Appendix D

A COMBINATION OF FLOW MODALITIES: A DISCUSSION OF THE APPLICATION OF PERTURBATION TECHNIQUES

D.1 The application of software-enabled perturbation techniques

The relative magnitudes of the ratio of the fluctuating velocities to the mean velocities (i.e. the turbulence intensity) will nominally vary with altitude in an atmospheric boundary layer (e.g., see Stull, 1988) and a prevailing wind flowing over and around the built-up environment will generate a whole host of wakes, mixing layers, and combinations thereof. These realities motivate the development of software-enabled perturbation techniques that can both increase the standard deviation of the fluctuating velocities about a desired mean as well as initiate, evolve, and combine flowfields in representative ways. Stated summarily, the perturbation strategy is achieved through three primary tactics:

- Randomize initial velocity conditions and play those through activated dynamic-ranging algorithms
- Statically-reconfigure (combine) the individual discrete fan units into a coarser representation and allow the flow to naturally evolve
- A combination of the two aforementioned

The random-phase (R-P) perturbation technique discussed in appendix C can actively dial the turbulence intensity higher through a prescriptable range that is limited amplitudinally by the available percentage-deviation to the maximum velocity output from the targeted mean. This perturbation technique distributes energy broadly amongst all the scales, particularly when ranged symmetrically (recall fig. C.1 and fig. C.4) and was shown in Chapter IV that a near doubling of the turbulence intensity corresponded to a nearly sevenfold increase of Re_{λ_T} for a mean velocity that stayed within 4% of the targeted mean velocity. Also showcased in Chapter IV was the static reconfiguration of the fan array into a so called quasi-grid. Significant increases of Re_{λ_T} were noted. Turbulence initializes from the principal shear layers generated at the fan outlet plane, diagrammed in fig. 4.1. In the following section a combination of techniques is explored, whereby within a coarser planar segment of statically-reconfigured fan units, dynamic-ranging algorithms are activated.

A discussion by way of example - a perturbed triple-stream mixing layer

The triple-stream mixing layer introduced in Chapter III is an exemplar flow modality candidate to leverage the aforementioned perturbation tactics. Since the mixing layers generated herein are implemented with virtually no boundary structure beyond the source-fan housing (i.e. "splitterplateless"), traditional boundary layer augmentation techniques are not an available option. Instead attempts to control the flowfield with the fluid medium itself are undertaken. One could argue that the static-reconfiguration of source fans through software is a pseudo-manipulation of boundary conditions, as it introduces a geometrically relevant length scale, but that discussion is left for another time. In either case, it is emphasized that no additional geometries are added to the multi-source configuration[1].

A brief overview of the behavior of perturbed free shear layers

Because mixing layers are susceptible to inviscid instabilities, they are good candidates for flow manipulation. By flow manipulation, two notions are implied in line with the two primary perturbation techniques. In the parlance of H. Fiedler and Fernholz (1990) a flow can be influenced 1) by the design choices of the wind tunnel flow management system (honeycombs, screens, static-reconfigurations, etc.) and 2) by flow control (dynamic-ranging algorithms), which is a process to manipulate certain characteristics of a flow to achieve "improvements" of a specified technical outcome.

Supported by a plethora of experimental evidence, the coherent structures of a conventionally-generated mixing layer are most receptive to periodic oscillations just downstream of the splitterplate edge (e.g., see Oster and Wygnanski, 1982), where mixing is initiated. In a similar manner, perturbations initiated through software-means in multi-source wind tunnels affect the local neighborhood of flow development where mixing is initiated. Ho and Huerre (1984) summarize some conditions to effectively manipulate the development of mixing layers. Amplitudinal fluctuations as small as $u'/U \sim 10^{-7}$ are enough to influence the behavior of the

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[1] In particular, no splitterplate geometry is added to divide the mixing layer, no turbulence-generating grids are added to increase freestream turbulence, and no loudspeaker or vibrating ribbon is added to periodically oscillate the flow. All the desired effects are attempted through software means alone. There is no reason (beyond convenience and principle) why any or all of the aforementioned elements could not be integrated into these kinds of experiments.

coherent structures if activated at the proper forcing frequency. First and foremost, the imposed fluctuation should be spatially coherent along the span. Secondly, vortex formation[2] can be controlled through careful selection of the forcing frequency. For example, in the range of $(1/2)f_n < f_f < 2f_n$, the vortices are found to form at the forcing frequency. The higher the initial energy at the forcing frequency in this range, the greater the suppression of the growth of the subharmonic $f_n/2$, which plays an important roll in vortex pairing. As such, the forcing frequency has a stabilizing effect in that the coherent structures stay distinct for longer.

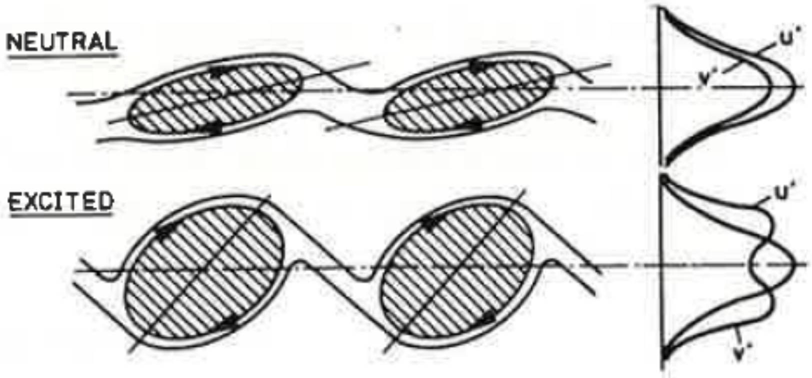

Figure D.1: The stabilizing effect on coherent structures through forcing, from Koepp et al. (1991).

When excited and stabilized, the ratio of the major axes of the coherent structures approach unity and the longitudinal velocity component along the streamwise direction is largely reduced. The spreading rate of the mixing layers can thus be increased by promoting vortex amalgamations or reduced by suppressing the subharmonic. The effect hinges primarily on the selection of the forcing frequency and secondarily on its amplitude. At very low forcing frequencies far from the natural frequency (i.e. $f_f << f_n$), larger perturbations on the order of 10^{-2} are necessary to effect similar behavior. At such low frequencies, mode competition becomes more evident, with the forced wave dominating the flow evolution.

The behavior of perturbed mixing layers can thus be summarized as follows:

- Coherent structures are generated upon initiation of the mixing layer and grow with downstream development; in virtually every situation, the expectation is

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[2] this is synonymous to the location of the first vortex rollup. In an excited shear layer, this occurs at the particular harmonic of the forcing frequency that is nearest but less than the natural frequency.

that the coherent structures exist quasi-two-dimensionally if they are initiated with spanwise coherence

- Manipulation of these turbulent shear flows are possible by manipulation of the coherent structures themselves
- Introducing forcing frequencies where the flow is most receptive is the best way to manipulate the coherent structures
- Changes in freestream turbulence may also affect the spreading rate of the mixing layer by encouraging the onset of mixing, but are observed to be secondary (less-effective) to manipulation of the coherent structures

Perturbation strategy for triple-stream mixing layers

These experiments, considered in its entirety, consist of a plant (the base flowfield) a measuring system (hotwire traverse in this case) and a controller (the software algorithms commanding the fan actuators). Open-loop control is employed throughout, though efforts are underway for closed-loop control for future studies. The processes triggered by the control of the fan actuators is intrinsically nonlinear, but the controllability of the flow is governed by the stability characteristics of the fluid medium, namely the temporal and spatial growth behavior of initial perturbations. The receptivity of the flow to external forcing can be expected to occur where the flow is locally and/or globally unstable, shown to occur where mixing is initiated in the case of the mixing layer.

With the above discussion in mind, the triple-stream mixing layer perturbation strategy acts to potentially influence the subsequent development of the merged dual-stream mixing layer in three primary ways:

- By encouraging amalgamations of a different kind by bringing two mixing layers into proximity of one another; these may act as superpositions if the natural frequencies are (near-)matched or mode competition may become evident
- By stabilizing/destabilizing the coherent structures with selection of perturbation frequency and amplitude at the fan outlet plane, the spreading rate can be augmented

- By increasing the energy content broadly in the freestream; if the scales of these random motions are of the order of the shear layer width, then quasi-steady bulk-flow behaviors like "snaking" may occur

Preliminary results and discussion

Fan arrays were shown to behave as low-pass filters (see Chapter II) frequency-limited to $f_f \lesssim 2$ Hz for the apparatus used herein. Greater-amplitude perturbations of at least order 10^{-2} are to be used, then, since the natural frequencies of the triple-stream mixing layers estimated from $f_c \sim f_{50} = U_c/\Lambda_x^u$ are greater than half the forcing frequency (see table 5.2). Perturbed triple-stream mixing layer experiments are currently being undertaken, but some tentative conclusions can be drawn for the completed datasets at $x = 88$ inches for the $ss = 4d$ case, shown in fig. D.2. Because the perturbation tactics require velocity margin above and below a targeted mean velocity, freestream velocities must be sufficiently far from the operational maximum and minimum velocity of the fan array wind tunnel to be effective. In the triple-stream mixing layer cases presented herein, ranged fluctuations, when applied everywhere through software, are not expected to be effective on the lower segment side (as those freestream velocities are near the idle velocity of the fan units). As such, the mean velocity profiles are collapsed upon the lower mixing layer parameters (which are not expected to change much) to highlight the qualitative effects of the upper mixing layer development due to implemented perturbation techniques.

The perturbation tactics are employed either at every planar segment (i.e. across the whole fan array) or on selected planar segments with the remainder segments left to baseline initial conditions. For instance, the random-phased ranged-fluctuation algorithm activated over a 60% amplitudinal range (an order 10^1 perturbation) is implemented across all three planar segments in one such experiment, but then is implemented on select planar segments (e.g. across only the center segment, subscripted as 'c', or the upper segment, subscripted as 'u') in other experiments. The same is true for the presented sinusoidal perturbations initiated at forcing frequencies of $f_f < 2$ Hz.

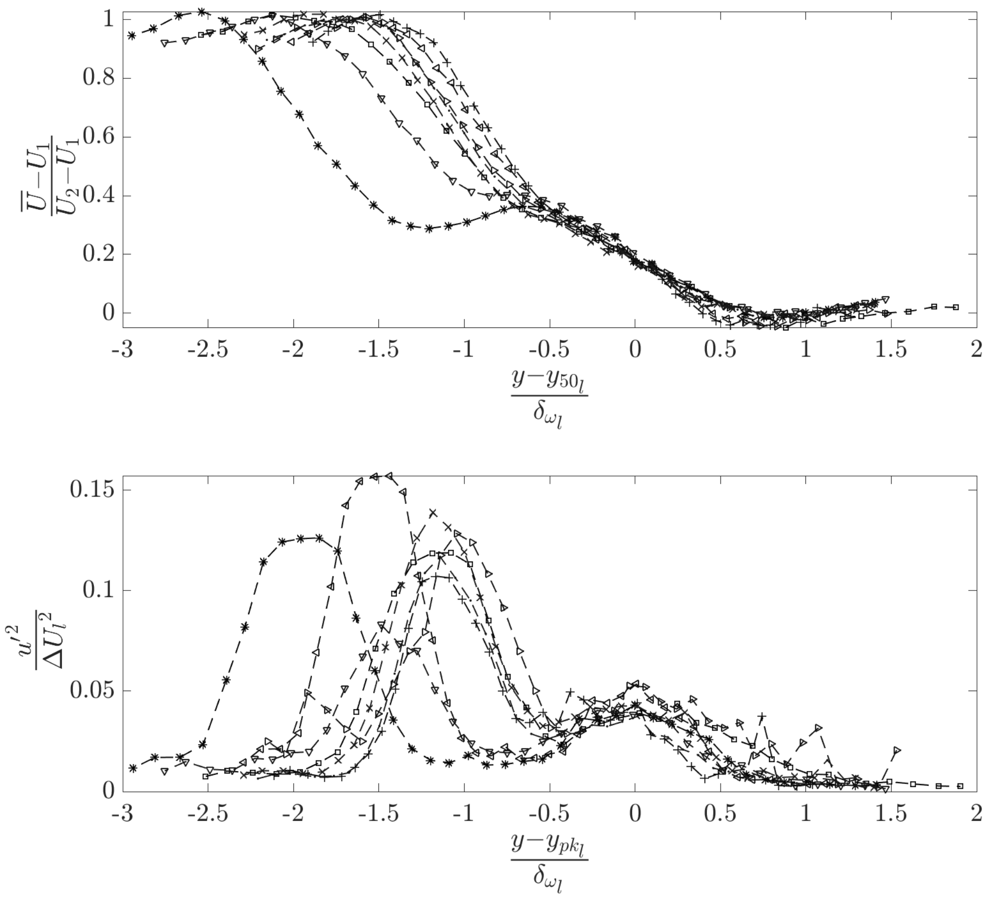

Figure D.2: Mean velocity profile (above) and fluctuating velocity profile (below) for the perturbed triple-stream mixing layer with initial separation of $ss = 4d$. The baseline (non-perturbed case) is denoted by the (□) marker. Random-phase perturbations are denoted by ($*$) when applied to the whole array, (+) the center segment, and the (◃) upper segment. Sinusoidal periodic perturbations of $f_f = 1$ Hz is applied to the whole array ($\cdot$) and the upper segment (▹), $f_f = 2$ Hz is applied to the whole array (x) and the upper segment (▽).

Immediately evident in the mean velocity profiles are changes in the separation distance between the upper mixing layer and lower mixing layer, seen as a 'fanning-out' relative to the baseline configuration (denoted by the (□) marker). The relative maximum-slope thickness, at first glance, also appears to change, suggesting the spreading rates are augmented. The fluctuating velocity distributions, when pinned at the peak u'^2 location for the lower mixing layer, show movement of the upper mixing layer fluctuating velocity peaks relative to the baseline case. Differences in behavior in the mean velocity profiles elucidated by this rather limited analysis is observed in the random-phase case applied over the whole array ($*$) and the periodic sinusoidal perturbation of $f_f = 2$ Hz applied only to the high-speed stream of the upper mixing layer ($\triangledown$). An effective movement of the peak centerline location of the upper mixing layer toward the high-speed stream in the case of the random-phase perturbation applied solely to the upper segment ($\triangleleft$) is clearly showcased in the fluctuating velocity distribution. These particular cases warrant further careful study. Traverses at the remaining downstream locations scheduled for near-future experimentation will allow calculation of the spreading rate and x-wire hotwire measurements will help determine the lateral fluctuating velocity evolution, which is likely to increase[3]when the mixing layers are excited and/or near merging.

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[3] Subsequent increases of mixing layer thickness deducible from mean velocity measurements is most likely due to increased lateral momentum transport on account of the increased lateral fluctuating velocity components though no direct experimental evidence can be provided from single-wire hotwire traverses. An estimate of the mean transport of turbulence energy for two-dimensional flow is given in the form $-\frac{\partial}{\partial y}\frac{1}{2}(\overline{u'^2 v'} + \overline{v'^3} + \overline{v' w'^2})$.