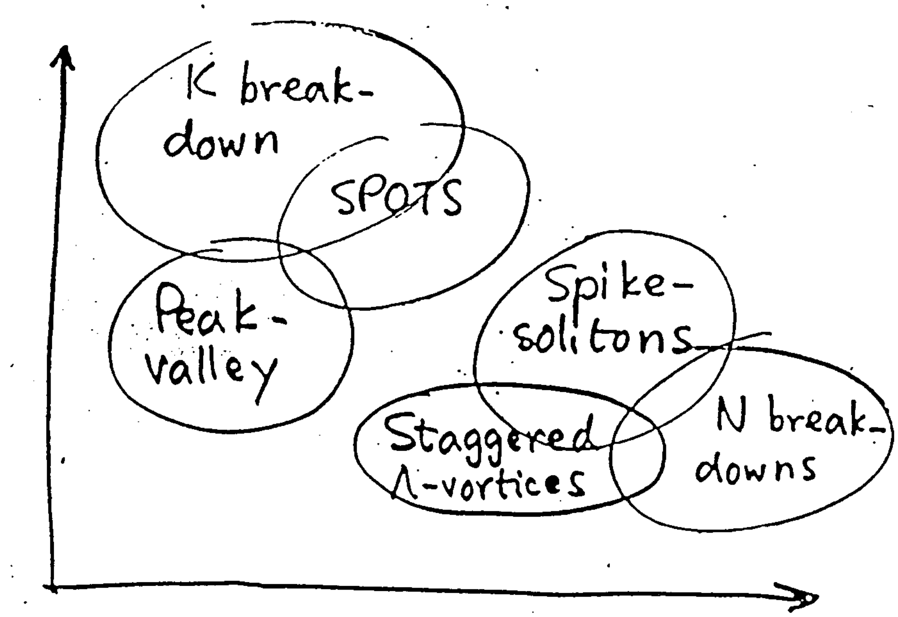

Virtual origin
of turbulent b.l./
position of birthplace
of first
spots
Stochastic
origin
?
Dynamical
chaos
stochastic forcing
harmonic forcing (fixed)

FIG 1



ATTRACTORS IN SOME
SUITABLE DISTURBANCE SPACE
(Positions in diagram NOT significant

FIG. 2

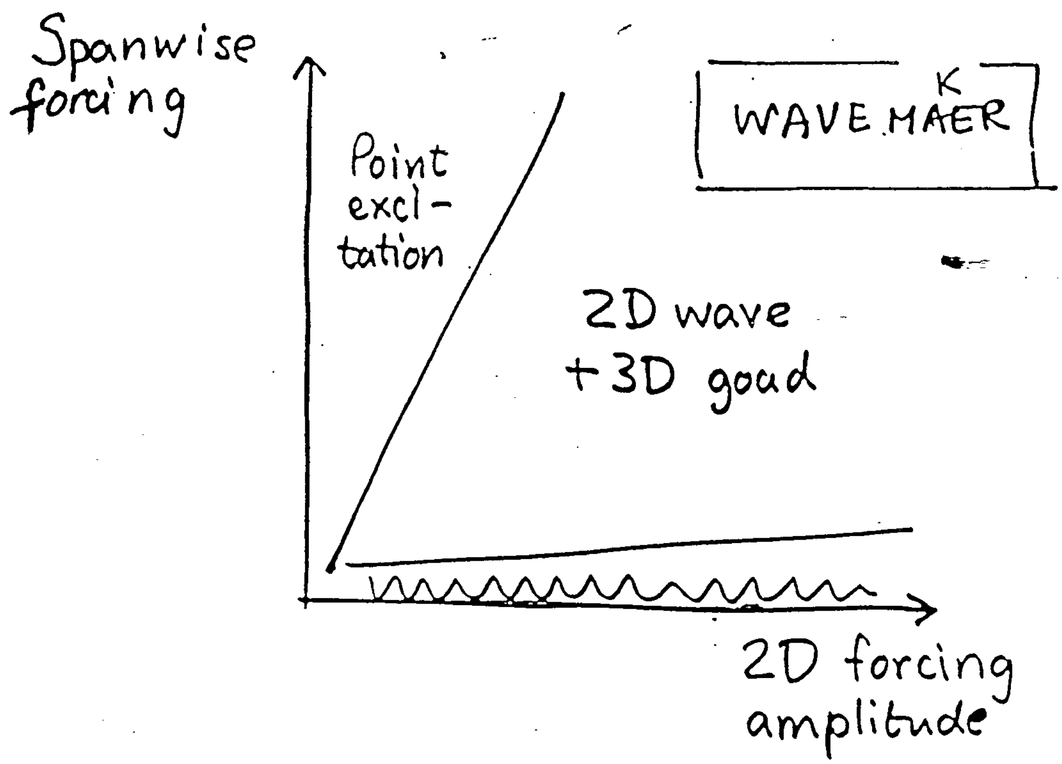

Spanwise forcing
Point excitation
WAVE MAKER
2D wave
+3D goad
2D forcing amplitude

FIG. 3