ON A NEW BY-PASS TRANSITION MECHANISM IN WALL BOUNDED FLOWS

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ABSTRACT

A new mechanism by pass in a wall bounded internal flow is proposed and the proposal is checked by direct numerical simulations of high temporal and spatial resolution. The mechanism is based on the interactions of the localized perturbations, rather than the effect of a single perturbation investigated so far in the classical by pass transition process. It is first shown by theoretical considerations that two pairs of quasi-streamwise vortices can interact near the wall in such a manner that the compression (stretching) of the existing wall normal vorticity induced by one of the pairs can enhance a new streamwise vorticity zone that can lead to new coherent structures and enhance considerably the transition process. Direct numerical simulations confirm this hypothesis.

INTRODUCTION

The transition scenario related to the disturbance growth on time scales significantly shorter than typical Tollmien-Schlichting (TS) waves that "by-passes" the spatial and temporal development of the two-dimensional disturbances and their inherent secondary instabilities is the subject of this investigation. The set-up of three-dimensionality leads to the achievement of finite amplitudes and of the non-linear effects. They can mainly be generated by local surface irregularities such as roughness. This scenario has been investigated in detail in the past both in internal (Henningson et al. 1993) and external (Bech et al., 1998) flows for single localized perturbations.

It is well known since a while that there is a large structural similarity between a turbulent spot and developed turbulence in wall layers. One of the key problems in wall turbulence is the generation of Reynolds stress producing eddies (Hamilton et al., 1995). There are a multitude of different hypothesis and conjunctures advanced so far, but most of them are contradictory with observed experimental results. The destabilization caused by large scale eddies is for example contradictory with the observed bursting behavior whose frequency scales with inner rather than the outer variables. The regeneration process in the wall turbulence, and in parallel, the development of turbulent structures through by-pass mechanism should be related in some way to the preexisting structures themselves. The aim of the present investigation is to study the interaction between the localized perturbations to determine whether they rapidly trigger the transition under some circumstances, or not. This aspect has not been investigated before to our knowledge.

BY-PASS TRANSITION THROUGH INTERACTION OF LOCALIZED PERTURBATIONS

One of the main characteristics of by-pass transition is the generation of quasi streamwise vortical structures (QSS) near the wall at the late spatial and temporal development stages of a localized perturbation (Henningson et al., 1993). The main generation term in the streamwise vorticity ω_x generation equation is the production term resulting from the tilting of wall normal vorticity by the shear that reduces to $-\frac{\partial w}{\partial x}\frac{\partial \overline{u}}{\partial y}$ where $\frac{\partial w}{\partial x}$ is the streamwise gradient of the spanwise velocity and $\frac{\partial \overline{u}}{\partial y}$ is the mean shear. Here x, y, z are respectively the streamwise wall normal and spanwise coordinates with the corresponding velocity components u, v, w. The base flow is a Poiseuille flow with the streamwise velocity distribution $\overline{u}(y)$. The set-up of the x dependence is problematic. A streamwise dependence is hardly conceivable in the immediate vicinity of the quite elongated quasi-streamwise vortices. Tardu (1995) proposed a mechanism that may lead to the QSS generation through interactions of existing structures with the wall normal vorticity layers generated by the QSS themselves (Jiménez, 1994). Consider the conceptual model given in Fig.1 that shows two pair of counter rotating vortices labeled respectively by A and B. Walls of normal vorticity layers ω_y are generated behind the vortices resulting from the kinematics induced by the near wall velocity distribution (Jiménez, 1994). One may rigorously show by making use of the Biot-Savart law that the streamwise variations of the spanwise velocity component are related to

$$\frac{\partial w}{\partial x} \propto \frac{1}{4\pi}\int_{-\infty}^{0} dz' \int_{-\infty}^{+\infty} \Delta(x', z', t) \log\left[(x-x')^2 + (z-z')^2\right] dx' \qquad (1)$$

where

$$\Delta(x',z',t) = \frac{\partial^2 \omega_y^+}{\partial x'} - \left|\frac{\partial^2 \omega_y^-}{\partial x'}\right| \quad (2)$$

represents the dissymmetry between the streamwise variations of the positive and negative wall normal vorticity layers shown in Fig. 1. The details are omitted here, but it is clear that a dissymmetry $\Delta(x',z',t)$ is obviously necessary to regenerate $\frac{\partial w}{\partial x}$ which in return may lead to new quasi-streamwise structures. The compression of one of the vorticity layers $\omega_{y\pm A}$ by the large positive straining induced by the left counterrotating vortex B in Fig. 1 may break up the symmetry and enhance the by-pass transition. It can be shown that for sufficiently large times the local dimensionless vorticity disappears exponentially in time according to $\omega_{y+A}{}^* \propto \exp(-\gamma^* t^*)$ under the stagnation flow with parameter γ^* induced by the sweep motion. The negative $\omega_{y-A}{}^*$ sidewall in return, is located far away from the stagnation flow. It is primarily under the effect of viscosity. The maximum vorticity in this layer decreases therefore as $\omega^*_{y-A} \propto \frac{1}{\sqrt{t^*}}$. For typically $t^* >> \frac{2}{\gamma^*}$ the positive vorticity disappears almost instantaneously giving rise to a large $\frac{\partial w}{\partial x} > 0$ wall layer that can subsequently be tilted by the shear and roll up to a new streamwise structure. Fig. 2 shows this concept in slightly more details as a function of the Reynolds numbers associated with the vortices. The aim of the present investigation is to check the validity of this regeneration concept based on a somewhat deterministic scenario.

DIRECT NUMERICAL SIMULATIONS AND INITIAL CONDITIONS

The channel DNS code of Orlandi (2001) has been adapted for the present purpose. The number of computational modes is $256\times128\times128$ in respectively streamwise, wall normal and spanwise directions. The sizes of the computational domain extend from $16\pi a$ in x, $2a$ in y and to $8\pi a$ in z where a stands for the half height of the channel. Stretched coordinates are used in the wall normal direction. Hereafter the quantities are normalized with respect to a and the centerline velocity of the Poiseuille base flow.

Two pairs of counter rotating vortices have been injected in the channel flow with streamfuctions of the form:

$$\psi = \varepsilon f(y)\left(\frac{x'}{l_x}\right) z' \exp\left[-\left(\frac{x'}{l_x}\right)^2 - \left(\frac{z'}{l_z}\right)^2\right] \quad (3)$$

where $x' = x\cos\vartheta - z\sin\vartheta$, $z' = x\sin\vartheta - z\cos\vartheta$ and ϑ is the angle of the perturbation which has been set to $\vartheta = 0$ here. The perturbation flow field is given by :

$$(u,v,w) = (-\psi_y \sin\vartheta, \psi_{z'}, -\psi_y \cos\vartheta) \quad (4)$$

and $f(y) = (1+y)^p(1-y)^q$. This is the same type of perturbation used by Henningson et al. (1993). The difference here, however is in the modeling of the configuration given in Fig. 1. We combined two different ψ respectively for the structures A and B and shifted B in the z plane. More clearly we have chosen $p_A = q_A = 2$, $\varepsilon_A = 0.1$, $l_{xA} = l_{zA} = 4$ for the structure A which is consequently centered at the centerline of the channel. The streamfunction corresponding to the structure B is of the same form but shifted in the spanwise direction by δ i.e.

$$\psi_B = \varepsilon_B f_B(y)\left(\frac{x'}{l_x}\right)(z'+\delta)\exp\left[-\left(\frac{x'}{l_x}\right)^2 - \left(\frac{z'+\delta}{l_z}\right)^2\right] \quad (5)$$

The perturbation parameter and p and q are chosen in such a way that B is closer to the wall and interacts sufficiently strongly with the wall vorticity layers generated by A. Thus, $p_B = 1.5, q_B = 6$, $\varepsilon_B = 0.02$ and $l_{xB} = l_{zB} = 2$ and B is centered at $y = -0.6$ ($y = 0$ is the centerline, and $y = -1$ is the upper wall. The Reynolds number based on the centerline velocity is $Re = 2000$ through the whole study. The imposed streamfunction is $\psi_A + \psi_B$. The perturbation parameters ε_A and ε_B are chosen in such a way that A and B cannot *individually* trigger the by-pass transition as it will be shown in the next session. Fig. 3 shows the initial wall normal and spanwise velocity perturbation contours in the $y-z$ plane at $x = 2$.

RESULTS

Fig. 4 shows the evolution of the total energy

$$E_{tot} = \iiint_V (u^2 + v^2 + w^2)\, dV \quad (6)$$

over the computational volume V divided by the initial energy of the disturbance E_i , versus time for the configuration given in Fig.1. It has to be emphasized once more that the structures A and B of Fig. 1 lead individually to stable states, the most dangerous structure in terms of triggering instability being due to the structure which is closer to the wall. For brevity the temporal and spatial evolution of $A+B$ will be compared with B only. It is seen in Fig. 4a that the energy increased by a factor of about 25 at $t = 150$. The energy associated with the wall normal and spanwise velocity components increase also, the increase in v being more significant (Fig. 4b). For the isolated structure B in return, the energy decreases continuously showing that the by pass transition is not triggered in this case (Fig. 4c). This behaviour is in agreement with the classical energy transfer process described by rapid distortion theory. Note that the Reynolds number used here is somewhat low compared with previous studies. The dynamics of localized perturbation differ considerably from the secondary instability mechanism. According to Lundbladh (1992) and Reddy and Henningson (1993), the maximum of the streamwise velocity perturbation growth is associated with the logarithm of the Reynolds number, i.e. $u'_{\max} \propto \log(Re)$. The onset of the secondary instability correlates directly both with $u'_{\max}$ and the maximum in time for the transient growth decreases also with the Reynolds number as $t_{\max} \propto Re^{1/3}$. Thus, a slight modification of the Reynolds number of about 20% may change $u'_{\max}$ nearly by a decade. At low Reynolds numbers $u'_{\max}$ may not be large enough to trigger the non-linear interactions and quite large initial perturbation magnitudes are needed for the transition to occur. That explains why most of the studies on the by-pass transition mechanism in canonical macro-scale flows have been limited to relatively large Reynolds numbers compared to the subcritical transitional Re. The Poiseuille channel flow investigations of Henningson et al. (1993) for example deal with $Re = 3000$ which is large compared to the subcritical limit $Re \approx 1000$ (Orszag and Patera, 1993). The Reynolds number used here $Re \approx 2000$ is moderately low. Yet the structure A combined with B trigger is capable to trigger transition.

By pass transition necessitates an a priori increase in the wall normal velocity component. Fig. 5 compares the v contours generated at $t = 120$ by $A + B$ and B alone. It has to be emphasized that the contours for B alone are systematically *five times smaller*. The interaction of B with A generates an extended zone of v with the apparition of small scale structures of high intensity. The structures are merely centered at $z \approx -6$ where the stretching of the wall normal vorticity layers is hypothetically largest. Note the total absence of activity at $z \geq 0$, where the effect of asymmetry discussed before is negligible. The structure B induces extremely weak v perturbations, since once more it is incapable to trigger alone transition as the structure A alone. Only their combinations in a specific way leads to the generation of a turbulent spot.

The model proposed here is based on the generation of streamwise gradients of w component. The contours of $\frac{\partial w}{\partial x}$ are shown in Fig. 6. An intense inclined $\frac{\partial w}{\partial x} > 0$ layer is generated at $z \approx -9$ and $y \leq -0.75$ in an apparent agreement with the mechanism suggested in Fig.2 and under the compressing effect of the wall normal vorticity layers corresponding to A through the effect of B. The structure B compresses and stretches the ω_y layers respectively at the lower and upper walls. The generation mechanism proposed before is similar in both cases but the intensity of the stagnation flow is higher near the lower wall. Thus, $\frac{\partial w}{\partial x}$ layers are also generated at $y \approx 1$. There are some residual $\frac{\partial w}{\partial x}$ walls near the channel centerline in case of B (Fig. 6, right) but they are weak and dynamically insignificant.

Fig. 7 shows the streamwise vorticity ω_x contours at $t = 120$ and $x = 30$ corresponding to structures $A + B$ (left) and B alone (right). The differences in the near wall activity generation are once more clear strengthening the present proposition. Two small scale streamwise vortices freshly rolled up are clearly seen near $y \approx -1$ at the left of Fig.7. They are coming from the tilting of $\frac{\partial w}{\partial x} > 0$ layers induced by the asymmetry. Other configurations show similar trends and will be discussed at the Symposium.

CONCLUSION

The basic characteristic of the by-pass transition mechanism is the generation of near wall streamwise vortices. The streamwise vorticity is merely produced by the tilting of the wall normal vorticity by the shear. This requires the formation of concentrated longitudinal gradients of the spanwise velocity zones. One way to generate these zones is to induce a spanwise asymmetry in the near wall ω_y layers. The genesis of new quasi-streamwise vortices depends upon the capability of the primary structures to regenerate x dependent intense wall normal vorticity. The DNS shows that the impingement of sweep flow caused by a parent structure razes rapidly one of the initially slightly x-dependent high speed streak. This leads to a local asymmetry between the streamwise evolutions of wall normal vorticity resulting in a secondary $\frac{\partial w}{\partial x}$ layer, which, in return is tilted by the shear and regenerates new quasi-streamwise structures. The bypass transition resulting from this process is significantly more rapid compared to the effect of localized single disturbances.

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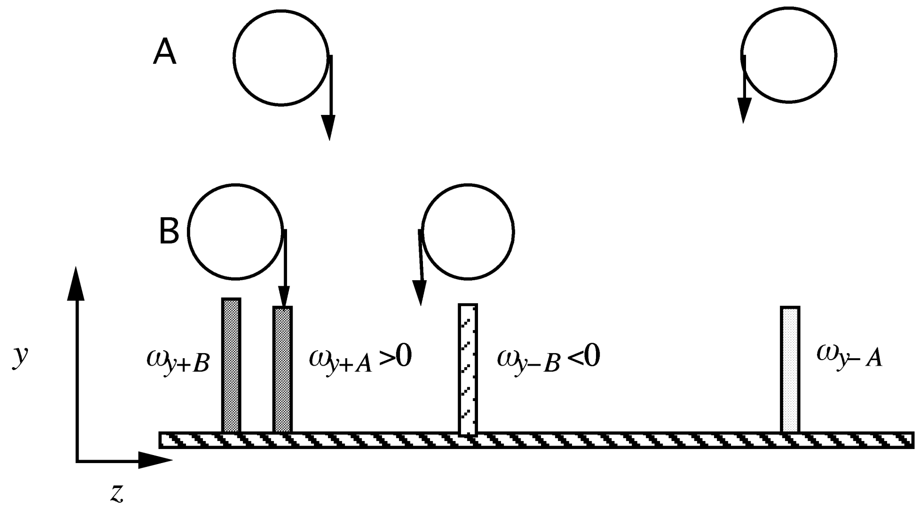


Figure 1 Cross sectional view of two pairs of counter rotating quasi-streamwise vortices in the plane $y-z$. The pair A regenerates wall normal vorticity layers denoted by $\omega_{y\pm A}$ positive and negative respectively at the left and the right. Similar vorticity layers $\omega_{y\pm B}$ are generated by the pair B.

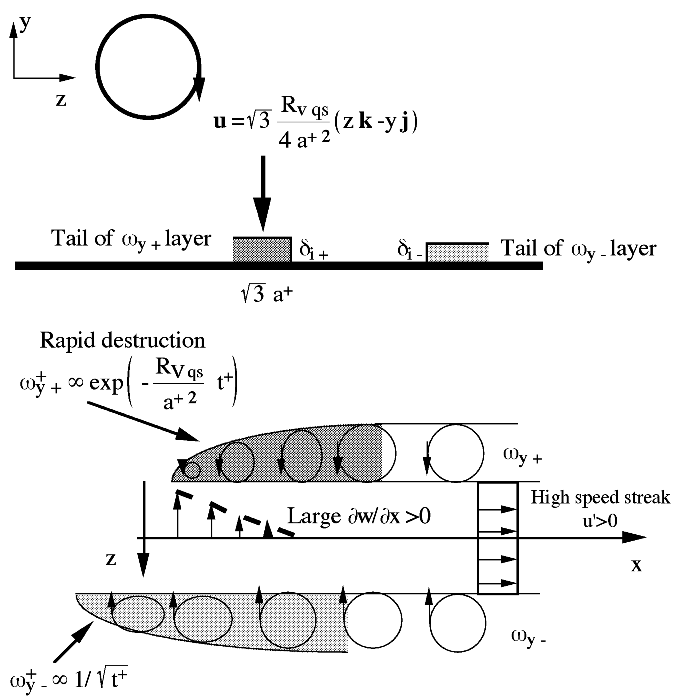


Figure 2 Conceptual model of generation of local streamwise variations of the spanwise velocity which is part of the major production term of ω_x vorticity.

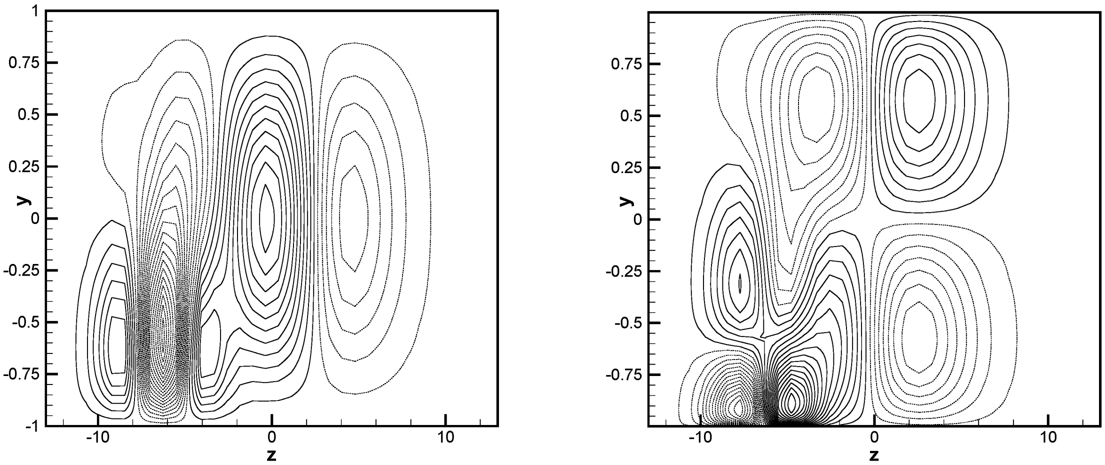
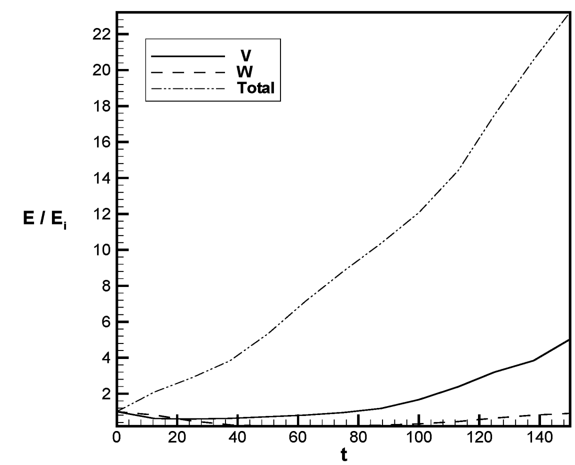


Figure 3 Initial wall normal (left) and spanwise (right) velocity distribution at $x = 2$ corresponding to the configuration given in Fig. 1. The structure A is centred at $y = 0$ and B at $y = -0.6$.

a



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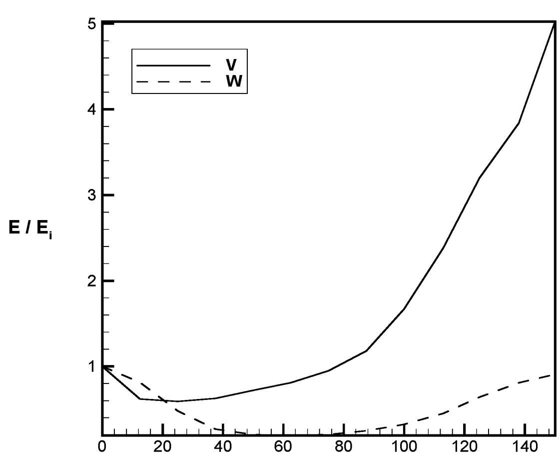

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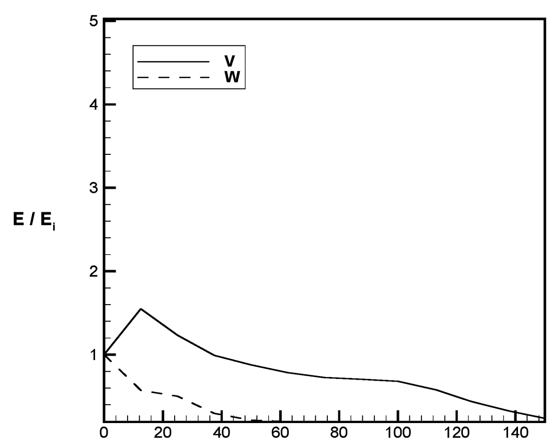

Figure 4 Temporal energy evolutions. a) Configuration $A + B$ of Fig.1, b and c: Energy associated with v and w respectively for $A + B$ and B only.

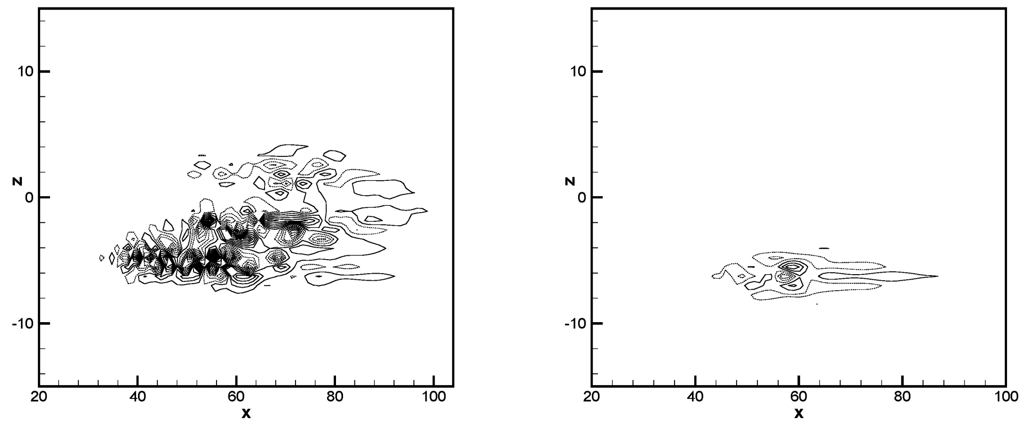

Figure 5 Wall normal velocity contours at $t = 120$ and $y = -0.6$ corresponding to structures $A + B$ (left) and B alone (right). Minimum and maximum at the left (-0.07,+0.07), contour spacing is 0.005. *The levels at the right are five times smaller.*

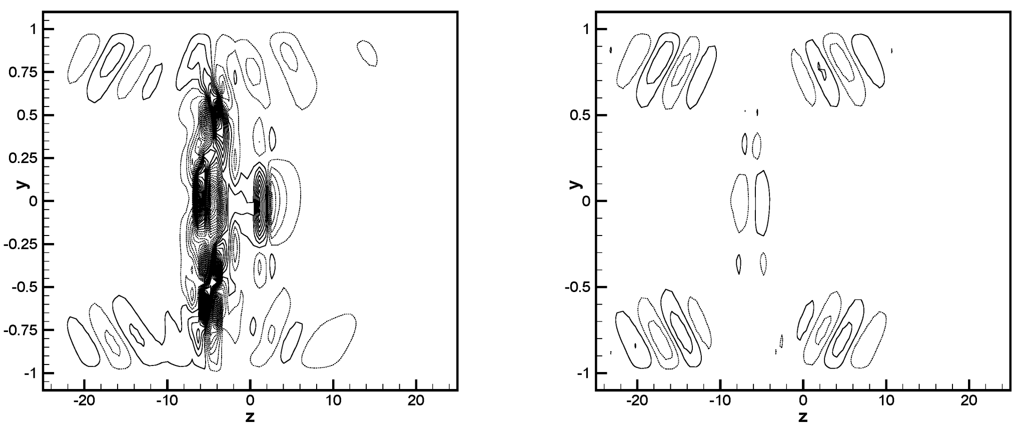

Figure 6 Contours of ($\partial w/\partial x$) at $t = 120$ and $x = 30$ corresponding to structures $A + B$ (left) and B alone (right). Minimum and maximum at the left (-0.006,+0.006), contour spacing is 0.0003. *The levels at the right are five times smaller.*

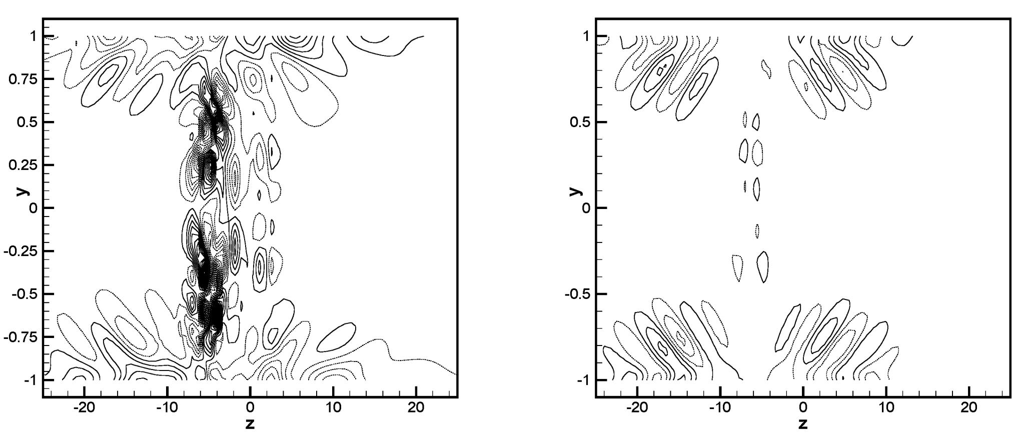

Figure 7 Streamwise vorticity contours at $t = 120$ and $x = 30$ corresponding to structures $A + B$ (left) and B alone (right). Min max at the left are used in both figures(± 0.07), contour spacing is 0.005. *The levels at the right are five times smaller.*