High-frequency excitation of a plane wake

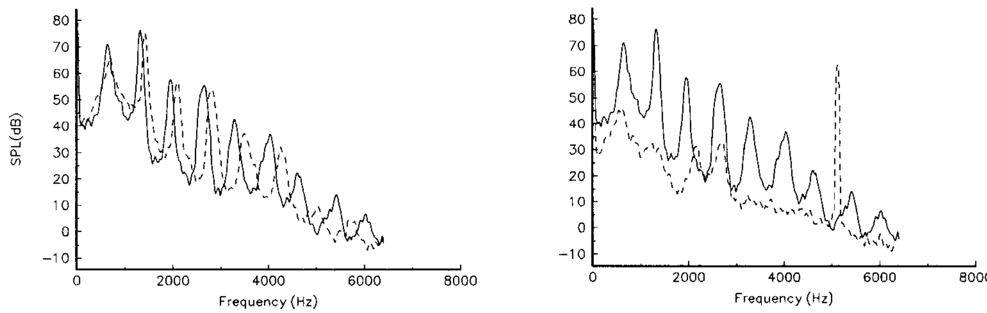
By Alan B. Cain† and Michael M. Rogers‡

1. Motivation and objectives

In the early 1990's, Glezer and his co-workers at Georgia Tech made a startling discovery. They found that forcing at frequencies too high to directly affect the production scales led to a dramatic alteration in the development of a turbulent shear layer. An experimental study of this phenomenon is presented in Wiltse & Glezer (1998). They used piezoelectric actuators located near the jet exit plane to force the shear layers of a square low-speed jet. The actuators were driven at a high frequency in the Kolmogorov inertial subrange, much higher than the frequencies associated with the large-scale motion (where the turbulent energy is produced and located) but much lower than those associated with the Kolmogorov scale (where the turbulent energy is dissipated). Measurements of the shear-layer turbulence showed that direct excitation of small-scale motion by high-frequency forcing led to an increase in the turbulent dissipation of more than an order of magnitude in the initial region of the shear layer! The turbulent dissipation gradually decreased with downstream distance but remained above the corresponding level for the unforced flow at all locations examined. The high-frequency forcing increased the turbulent kinetic energy in the initial region near the actuators, but the kinetic energy decreased quite rapidly with downstream distance, dropping to levels that were a small fraction of the level for the unforced case. Perhaps most importantly from the present standpoint, the high-frequency forcing significantly decreased the energy in the large-scale motion, increasingly so with downstream distance. Wiltse and Glezer interpreted this behavior as an enhanced transfer of energy from the large scales to the small scales.

The initial work by Wiltse & Glezer (1998) has expanded into other applications. To explore the potential of high-frequency forcing for active acoustic suppression, in 1998 the first author proposed a set of experiments involving an edge tone shear layer and an open cavity flow. This work was funded by the US Air Force Research Laboratory, and the experiments were developed and executed at Boeing by Raman and Kibens (Raman, Kibens, Cain & Lepicovsky 2000). These experiments involved high-frequency forcing applied to low-speed flows using wedge piezo actuators and powered resonance tubes. The system is simple, open loop, compact, potentially requires little power, and is easily integrated. Dramatic results, such as reductions of 20 dB in spectral peaks and 5-8 dB in overall levels across the entire acoustic spectrum, were obtained in some cases. Sample results are presented in Fig. 1. Following this success in low-speed flows, an international cooperative program continuing this work involved transonic experiments in a mid-size facility in the United Kingdom. Similar reductions in noise level were obtained in these transonic experiments. Discussion of this work is given in Raman *et al.* and Stanek, Raman, Kibens, & Ross (2000). Other experiments at Georgia Tech have shown significant potential of high-frequency forcing in controlling reaction rates in chemically reacting flows (Davis 2000).

† Innovative Technology Applications Company, Chesterfield, MO 63006
‡ NASA Ames Research Center, Moffett Field, CA 94035



(a) (b)

FIGURE 1. Effect of high-frequency excitation on an edgetone spectrum. Mach number M=0.07. Primary edgetone at 672 Hz. Excitation amplitudes (actuator displacement) (a) 0.2mm and (b) 6.0mm. ——— : (a) & (b) Run 23a; - - - - : (a) Run 25a, (b) Run 32a. Figure taken from Raman, Kibens, Cain and Lepicovsky (2000).

This recent work at Georgia Tech and Boeing is in sharp contrast to earlier ideas on how control of free shear flows should be approached. The review by Ho & Huerre (1984) characterizes the perspectives of the 1970's and 1980's, demonstrating the link between large-scale structures and linear stability theory. Drazin & Reid (1981) identify approaches to linear stability theory that determine the scale of exponentially growing disturbances. The work by Ho & Huerre extends the earlier stability theory/large-scale structure ideas by discussing vortex pairing and the more general merging of many large-scale structures. Ho and Huerre provide convincing experimental demonstrations of flow control by excitation frequencies that produce exponentially growing disturbances according to linear stability theory. Cain & Thompson (1986) provide another example of the merits of linear stability analysis. They show that the growth rates predicted by linear theory are able to predict the evolution of finite amplitude disturbances to a saturated state as given by a full nonlinear simulation. These are a few examples of many studies that characterize the control possibilities of free shear flows using "low-frequency", stability-theory-guided frequency selections. The Georgia Tech/Boeing studies constitute a major departure from earlier work. These recent studies do not dispute the results of the earlier work, only the assumption that turbulence theory and linear stability theory preclude interesting effects in the "high-frequency" excitation regime. The new "high-frequency" regime is currently without a theoretical basis, and the present study is aimed at adding detailed quantitative insight into this phenomenon.

There is a need to understand the basic mechanism behind effective high-frequency forcing so that scaling laws can be developed to facilitate reliable large-scale system design. The Boeing experiments sometimes produce dramatic results, but other high-frequency control systems don't show the same improvement. An understanding of the physics is required to ensure reliable application of the technology.

2. Results

Here we use direct numerical simulations of free shear layers to investigate the impact of high-frequency forcing on various aspects of shear layer evolution. To ensure that the results found are representative of what would be observed in flows of practical interest, it is necessary to have the ability to simulate realistic high-Reynolds number turbulent shear flows. For this purpose, the pseudospectral free shear layer code used by Rogers and Moser (1994) and Moser, Rogers, and Ewing (1998) has been chosen (the version of the code used to generate the simulations described here actually uses a different numerical representation of the flow variables in the inhomogeneous direction, as described in Rogers (2001)). This code is designed to simulate incompressible temporally evolving plane free shear layers. By simulating a temporally evolving flow, much higher turbulence Reynolds numbers can be achieved and cleaner boundary conditions can be implemented. Although the temporally evolving flow possesses symmetries not present in spatially developing flows, the dynamics of the large-scale structures are similar between these two flows, and the results obtained here should be relevant to spatially developing flows as well. Thus the incompressible flows simulated here should be comparable to the experimental flows of Wiltse & Glezer (1998).

The turbulent plane wake flow was selected as the first flow of investigation, with the new simulations being compared to the baseline cases presented in Moser *et al.* (1998). These previously simulated baseline cases include three different plane wake flows, an "unforced" case, a (weakly) "forced" case, and a "strongly forced" case, the two forced cases having additional energy added to the two-dimensional modes of the computation at the initiation of the wake. The "strongly forced" case does not achieve self-similarity and is, therefore, a poor choice for a baseline flow. Both the "unforced" and "forced" cases evolve self-similarly once developed and exhibit statistical properties similar to experimental wakes. The "unforced" case spreads relatively slowly compared to the "forced" case and to most experiments, and it has little large-scale organization. One of the goals of this work is to determine whether high-frequency forcing can reduce the spreading rate of a free shear layer (and perhaps the associated level of large-scale organization) and this may not be possible for a baseline flow that is already spreading at a minimal rate. For this reason, the "forced" case (termed "FWAK") was chosen as a baseline flow for the investigation described here; although spreading at a rate typical of experimental flows, it is possible for the flow spreading rate to be reduced.

As described in Moser *et al.* (1998), the wake flows are generated by placing two different realizations from a turbulent boundary layer simulation (Spalart 1988) together as if they were forming on either side of an infinitely thin plate. At time $t = 0$ the plate is removed and the boundary layer turbulence evolves into free shear flow turbulence. For the forced case considered here, additional turbulent kinetic energy is added to all of the two-dimensional Fourier modes of the computation at $t = 0$ as well. As noted in Moser *et al.*, statistics from the forced wake case indicate self-similar evolution for non-dimensional times $\tau = tU_d^2/\dot{m}$ greater than about 65 (where U_d is the initial free-stream velocity of the turbulent boundary layers relative to "the plate" and $\dot{m}$ is the conserved mass flux deficit of the wake). After about $\tau = 120$, the observed self-similarity begins to break down as a result of the limited computational domain size of the simulation. The Reynolds number based on the wake half velocity width and velocity deficit is about 2,000 during the self-similar period.

In order to document a sustained impact of high-frequency forcing on the wake, we hope to observe a change in the self-similar state achieved by the wake. Thus the high-frequency forcing should be applied prior to the start of the self-similar period at $\tau = 65$. On the other hand, the turbulence at $\tau = 0$ is still "boundary-layer" turbulence with significant viscous diffusion and a cusp-shaped mean velocity profile. In most experiments

Case	$\lvert k_x b^0 \rvert$	$\lvert k_x L_x \rvert/(2\pi)$	$\lvert k_z b^0 \rvert$	$\lvert k_z L_z \rvert/(2\pi)$	a_0	f	α	l/b^0
TURB1	[22.49,23.83]	[84,89]	0	0	0	20	0.0	0
TURB2	[22.49,23.83]	[84,89]	[27.85,29.99]	[26,28]	0	20	0.0	0
TURB3	[34.54,37.22]	[129,139]	[40.70,42.85]	[38,40]	1.0	250	0.5	1.64
TURB4	[34.54,37.22]	[129,139]	[0,1.07]	[0,1]	1.0	250	0.5	0.94
FTRANS	[34.54,37.22]	[129,139]	[0,1.07]	[0,1]	1.0	2500	0.5	0.94
HTRANS	[34.54,37.22]	[129,139]	[0,1.07]	[0,1]	0	25	0.5	0.94

Table 1. Parameters of the high-frequency forcing for each forced case. The first four columns indicate the (k_x, k_z) wavenumber range over which the forcing is applied and the last four columns characterize the y-profile of the forcing, given by $a_0 + f\exp\{-\alpha(|y|-l)^2/{b^0}^2\}$. The "TURB" cases are begun from the "FWAK" baseline case at $\tau = 12.17$. The "FTRANS" and "HTRANS" cases are begun from the "TRANS" case at $\tau = 12.17$ and $\tau = 89.43$, respectively.

the high-frequency forcing is applied somewhat downstream of the initiation of the free shear layer, and this choice has also been made in the computations, with the high-frequency forcing typically being applied at $\tau = \tau_f = 12.17$.

2.1. *Description of cases simulated*

Two classes of high-frequency forced simulations have been generated. The first consists of turbulent cases in which energy has been added to various high-frequency modes of the baseline FWAK computation at $\tau_f = 12.17$. The second consists of transitional flows in which energy has been added to high-frequency modes of a modified baseline flow, this modified flow being generated by reducing the amplitude of all the turbulent fluctuations of FWAK by a factor of ten at $\tau_f = 12.17$ (while leaving the mean profile unaltered). This modified base flow, labeled "TRANS" here, has thus been "relaminarized" to a large extent but still contains broad band three-dimensional disturbances. Flow visualization confirms that the flow is dominated by large-scale vortices that form an irregular Karman vortex street and have small-scale motions superimposed on them.

The baseline flows without high-frequency forcing are thus here referred to as FWAK and TRANS. The parameters for the cases with high-frequency forcing are listed in Table 1 and described below. Four simulations with high-frequency forcing were begun from the FWAK flow at $\tau_f = 12.17$. These cases differ in the amount of high-frequency forcing, the k_x (streamwise) and k_z (spanwise) wavenumbers into which energy has been added, and the y (cross-stream) profile of the forcing. The high-frequency forcing in the "TURB1" flow has been applied to two-dimensional modes ($k_z = 0$) over six streamwise wavenumbers $22.49 < |k_x b^0| < 23.83$ across the entire wake (i.e. for all y). The existing amplitudes of these Fourier modes have been increased by a factor of 20, corresponding to an initial increase in turbulent kinetic energy of 3.7%. Case "TURB2" uses the same multiplicative factor of 20 for the same k_x wavenumber range but for $27.85 < |k_z b^0| < 29.99$ rather than $k_z = 0$. The increase in turbulent kinetic energy for this flow is 5.0%. For the "TURB3" case, the forcing has been limited to narrow layers in the cross-stream (y) direction according to the profile $1 + 250\ \exp\{-0.5(|y|-l)^2/{b^0}^2\}$, where l is chosen to be $1.64b^0$. This forcing is applied only for wavenumbers $34.54 < |k_x b^0| < 37.22$ and

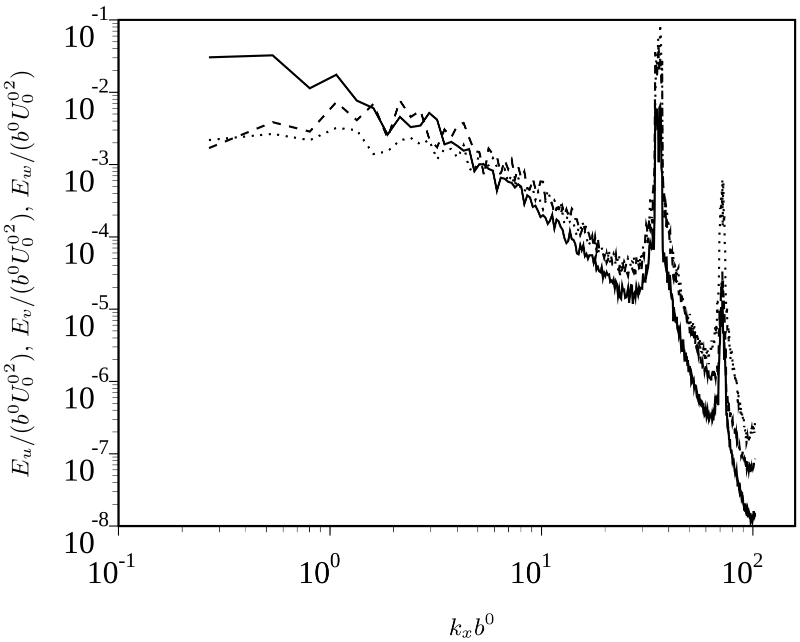


FIGURE 2. Energy spectra of the three velocity components for case TURB4 at $\tau = 12.30$, shortly after the high-frequency forcing is applied.

$40.70 < |k_zb^0| < 42.85$. The multiplicative factor of up to 251 by which the existing amplitudes have been amplified is only active over a limited range in y; despite this large value, the overall increase in the y-integrated turbulent kinetic energy is only 0.9%. The high-frequency forcing in case "TURB4" is applied to the same k_x wavenumbers as in TURB3 but for only the lowest three k_z wavenumbers of the computation, 0 and $\pm 1.07/b^0$. The forcing has also been applied closer to the layer centerline, with $l = 0.94b^0$. The initial increase in y-integrated turbulent kinetic energy is substantially larger for this case, being 49%.

Two other simulations with high-frequency forcing were run from the TRANS baseline case. In both, the high-frequency forcing was applied to the same k_x and k_z wavenumbers as in the TURB4 flow. In the "FTRANS" flow, the high-frequency forcing was applied at $\tau_f = 12.17$ in narrow layers located at $l = 0.94b^0$. The y-profile of the forcing is as given above except that the multiplicative factor has been increased to 2500 from 250. The "HTRANS" flow is the result of high-frequency forcing applied at a later time, $\tau_h = 89.43$, when the flow is more developed. At this point in the transition, the y-integrated production of turbulent kinetic energy is near its maximum. The forcing profile is given by $25 \exp\{-0.5(|y| - l)^2/b^{02}\}$, with l again equal to $0.94b^0$. The multiplicative factor is reduced because the growing disturbances at the later time τ_h are larger in amplitude. The increase in the initial y-integrated turbulent kinetic energy caused by the forcing was 4784% and 35% for the FTRANS and HTRANS cases, respectively.

In order to verify that the forcing used in the computations is qualitatively similar to that found in the experiments, energy spectra from the forced flows have been examined. The streamwise k_x wavenumber spectra for $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ at $\tau = 12.30$ (shortly after the forcing has been initiated) in the TURB4 flow are shown in Fig. 2. The spectra are similar to those observed by Wiltse & Glezer (1998), with the energy associated with the

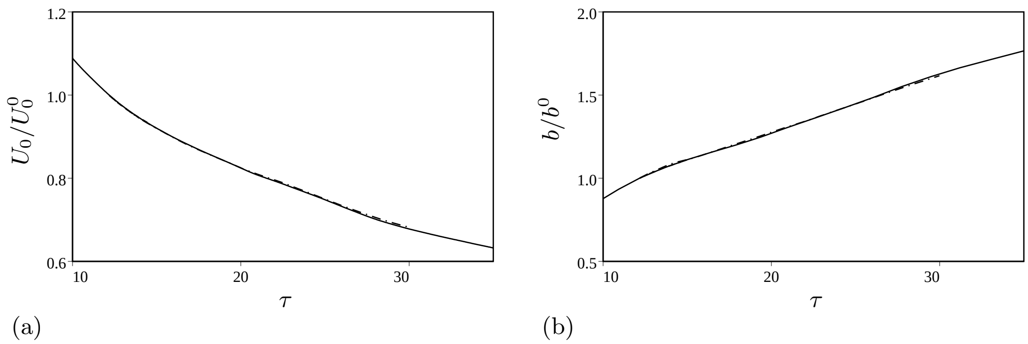


FIGURE 3. Time evolution of (a) the wake peak mean velocity deficit U_0 and (b) the wake width b. ——— FWAK, - - - - TURB1, ········ TURB2, — — — TURB3, and —·— TURB4.

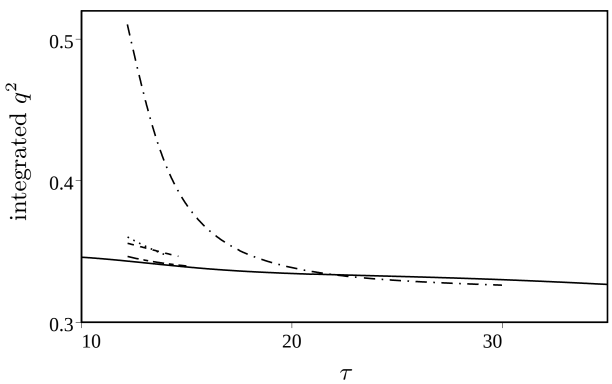


FIGURE 4. Time evolution of the cross-stream integrated turbulent kinetic energy. ——— FWAK, - - - - TURB1, ········ TURB2, — — — TURB3, and —·— TURB4.

forcing being at about the same relative wavenumber, of similar relative width, and of similar amplitude compared to the energetic large scales of the turbulence.

2.2. *Forcing of a fully turbulent wake*

In this section the impact of high-frequency forcing on a fully turbulent plane wake is investigated. The figures presented here contain results from the four "TURB" simulations as well as for the unforced baseline case "FWAK". As noted above, the forcing is applied at $\tau_f = 12.17$. The forced runs are terminated at $\tau \approx 15$ for TURB1, TURB2, and TURB3, and at $\tau = 30$ for TURB4.

The evolution of the scale parameters describing the wake mean velocity profile, the magnitude of the peak mean velocity deficit U_0, and the full width of the wake at the half-deficit points b are shown in Fig. 3. These parameters have been non-dimensionalized by their values at $\tau = 12.17$, denoted by U_0^0 and b^0. The mean profile evolution for all four forced flows is virtually identical to the baseline case, with only barely perceptible differences in U_0 and b.

The evolution of the turbulence is impacted to a greater degree than the mean velocity profile. The evolution of twice the cross-stream (y) integrated turbulent kinetic energy is shown in Fig. 4. Relatively little turbulent kinetic energy has been added to the TURB1, TURB2, and TURB3 cases by the forcing, and what has been added starts decaying fairly rapidly. In contrast, the integrated kinetic energy has been greatly (by 49%) augmented

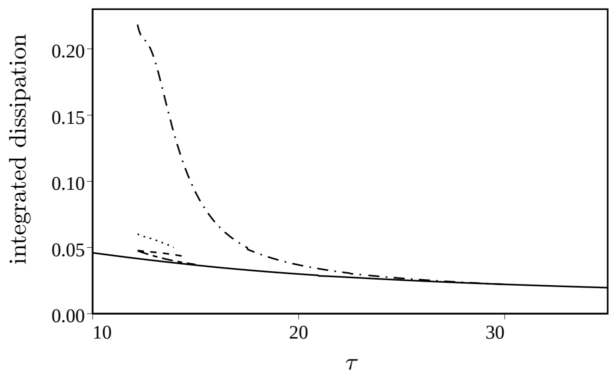


FIGURE 5. Time evolution of the cross-stream integrated turbulent kinetic energy dissipation. ——— FWAK, - - - - TURB1, ········ TURB2, — — — TURB3, and —·— TURB4.

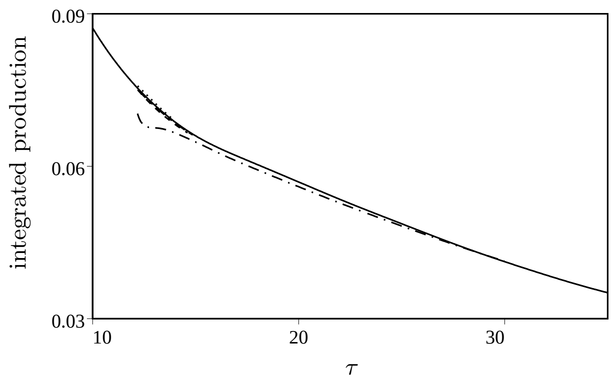
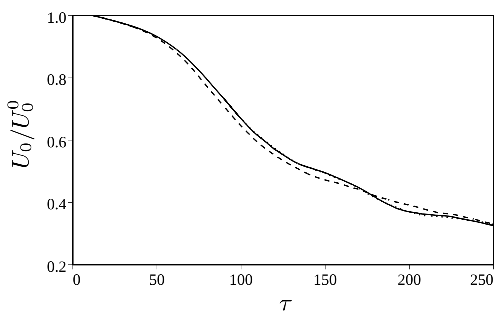


FIGURE 6. Time evolution of the cross-stream integrated turbulent kinetic energy production. ——— FWAK, - - - - TURB1, ········ TURB2, — — — TURB3, and —·— TURB4.

by the forcing in TURB4. In this case too, however, the energy decays rapidly, assuming a value slightly (1.2%) below that of the baseline unforced case by $\tau = 30$. Although this reduction in turbulent kinetic energy once the flow is developed is qualitatively similar to the experimental observations of Wiltse & Glezer (1998), the magnitude of the effect is much weaker.

The impact of the forcing on the turbulent kinetic energy dissipation rate is even more pronounced, as expected since the dissipation is associated with strong velocity gradients at small scales. The evolution of the cross-stream integrated turbulent kinetic energy dissipation rate is shown in Fig. 5. The relative increase in dissipation rate is thus higher than that of the kinetic energy, reaching 425% initially at τ_f for case TURB4. This increase also decays rapidly, with the TURB4 dissipation level at $\tau = 30$ being indistinguishable from the baseline case, indicating that the high-frequency forcing has not resulted in a sustained increase in dissipation level.

The impact of the forcing on the production of turbulent kinetic energy is much less pronounced, as expected since production is not strongly impacted by the small-scale motions. The evolution of the cross-stream integrated turbulent kinetic energy production rate is shown in Fig. 6. The TURB1, TURB2, and TURB3 flows depart only negligibly from the baseline case. The high-frequency forcing results in a 6.7% reduction in the



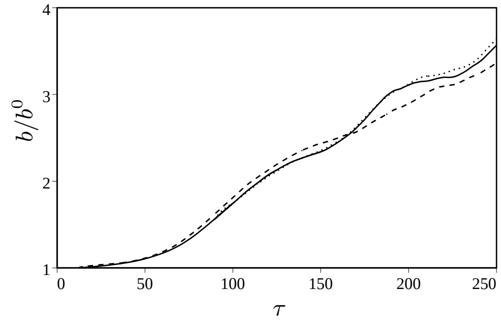


FIGURE 7. Time evolution of (a) the wake peak mean velocity deficit U_0 and (b) the wake width b. ——— TRANS, – – – – FTRANS, and ········ HTRANS.

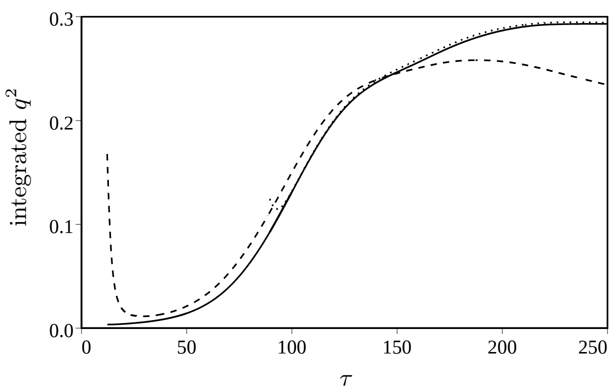


FIGURE 8. Time evolution of the cross-stream integrated turbulent kinetic energy. ——— TRANS, – – – – FTRANS, and ········ HTRANS.

production for case TURB4, but after initially further decreasing relative to the baseline case, the evolution becomes identical to that of FWAK by $\tau = 30$.

2.3. *Forcing of a transitional wake*

The effects of high-frequency forcing in the simulations of fully turbulent wakes die out quickly and have no lasting impact. In order to determine whether transitional wakes are more sensitive to high-frequency forcing, three additional simulations were made as outlined in section 2.1.

The impact of the high-frequency forcing when applied early in the transition process (FTRANS) is more significant than when applied later (HTRANS) or when applied to the fully turbulent wake examined in section 2.2. Additionally, it appears that some of the effects may be sustained, persisting even once the wake is developed.

The time evolutions of the peak mean velocity deficit and the wake width are shown in Fig. 7. The evolution of both quantities in the HTRANS flow is very similar to the corresponding evolution in the unforced TRANS case, while the behavior in the FTRANS case is somewhat different. In FTRANS the wake spreads more uniformly in time and ultimately is not as wide as in the TRANS case at the same time.

Similarly, the evolution of the y-integrated turbulent kinetic energy shown in Fig. 8 shows little difference between the HTRANS and TRANS cases, but forcing early in the transition, as in FTRANS, results in sustained lower levels of turbulent kinetic energy

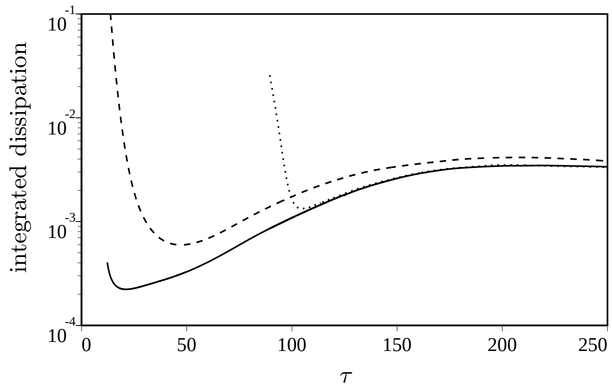


FIGURE 9. Time evolution of the cross-stream integrated turbulent kinetic energy dissipation. ——— TRANS, - - - - FTRANS, and ········ HTRANS.

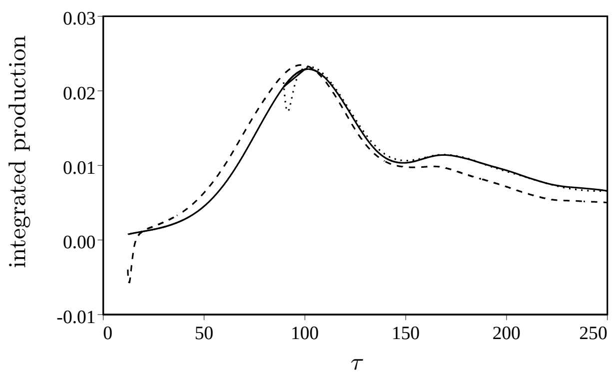


FIGURE 10. Time evolution of the cross-stream integrated turbulent kinetic energy production. ——— TRANS, - - - - FTRANS, and ········ HTRANS.

after $\tau \approx 150$. At $\tau = 250$ this reduction (FTRANS relative to TRANS) is 20.0%, whereas the reduction in wake width noted above is only 5.6%. The average turbulent kinetic energy density in the wake is thus reduced by 15%.

The sustained reduced turbulent kinetic energy levels in FTRANS are accompanied by sustained increased levels of turbulent kinetic energy dissipation. As seen in Fig. 9, the initial large increase in turbulent kinetic energy associated with the high-frequency forcing decays quickly, but in FTRANS there is still a 13% increase relative to TRANS at $\tau = 250$. In contrast, the differences between HTRANS and TRANS is virtually undetectable for $\tau > \tau_h + 20$.

Reductions in turbulent kinetic energy come about not only as a result of sustained increased dissipation levels, but also because of sustained decreased production levels. The time evolution of the y-integrated production of turbulent kinetic energy is shown in Fig. 10. In both FTRANS and HTRANS the high-frequency forcing results in a short term (for $\Delta\tau \approx 5$ to 7) reduction in production. In FTRANS the integrated production actually becomes negative; in HTRANS it is reduced by about 18%. As before, the evolution in HTRANS quickly relaxes to the unforced behavior, whereas FTRANS maintains a sustained reduction of 24% at $\tau = 250$. For $\tau < 100$ the main effect of the high-frequency forcing in FTRANS is to shift the integrated production and dissipation curves about $\Delta\tau = 6$ to earlier times. It is thus possible that the primary effect of the forcing is to

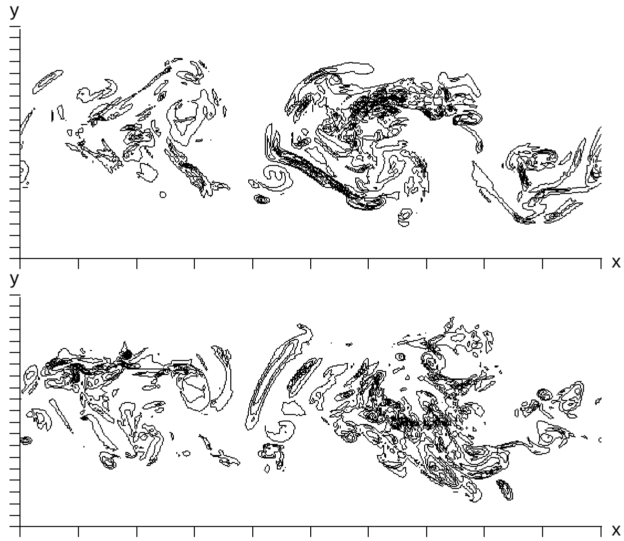


FIGURE 11. Contours of vorticity magnitude in the $z = 0$ plane at $\tau = 200$ for (top) TRANS and (bottom) FTRANS. Contour increment is U_0^0/b^0.

initiate an earlier transition, which in turn results in a narrower wake with reduced levels of turbulent kinetic energy.

Given the reduced wake width and turbulent kinetic energy density in the FTRANS flow, it is of interest to examine the structure of the flow to determine what, if any, structural changes are associated with the changes in wake statistics. Early in the flow evolution the differences between the FTRANS and TRANS flows are minimal. Once the flow is developed, however, detectable differences are evident. Contours of vorticity magnitude are shown in Fig. 11 for both flows at $\tau = 200$. The forced flow FTRANS is less organized, with smaller, less coherent intrusions of irrotational flow into the layer from both freestreams. These differences are the same as those observed in Moser *et al.* (1998) for wakes of differing self-similar spreading rates that arise from large scale two-dimensional forcing. Also evident in the figure is the limited statistical sample of large-scale eddies (about 2.5) in the computational domain at $\tau = 200$, suggesting the need for some caution when drawing conclusions from these late-time results.

3. Conclusions and future work

In conclusion, simulations of fully turbulent wakes suggest that high-frequency forcing has a minimal impact on the evolution of this developed flow after a brief transient. On the other hand, transitional wakes appear to be more sensitive to high-amplitude, high-frequency forcing. Such forcing must be applied while the disturbance amplitudes are still small compared to their amplitudes in fully turbulent flow. In this case, the simulations suggest that sustained reductions in wake spreading and turbulent kinetic energy density may be possible. In particular, reductions in y-integrated turbulent kinetic energy of up to 20% were observed in the simulations, resulting from both increases in the dissipation-rate of turbulent kinetic energy and decreases in the turbulent kinetic energy production rate. Longer simulations might show even more significant effects but a much costlier, larger domain calculation would be required to confirm this.

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