Appendix C

TURBULENCE ON-DEMAND (TOD)

A technique to increase turbulence intensity without significant changes to the mean velocity profile (i.e. increased background turbulence decoupled from a targeted mean) is briefly presented. With the receptivity of the flow to commanded discrete forcing frequencies for uniform flow modalities established in section 2.1, pseudo-random perturbation algorithms can be developed. Collectively referred herein as turbulence on-demand (TOD) are the techniques for the tailoring of specific turbulence parameters through software interfacing alone. This is not unlike the toolset available to the numericist in simulated environments[1], but manifested in experimental domains to the extent possible with existing hardware. A couple salient features of TOD are enumerated below.

C.1 Fluctuations about a desired mean - random-phase (R-P) mode

A straightforward consequence of having individual and separate control of each fan unit (particularly in the stacked dual-unit design) allows for prescript and ranged fluctuations about a desired mean. This effectively decouples the turbulence intensity from the mean (which is not possible through geometric means). The algorithm is straightforward and is quickly described as follows:

- assign allowable deviation percentage from the desired mean
- assign "phase" or starting point within the allowable range to be randomly distributed spatially across the fan units
- activate fans and allow them to cycle within the range allotted

[1] A form of the Navier-Stokes equations common in forced incompressible flow simulations is $\frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\frac{1}{\rho}\nabla p + \nu \nabla^2 u + f$. Similarly, the effect of environmental disturbances can be explored with suitable forcing functions developed in the experimental domain.

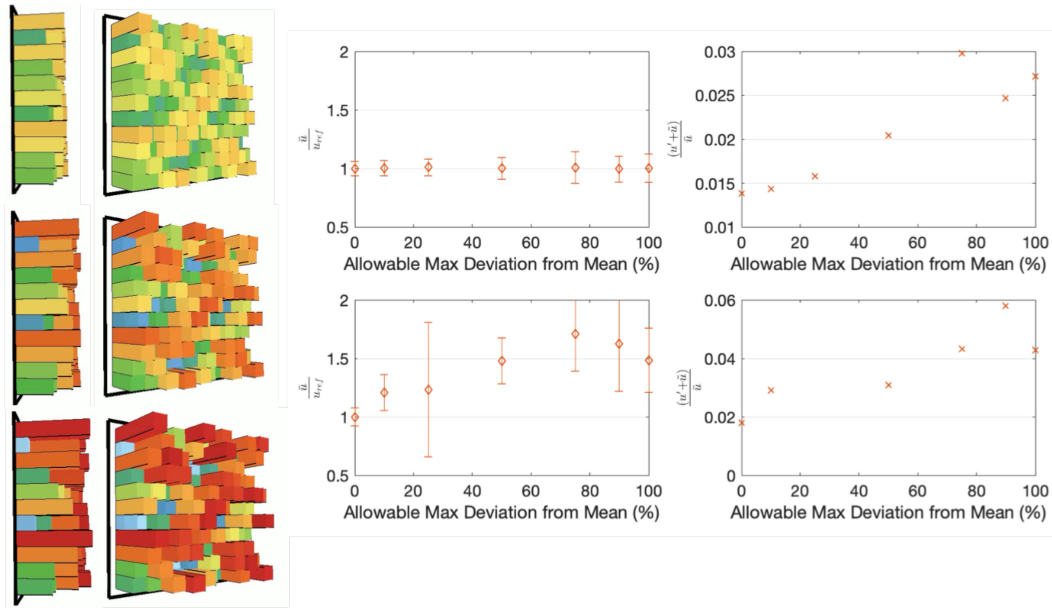

Figure C.1: Example of varying turbulence intensity about a desired mean. The above row shows the effect when the algorithm is active compared to the bottom row where it is initialized as spatially random but not active.

Because the respective fan inputs are pseudo-randomly-phased relative to each other, this flow augmentation is called the random-phase mode (R-P), after Ozono and Ikeda (2018). For reference, a spatially random but static implementation is shown in the bottom row of fig. C.1, which is unable to maintain a targeted mean[2]. The top row presents results when the R-P algorithm is active. Pictorials along the left of fig. C.1 are snapshot representations of select ranged deviation percentages corresponding to 30%, 50% and 90% (top moving down), respectively. The target nondimensional mean of $\overline{u}_{target}/\overline{u}_{actual} = 1$ is maintained through the sweep of deviation percentage increases (top leftmost plot) with a corresponding increase in velocity fluctuations as deviation percentage increases (top rightmost plot). This effect can further be exploited in the dual-unit abstraction, as an extra array layer is available for dual-unit builds, as is explored in the next section. By decoupling the mean velocity from the fluctuations, input energy can be distributed broadly amongst the frequency scales, opening up new parameter spaces to explore for a given desired mean profile. Though a uniform flow profile was used as an example, R-P algorithms can be activated for any such steady (non-uniform) mean profile.

[2]Though not desirable in this particular implementation, the ability to create bulk-flow unsteadiness without introducing input unsteadiness should prove advantageous for future experimentation.

C.2 TOD Considerations: single vs. dual-layer FAWT

There exist two primary implementations of FAWT technologies. Dual-layer FAWT provide an additional stacked layer of fan units, oftentimes rotating in the opposite sense. The extra layer can be solely reserved to prescribe fluctuations or used to enhance velocity throughput when coupled to the main layer. Figure C.2 compares the ability of a single and dual-layer FAWT to track a targeted mean velocity over a range of allowable percentage deviation. The dual-layer FAWT cannot track $\overline{u}_{target}$ as accurately as the single layer FAWT, due in large part to the unmodeled complex nonlinear internal flow interactions of the counter-rotating stacked fan units which further deviate the desired output from the commanded inputs based on the simplified mathematical treatment presented in section 2.1. The corresponding increase in turbulence intensity for the dual-layer, however, is substantive and provides a greater range of amplitudinal perturbation potential. For these reasons, dual-layer FAWT are preferable for most applications requiring various turbulent fluctuations.

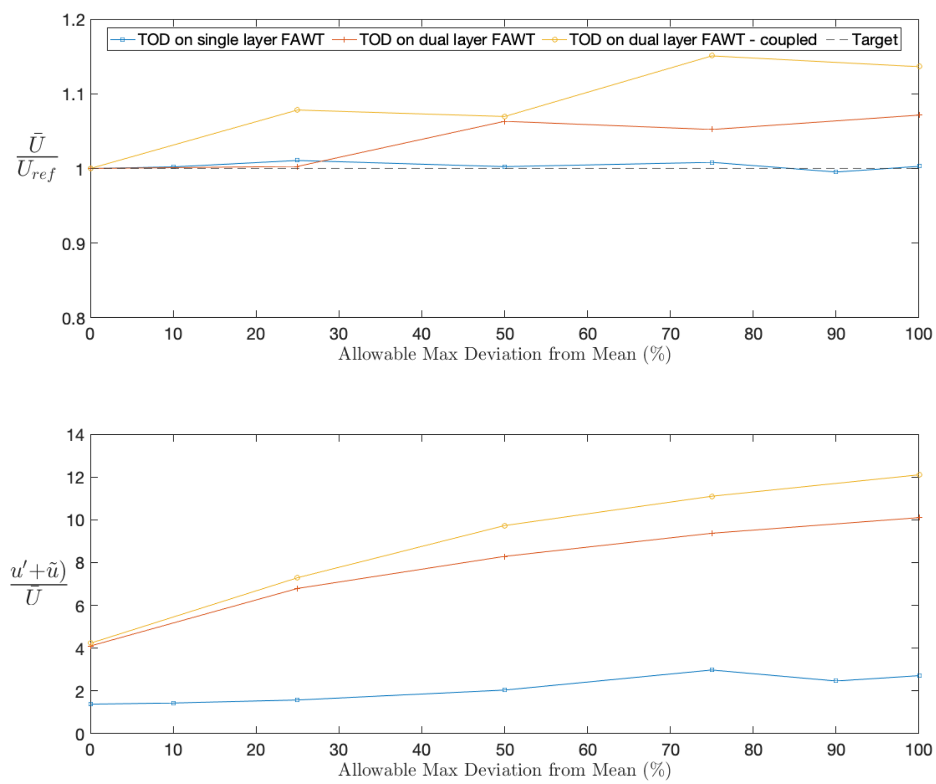

Figure C.2: Comparisons of the TOD algorithm on a single- and dual-layer FAWT.

Due to the nonlinear acceleration/deceleration profiles of the fan units tested herein, the mean velocity of the flowfield in the breathing modality increases with increasing allowable deviation. When decoupled (i.e. one layer used for a desired mean profile and the other for disturbance), a maximum deviation from the mean of 7% is recorded. When both layers are coupled with the TOD algorithm active, this trend worsens with maximum deviations from the mean approaching 11.5%. With algorithmic optimization, this undoubtedly can be improved.

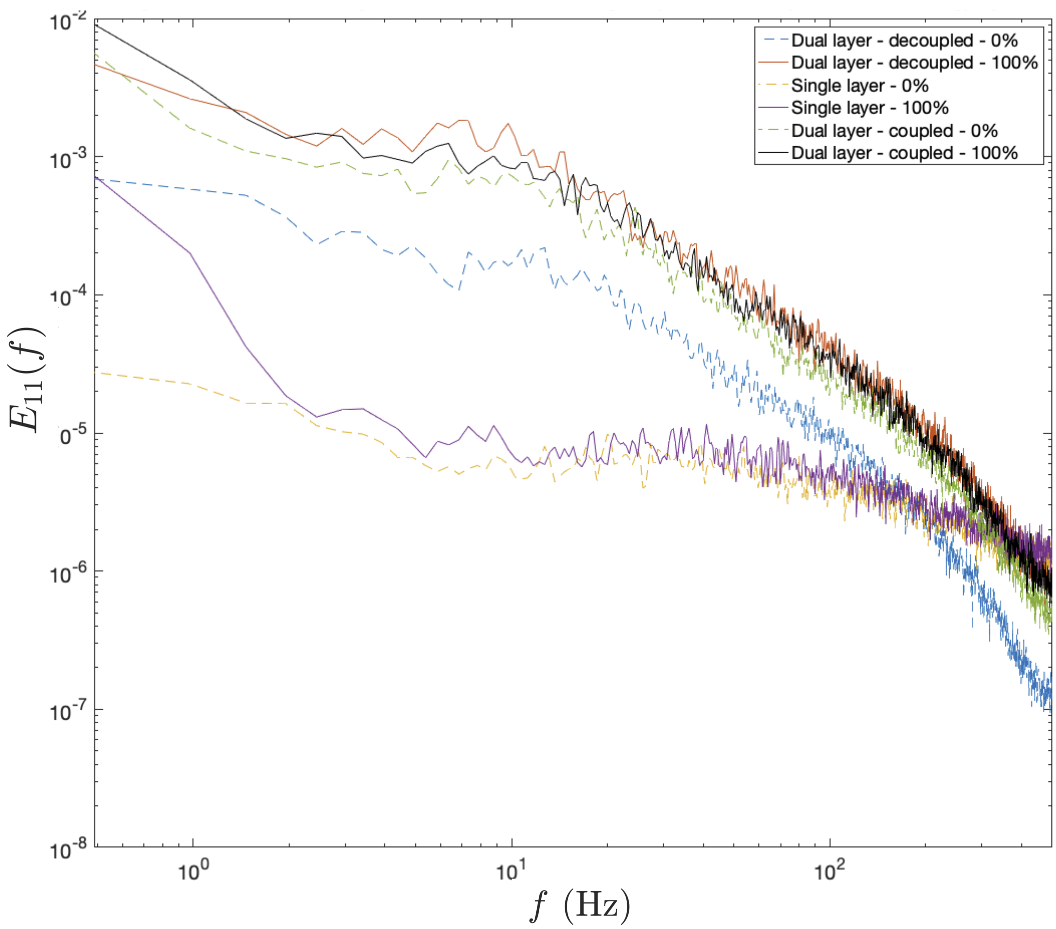

Figure C.3: Comparisons of the energy spectra of the TOD algorithm implemented on a single- and dual-layer FAWT.

One particular advantage of the dual-layer implementations is made evident when comparing energy spectra. Single layer arrays are overall less energetic and flatter responding compared to the dual-layer arrays when the TOD algorithm is active. For the single layer arrays, energy is added only in the lower frequency region and not broadly distributed. A *coupled* dual-layer is in many ways analogous to a single layer FAWT, and little change is observed in the energy spectra beyond energetic content being added to the low frequency region. A marked difference is observed, however, when the two layers of the dual-layer are decoupled, with one layer devoted to the mean profile (in this case, a uniform flow) and the other to disturbances about the desired mean. The trend is made readily apparent in fig. C.4. TOD algorithms effectively add energy to the flow broadly in the decoupled dual-layer FAWT implementation without dramatically affecting the nature of that turbulence. In this sense, turbulent fluctuations can be dialed up or down through software without principally changing the flowfield.

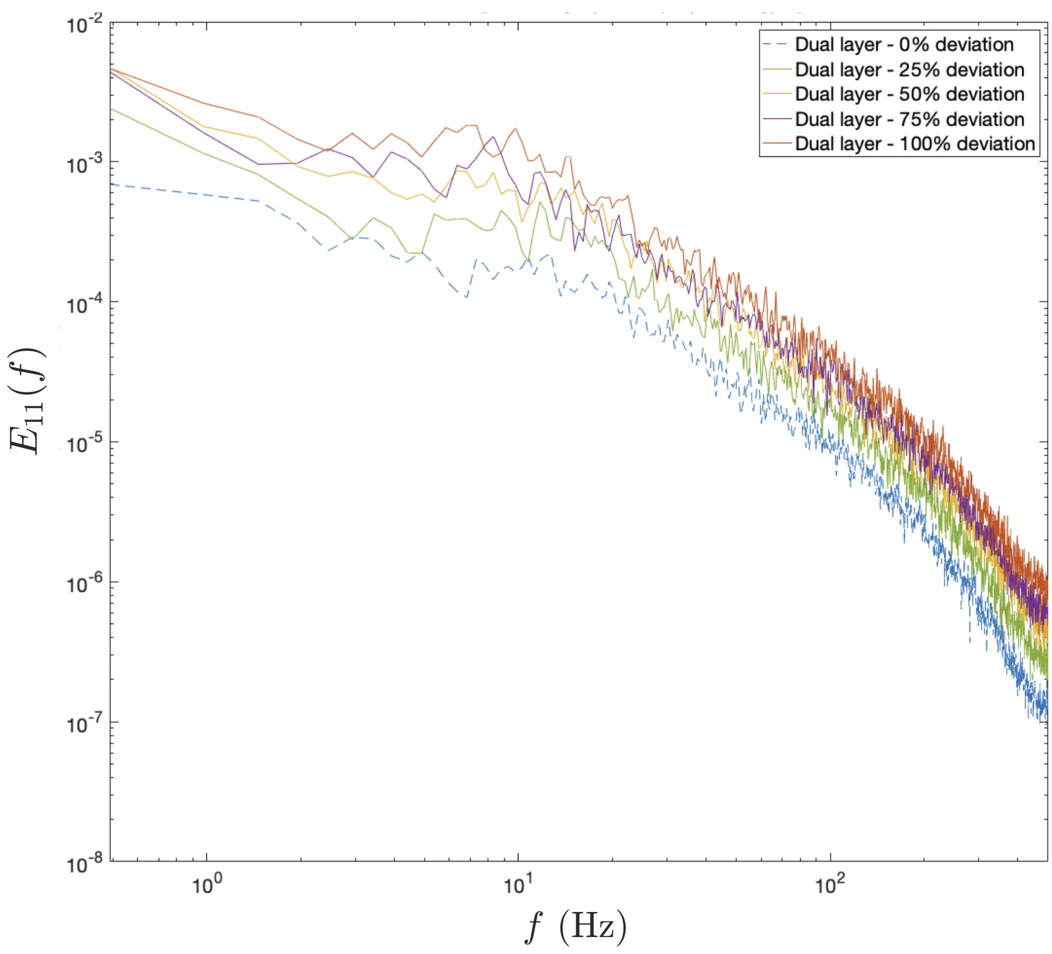

Figure C.4: The energy spectra for the TOD algorithm applied to the backmost layer of a decoupled dual-layer fan array showcases that the increase of the total fluctuation energy is broadly distributed across all relevant scales as the maximum allowed percentage deviation range in the TOD algorithm is consistently increased.