‘SYNTHETIC’ LARGE SCALE MOTIONS ORGANIZE SMALL SCALE MOTIONS IN THE TURBULENT BOUNDARY LAYER

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Abstract The relationship between large- and small-scale motions in a non-equilibrium turbulent boundary layer was studied experimentally. A zero-pressure-gradient flat plate turbulent boundary layer was perturbed by a short array of two-dimensional roughness elements, both statically and under dynamic actuation. The dynamic forcing generated a ‘synthetic’ very-large-scale motion (VLSM) within the flow which was observed by phase-locked flow measurements. The phase-relationship between both synthetic and natural VLSMs and the small scale motions within the boundary layer was studied by cross-correlation and cospectral techniques, to reveal an organizing effect of the artificial VLSM on smaller scales.

MEASURING SCALE INTERACTIONS

The interaction between large- and small-scale motions in the turbulent boundary layer has significant implications for both better understanding the dynamical processes occurring within the boundary layer and designing smarter control strategies to exploit boundary layer physics. In early studies, direct comparison of filtered instantaneous velocity signals was employed to show evidence for amplitude modulation between the large- and small-scale motions [2, 6]; these comparisons were then made more rigorous through the use of correlation coefficients [9, 12, 10] and conditional averaging techniques [3, 4]. Recognition of the important role of very-large-scale-motions (VLSMs) in the turbulent boundary layer [1, 5, 11] has only highlighted the need to relate these energetically dominant structures to the small-scale motions near the wall.

By considering a spectral decomposition of the cross-correlation methodology, Jacobi & McKeon [8] showed that among all the large-scale motions in the flow, one particular range of large-scale motions (as defined in the frequency domain) is more strongly correlated with the envelope of small-scale fluctuations, and that band of large-scale frequencies corresponds precisely to the very-large-scale motions (VLSMs) which are thought to be crucial to understanding wall-bounded flows (e.g., [6]). Moreover, it was shown that this interaction between large- and small-scale motions can be conceptually described in terms of a phase-shift [3] between the scale fluctuations. Therefore, the physical observation that small-scale fluctuations in the turbulent boundary layer tend to lead fluctuations in large-scale motions can be interpreted as a relative phase-lag in temporal signals describing the large-scale motions. Combining these two observations, Jacobi & McKeon [8] concluded that VLSMs are the key determinant in establishing a phase-relationship between large- and small-scale motions in the turbulent boundary layer, and thus modifying or controlling VLSMs offers the possibility of indirectly modifying small-scale motions. The present investigation considers precisely this possibility, by investigating how the phase relationship between scales responds when a synthetic VLSM is induced in a perturbed boundary layer.

SCALE INTERACTIONS IN THE PERTURBED BOUNDARY LAYER

A dynamic perturbation of the turbulent boundary layer was generated using an oscillating roughness patch, described previously [7]. The perturbation resulted in the generation of a synthetic VLSM with wavelength $\lambda_x/\delta \approx 18.7$, along with a ‘stress bore’ within the boundary layer, which was a result of the static roughness alone. The velocity field downstream of the perturbation was measured by hotwire and PIV and the large- and small-scale components of the instantaneous velocity signal, u_L and u_S were separated by filtering [9].

The streamwise cross-correlation function between the large- and small-scale motions can be represented as an iso-contour map, as shown in figure 1a, where the time lags indicate the phase relationship between the aggregate large scales and the envelope of small scale motions across the thickness of the boundary layer. In order to fully describe the phase relationships between large- and small-scale motions on a scale-by-scale basis, the correlation between different scales of motion can be decomposed using the cospectral density function. The cospectral density is essentially the Fourier transform of the cross-correlation between u_L and u_S, normalized appropriately. By expressing the correlation information in the frequency domain, the cospectral density highlights the relationship between the range of large scales in the large-scale signal, u_L and comparable scales generated in the small-scale signal as a result of the filtering process. The cospectral density map for the dynamically perturbed flow is shown in figure 1b. The ridge-line of maximal cospectral energy indicates the particular sizes of large-scale which dominantly organize the smaller scales in the flow. In the dynamically

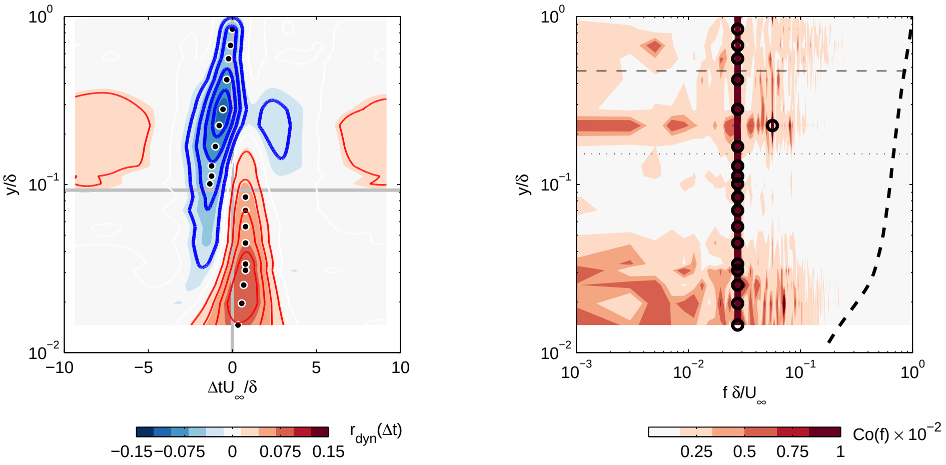

Figure 1. (Left) The isocontour map of the streamwise cross-correlation function between u_L and u_S, without normalization, from the dynamically perturbed flow, using the hotwire measurements at streamwise location $x/\delta \approx 3.4$ downstream of the dynamic perturbation. (Right) The cospectral density for the cross-correlation. The peaks from the amplitude at each wall-normal location are denoted by circles. The filter size of $\tau = 1\delta/U$ is marked by a dashed line, which varies as a function of convective velocity. Note how the synthetic VLSM and small scale motions are highly organized across the boundary layer.

perturbed flow, the ridgeline shifts completely to the location of the dynamic forcing (the synthetic large-scale motion), indicating that the synthetic large scale has a strong organizing effect on the envelope of small-scale motions in the flow.

By tracing along the ridgeline in the cospectral density, the phase corresponding to the lag between each peak frequency and the envelope of small-scale motions can be retrieved, thus providing the phase lag for just the dominant (not aggregate) large-scale motions. For the unperturbed flow, the phase increases from 0 at the wall to approximately π at the mean edge of the boundary layer, with an extensive residence in the vicinity of $\pi/2$. The dynamically perturbed flow shows significant departures from this phase trend: within the second internal layer formed downstream of the perturbation, there is little phase difference between the artificial VLSM and the envelope of small scales, where the re-organization is strongest. Within the ‘stress bore’ generated by the roughness, there is a change in sign in the phase lag, which suggests that the small-scale fluctuations actually begin to lead large-scale fluctuations by more than half a period, consistent with the very shallow local inclination of the artificial VLSM. Ultimately, the cospectral maps confirmed that an artificial VLSM can be a powerful tool to organize small-scale motions in the boundary layer and to alter the phase relationship between particular large- and small-scale motions.

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