Short paper
Reconsideration of the turbulent burst in boundary layers

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1. Outline of the turbulent bursting

"Bursting" is the term popularly used since the work of Kline et al. [1] to refer to the production of turbulence in the boundary layer via violent outward eruptions of near-wall fluid. This concept is commonly invoked in the literature of turbulence physics, but its definition and usage have long been a source of confusion and miscommunication. The meaning of the term has evolved over the years but in an accumulative sense. Thus, several meanings are now ascribed to "bursting" without a clear consensus. A partial history of the usage is as follows:

(1) violent breakup of a low-speed streak after lifting (1963-1967);

(2) three-stage process of low-speed streak lift-up, oscillation, and breakup (1971);

(3) shear-layer interface sandwiched between an upstream, high-speed "sweep" and a downstream low-speed "ejection" (numerous authors, early 1970s-present);

(4) occurrence of a single-point event found by a specified detection criterion, usually VITA **(variable interval time average)** or quadrant splitting (numerous authors, mid-1970s-present);

(5) one or more $(u'v')^2$ ejections emanating from a single low-speed streak.

In Contrast to the diversity on the concept of busting and its stages, it has been found that the behavior of the nonlinear wave called solitons/like coherent structure (SCS) and related flow structures are the same in the above five alternative descriptions of "bursting", as summarized in Table 1. Therefore, it becomes possible to develop a unified description of bursting in terms of the SCS and subsequent flow structures. We do this below, along with some comments on selected existing descriptions.

	DTBL	**TBL**
Production position	Low-speed streak	Low-speed streak with several SCS
Process 1	Rapid outward motion	Rapid outward motion of the SCS
Process 2	Rapid growth of oscillatory motion	Formation of the secondary closed vortex
Process 3	Chaotic flows	Formation of the chain of ring vortices

Table 1. Bursting process in developed turbulent boundary layer (DTBL) versus turbulence production in a transitional boundary layer (TBL).

2. Reconsideration of turbulent bursting

The complete process of "bursting" is a continuous chain of events from a relatively quiescent wall flow to the formation of relatively large and chaotic fluctuations. The process is intermittent. For clarity, the bursting process was described as three somewhat artificially divided sub-processes [1](1) Slow lifting of a low-speed streak continues until a shift occurs involving more rapid outward motion of the low-speed streak, when an inflected instantaneous velocity profile is also observed; (2) rapid growth of an oscillatory motion downstream from the inflected zone, which continues for a few cycles; and (3) the termination of oscillation by the onset of a more chaotic fluctuation called "breakup". Thus, the cycle is completed and the velocity profile returns to a form which looks generically like the mean profile shape. These general processes have been observed in all detailed studies up to the end of the stage of first low-speed-streak-lift. But the structural details of the second and third stages vary from case to case.

A low-speed streak is composed of several nonlinear wave called solitons/like coherent structure (SCS) whose motion rapidly lifts fluid from the wall (at 10% of the free-stream velocity)(Figure 1). The SCS moves downstream as it gradually moves away from the wall (Figure 2). In the first stage of turbulent bursting in a turbulent boundary layer, the SCS first leaves the wall very slowly over a very long streamwise extent, which is perhaps a cumulative effect over a long distance (or time) of a small streamwise vorticity. However, once the SCS has developed, it appears to turn outward much more sharply, as it continues to move downstream. This more rapid outward motion is the same as the “low-speed-streak-lift” (or “streak-lift” in short) in turbulent bursting.

Then, when an SCS moves upward, it carries fluid particles of very low relative speed away from the wall, and thereby create a high-shear layer along its border formed from the motion of the secondary closed vortex. Most significantly, the instantaneous inflectional velocity profiles lead to a very rapid growth of an oscillatory disturbance just downstream of the inflectional zone, which reaches a relatively large scale within several periods. A more complete description can then be given to the oscillatory growth during the second stage of bursting. The dominant mode appears to be the secondary closed vortex motion with growing size and strength as the vortex proceeds downstream. Once such a vortex is formed, it begins to interact the head of the Λ-vortex, which in turn generates the chain of 4 ring vortices (for details see [8]). The dye visualization and phase-locked hot film measurements reveal this strong vortical nature of the flow on a large number of photos. The regular breakdown of the chain of ring vortices corresponds to the third stage of the turbulent bursting. Because of the controlled initial conditions, the phenomena are periodic rather than random in our experiments. In fact, in the turbulent boundary layers, all the three stages of turbulent bursting have been found quite regular.

Since Kline et al.[1] suggested the bursting phenomenon, people have already been very close to understanding the physical nature of turbulent production in boundary layers. But the relation between transition and turbulent bursting has not been compared even for the case of by-pass transition; while for the K-regime of transition, few people have explored the relevance of the turbulent bursting. Our research has shown clearly that the bursting phenomenon in both transitional and turbulent boundary layers is essentially from the same physics. Furthermore, the “ejection” of turbulent bursting is the behavior of the SCS.

Having said these, it seems to be the time to revisit a repeatedly asked question: Does there exist a unified path of the turbulent production under different conditions?

In our view, the answer is positive. Bypass transition and controlled transition (the K-regime, C-regime and H-regime) represent different mechanisms for the formation of flow structures. Because in both by-pass and K-regime transitions the T-S wave is not necessary and the turbulent bursting is their common essence, the fact that the SCS is a corpus of turbulent bursting makes it possible to unify these two regimes into a universal scenario. A “Low-speed streak” is constituted by a few SCS, which does the “ejection” in turbulent bursting.

3. Reconsideration of relevant theories based on the present experiments

In the preceding discussions, we have attributed turbulent bursting mainly to the SCS that dominates the turbulent production in wall-bounded flows. It is thus of interest to compare this proposed mechanism with existing theories.

Hocking & Stewartson [2，3] have investigated the structure of localized bursting solutions**,** and found two distinct types. Haberman [4, 5] has considered how bursting evolves from initial linear disturbances. Most of his analytical results agree with the computations for similar initial packets by

Hocking & Stewartson [6]. Craik [7] believed that theoretical bursting is not directly connected to the development of turbulent spots in unstable shear flows. The reason is not very difficult to be explained. The theories outlined above are confined to disturbances centered at a single wavenumber and frequency, whereas turbulent spots are characterized by wavenumbers and frequencies much greater than those of the fundamental wave**.** Of course, since the “burst” arises when the fundamental wave is modified so rapidly for which the weakly nonlinear theory breaks down, subsequent events such as local secondary instabilities are liable to proceed rapidly. Recent studies [8-13] have shown that bursting is directly connected to the development of the SCS in unstable shear flows, with turbulent spots consisting of several SCS and vortices at their borders such as streamwise vortices, chain of ring vortices, and the secondary closed vortices and their pieces. Therefore, it becomes possible to use the previous theories developed by Hocking et al.[7] to predict the evolution of the SCS.

[1] Kline, S. J., Reynolds, W. C., Schraub, F. A., and Runstaller, W. P., 1967, “The structure of turbulent boundary layers,” *J. Fluid Mech.,* **30**, pp. 741.

[2] Hocking, L. M., and Stewartson, K., 1971, “On the non-linear response of a marginally unstable plane parallel flow to a 3D disturbance,” *Mathematika* **18**, pp. 219.

[3] Hocking, L. M., and Stewartson, K., 1972, “On the nonlinear response of a marginally unstable plane parallel flow to a 2D disturbance,” *Proc. R. Soc. London. Ser. A* **326**, pp. 289.

[4] Haberman, R., 1973, “Note on slightly unstable nonlinear wave systems,” *J. Fluid Mech.,* **58**, pp. 129.

[5] Haberman, R., 1979, “Energy bounds for the slow capture by a center in sustained resonance,” *SIAM Journal on Applied Mathematics,* **37**, pp. 69.

[6] Hocking, L. M., Stewartson, K., and Stuart, J. T. 1972, “A nonlinear instability burst in plane parallel flow,” *J. Fluid Mech.,* **51**, pp. 705

[7] Craik，A. D. D. 1985, Wave interaction and fluid flows , Cambridge University Press, Cambridge

[8] Lee, C. B., Wu, J. Z. 2008 Transition in wall-bounded flows, Applied Mechanics Reviews, **61**, 030802-1

[9] Lee C. B., and Fu, S., 2001, “On the formation of the chain of ring-like vortices in a transitional boundary layer,” *Experiments in Fluids,* **30**(3), pp. 354–357.

[10] Lee, C. B., 2001, In Proc. of Heat Transfer & Fluid Mech. Inst. pp.61-80. California State University Press.

[11] Lee, C. B., 1998, “New features of CS solitons and the formation of vortices,” *Phys. Letts.* **A 247**, pp. 397.

[12] Lee, C. B., 2000, “Possible universal transitional scenario in a flat plate boundary layer: Measurement and visualization,” *Phys. Rev.* **E62**, pp. 3659; Lee, C. B. and Li, R. Q. 2007, “A dominate flow structure in a transitional boundary layer,” *J. of Turbulence*, in press.

[13] Lee, C. B., and Chen, S. Y., 2005, “Chapter 2: Dynamics of transitional boundary layers,” In Transition and Turbulence control (ed. Mohamed Gad-el-Hak & Her Mann Tsai), pp.38–85, World Scientific.

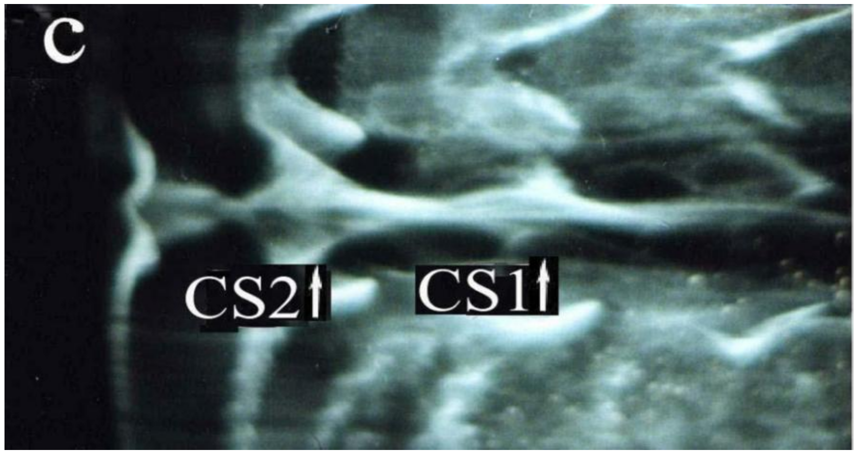

Figure 1. A low-speed- streak composed of several SCSs (arrows CS1 and CS2).

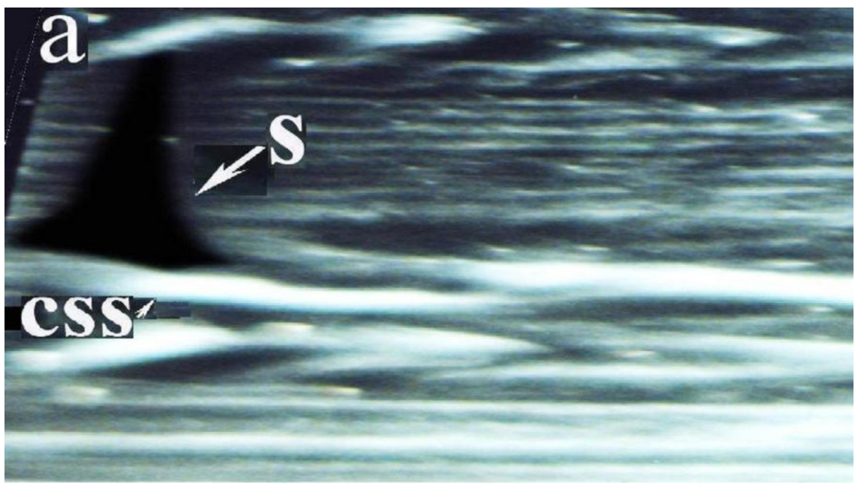

Figure 2. The shadow (arrow S) showed the ejection of the flow from the near wall to the outer layer which is the performance of the SCS.