Appendix A

FAN ARRAY WIND TUNNELS

Appendix A is adapted from:

C. Dougherty, M. Veismann, A. Stefan-Zavala, P. Renn, M. Gharib. "The design and characterization of fan array wind tunnels." Awaiting submission to: *Measurement Science and Technology*
C.D participated in the conception of the project, performed certain experiments, prepared certain data, and wrote the manuscript.

The fan array wind tunnel (FAWT) is a multi-source wind tunnel capable of generating a host of spatiotemporally-varying flowfields via software interfacing, offering a versatile, configurable alternative to traditional wind tunnel design and testing. By utilizing an array of DC-powered off-the-shelf cooling fans (in place of one singular drive section), greater flow control and decreased mixing lengths are achieved. The open-loop design of FAWT provide a substantially large useable test section area when compared with its effective footprint. This, in turn, allows FAWT to be implemented in confined spaces that otherwise could not accommodate wind tunnel testing. The fan array itself is fully and individually software addressable, which translates to the capability of generating a variety of traditional and non-traditional spatially- and temporally- varying flows. Some representative examples with implementation are given in table A.1.

A.1 Design Intent

FAWT seeks to accommodate both traditional static aerodynamic testing as well as dynamically controlled free flight investigations subject to configurable flow patterns, though any application that requires spatiotemporally-varying flows can be accommodated. This new wind tunnel class, at its core, provides a paradigm shift in the field of multi-source wind tunnels by incorporating a wide variety of flow conditions in a space-efficient and scalable package. By generating flow patterns not dependent upon obstacle geometries (which result in major pressure losses), an open loop tunnel concept can be implemented, maximizing test section size in a limited space environment. Additionally, FAWT methodology encourages appropriate interfacing between computer modeling and experimentation by providing an input-output domain familiar to both. Discrete fan units, uniquely addressable, provide source input of nearly endless combination, limited only by the top-end speed and responsiveness of each source-unit.

A.2 Schematic Overview

An overall diagrammatic view of FAWT design is presented in this section in order to categorize and generalize the various forms that can be built. The unifying concept between any FAWT implementation is the number of fan units per given array dimension. In this sense, a fan unit is akin to a pixel comprising an image (or array), such that fan arrays are labeled similar to pixel resolutions as $number$ x $number$. The value that will be most useful throughout, however, is the ratio of the smallest flow-producing hardware dimension d to the overall fan array dimension, either height h or width L. In this way, particularly for square arrays, it is immediately clear how finely the array is divided. For example, a 10 x 10 fan array would have a $d/h = d/L = 1/10 = 0.1$.

The FAWT can be divided into 2 main systems:

- Hardware
  - Fan Unit
  - Power Distribution System (PDS)
  - Micro-controller
- Software
  - Network Architecture
  - (External Control)

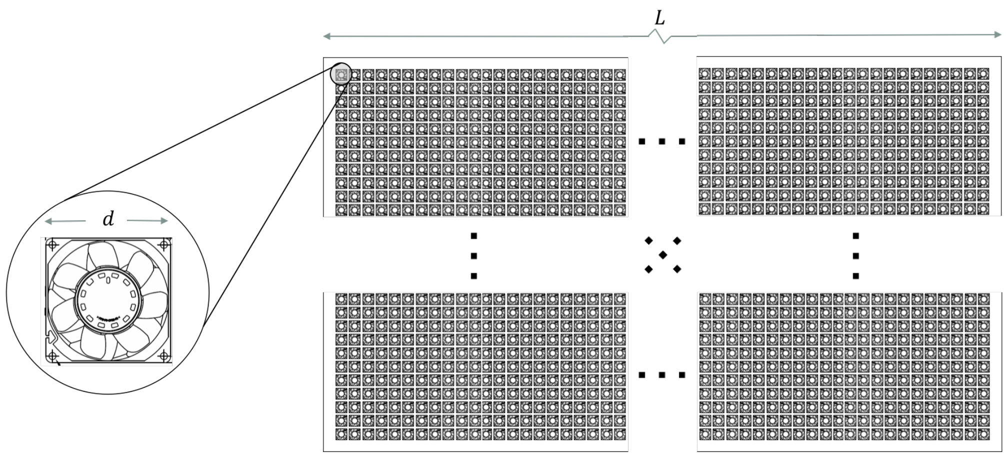
Hardware

Fan Unit:

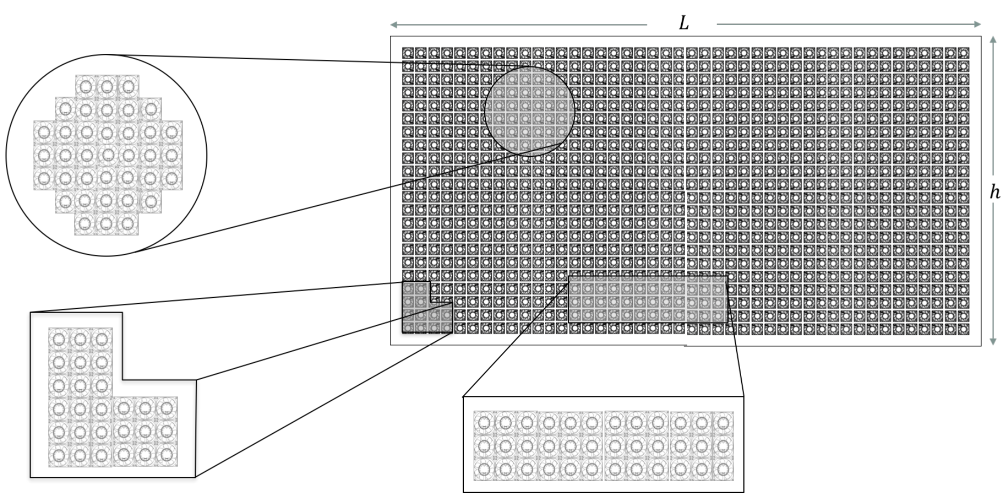
The fan unit is the primary hardware component comprising FAWT. The size, electrical requirements, and total number of fans can be selected based on a number of considerations, including desired performance (i.e. resolution and speed), available space/infrastructure, and/or cost. Depending on the desired use case, a number of configurations can be built with the smallest spatial building block being the fan unit size itself. The FAWT implementations presented herein each use a PWM-capable fan unit[1] with tachometer rpm feedback configured in a square array geometry, unless otherwise noted.

Table A.1: Fan RPM distributions for example implementations for FAWT.

Flow Type	Implementation
Uniform flow	Assign same RPM to all fans
Shear flow	Assign desirable gradient of RPM to all fans
Vortex flow	Introduce transverse velocities using side arrays
Gusting flow	Accelerate/decelerate fan RPMs



(a) Exploded view highlighting a fan unit of outer case dimension d, the smallest building block of the array.



(b) Various examples of how the fan units can be grouped into "modules" to build up an array with overall dimensions L x h.

Figure A.1: Annotated hardware overview of FAWT.

[1]**PWM-capable fan unit:** 4-wire DC cooling fan with PWM signal control and tachometer feedback through a built-in hall effect sensor.

Power Distribution System (PDS):

In place of a single-drive system, FAWT typically employs a multi-layered power design approach. The power distribution system (PDS) consists of the cascading assortment of electrical hardware necessary to step down source power (typically from the wall of a building) to the specified fan unit power requirements. For relatively small implementations, power can be supplied directly to the fan units using a modified computer power supply. For larger builds, a distributed power bus/bank is preferable. Although a seemingly simple consideration, the electrical power required to generate reasonable flow speeds can be considerable.

Micro-controller:

A PWM capable micro-controller is utilized to set the duty cycle (%) of a given set of fans. The micro-controller can also be used to read in the tachometer signal from the built-in hall effect sensor in the fan unit. Most micro-controller boards have limited digital output pins, typically < 50, such that a network of boards is required for builds with fan unit numbers greater than this amount.

Software

The control software, in the simplest sense, interfaces with the PWM-capable digital pins of the micro-controllers. The user can send a series of coordinated duty cycle inputs that cause the fans to spin to a desired RPM, which can be read back through the micro-controller accessing the tachometer signal of the fans. More integrated software implementations can use this tachometer feedback for closed-loop control.

Network Architecture:

For FAWT implementations with a sizable number of fan units, it is often required to develop a network architecture to handle the simultaneous pipeline of data to and from the micro-controller boards. This is effectively done through a Local Area Network (LAN) that terminates into a router, from which each micro-controller board and ultimately each fan unit is uniquely software-addressable. This provides operational control and feedback to single fan units, groups of fans, and/or the entirety of the fan array depending on the desired level of distinction.

External Control:

Since the control input to the fan array is a user-defined matrix data structure accessed through a network, virtually any external source or software can be used to control the array. This is useful in implementations where it is desirable to have feedback automation mapped by some measured quantity, recorded by a DAQ for instance.

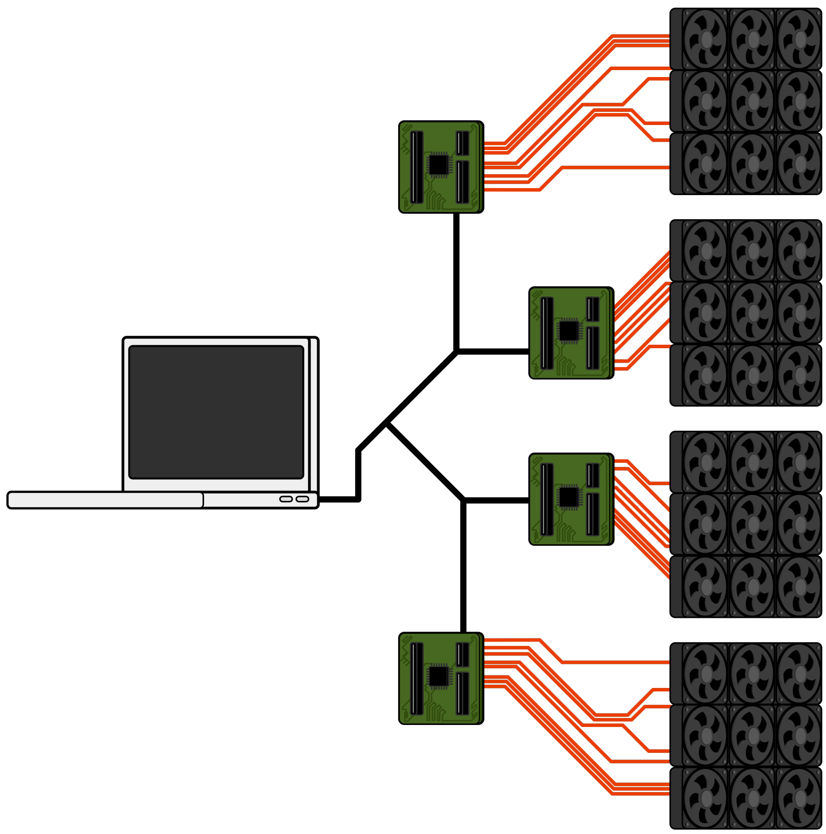


Figure A.2: Flow of information from module to micro-controller to computer through a network.

A.3 Flow Quality

The Effect of Measurement Location

The typical fan units used in FAWT have non-negligible hub geometries where the internal fan circuitry is housed. To determine the effect of the hub geometry on the development of the flow, three measurement locations relative to the face of the fan unit were identified (see fig. A.3) and the development of a uniform flow modality was measured at various downstream locations.

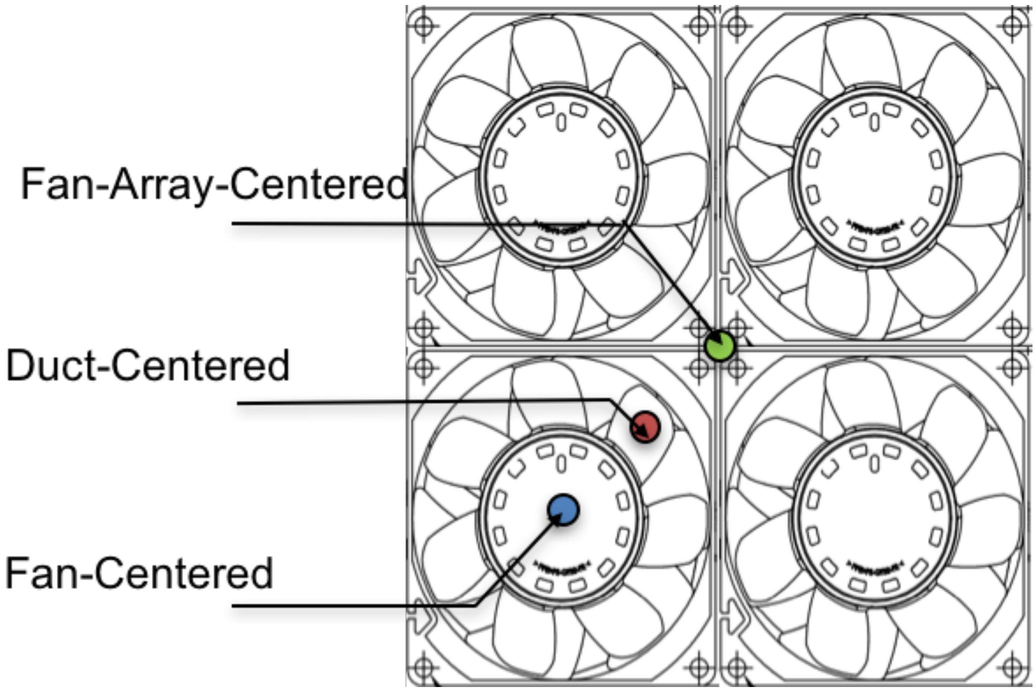


Figure A.3: Three identifiable regions of the simplest square array configuration. The “fan-centered" and “fan-array-centered” locations represent a stagnation condition whereas the “duct-centered” represents an accelerated inlet condition.

The inlet condition at the face of the fan unit ultimately dictates the initial flow development, which varies depending on the measurement location relative to the fan unit geometry when close to the fan source. This is clearly showcased in Figure A.4. As velocities are increased, the initial deviation from the desired reference velocity increases as well, though the effect of the fan unit geometry is no longer observed beyond $x/L \approx 0.5$. The initial flow development is considered simply to highlight the expected flow evolution of FAWT from source to measurement apparatus. The effect of the individual fan geometry in the formation of a uniform flow diminishes quickly and can effectively be ignored when measuring sufficiently far downstream, as will most frequently be the case. These results are included for completeness and to further give context to subsequent analysis. In the following section, the useable testing volume relative to the fan array and fan unit dimensions is established.

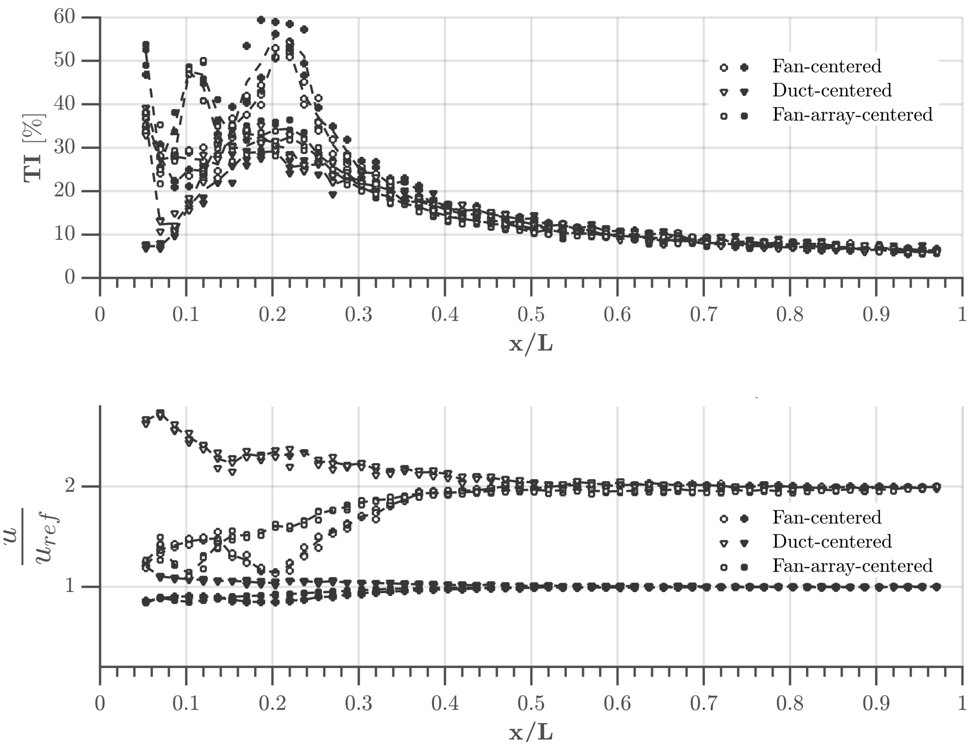


Figure A.4: The downstream convergence of the measured values of turbulence and freestream velocity indicate that the flow has fully mixed and is invariant to the measurement location beyond $x/L \approx 0.5$.

Useable Test Section

Configurations:

Unlike a traditional wind tunnel, the test section of the FAWT oftentimes occupies the volume *immediately* downstream of the source fan(s) and associated flow manipulators. It is important to quantify how the flow evolves spatially through this test section in the primary two implementations of FAWT: **enclosed** and **non-enclosed**.

- **enclosed:** An optically-clear enclosure is sometimes included to further confine the flow and provide adequate mounting structure for quantitative flow diagnostics. The boundary condition of the *enclosed*-configuration is the canonical boundary layer of a flat plate.

- **non-enclosed:** Uninhibited dynamical free flight testing is achieved by removing any test section enclosure to allow for flyers to plunge, translate, and otherwise interact with FAWT in realistic simulated flight scenarios. In this *non-enclosed*-configuration, the boundary condition is a shear layer formation that grows due to entrainment as the flow evolves downstream.

Effective Size:

It is important that proper mixing occurs prior to encountering the test apparatus to ensure flow uniformity through the extent of the test setup. In general and irrespective of the configuration chosen, FAWT deliver a useable test section that is $\sim$ 80% of the array outer dimension at $x/L \approx 0.5$. The 20% spatial margin is most clearly seen in spanwise velocity cross sections, as in fig. B.3. Values are considered approximate simply because the downstream development of the flows generated from FAWT vary slightly from build-to-build (e.g. due to differences in room geometry, distance from floor, available air reservoir, etc.), though the core development of the flow remains largely unaffected, as is demonstrated in the centerline analysis of the following section.

Turbulence Decay

Turbulence decay is a useful measure of the downstream development of the core region of the flow. Since turbulence is generated at the scale of the source fan, normalization of the downstream location by the primary dimension of the fan-unit, d, is used instead. The centerline turbulence decay for a variety of fan-unit and fan-array sizes is given in Figure A.5, with configuration noted. The homogeneous, exponential downstream decay of turbulence for the cohort of FAWT sizes and configurations tested highlights the centerline invariance of the flow with respect to the boundary condition. Thus, it is reasonable to predict downstream centerline characteristics of a steady uniform flow by simply considering the fan-unit size itself. The relatively short mixing lengths contribute to the compactness and utility of FAWT. The spread of data observed in the 92 mm fan is on account of the various flow manipulator configurations tested in that particular implementation, the primary subject of the subsequent section. Flow conditioning is first explored from the point-of-view of the traditional low-speed wind tunnel design process and then expounded to include some more modern considerations.

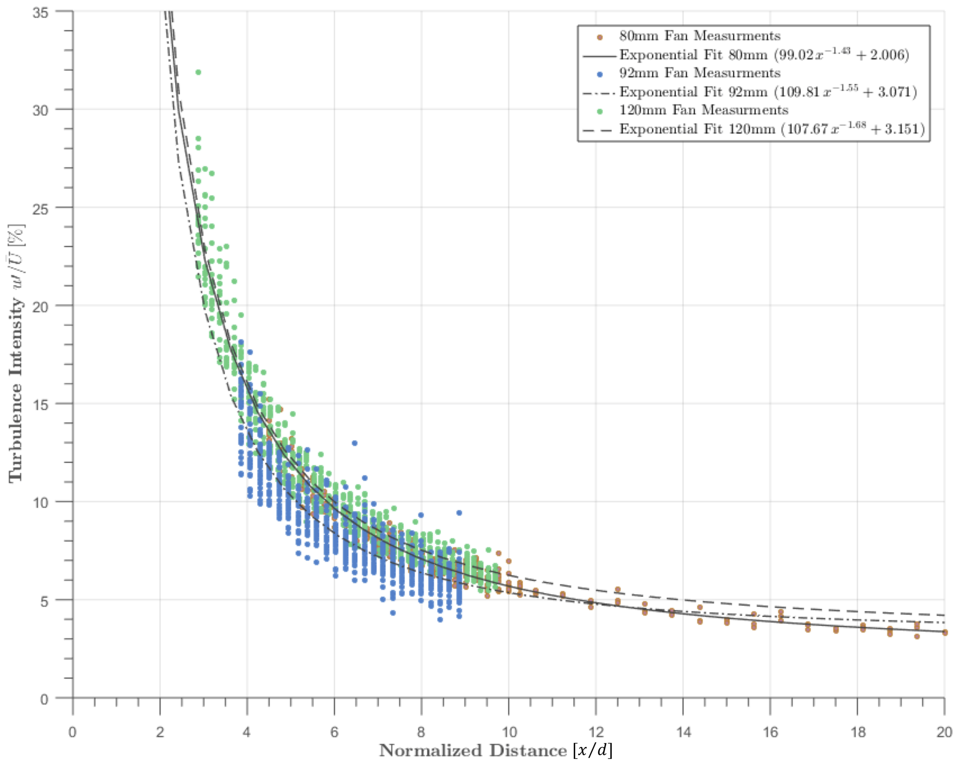


Figure A.5: Centerline homogeneous turbulence decay for three different sized fan units configured into arrays. The $d = 0.080$ m fan unit corresponds to a 36×36 dual-layer array, the $d = 0.092$ m fan unit corresponds to a 11×11 single-layer array, and the $d = 0.120$ m fan unit corresponds to a 10×10 single-layer array.

Flow Manipulator Configurations

Due to the geometry of FAWT, installation of flow manipulators can be thought of as extensions or inserts immediately downstream of the main fan array. For a given test section size, spanwise turbulence initializes in smaller length scales by virtue of utilizing many small source fans in place of one large one. Though not a requisite, all fan units of a given array presented herein are identically manufactured and thus rotate in the same sense. To determine the influence of single and/or combinations of flow manipulators on the turbulence properties of fan array wind tunnels, a specially designed enclosure extension was installed on a representative FAWT (11×11, $d/L = 0.09$) and hot-wire measurements were recorded. A diagrammatic view of the flow manipulator placements is given in fig. A.6.

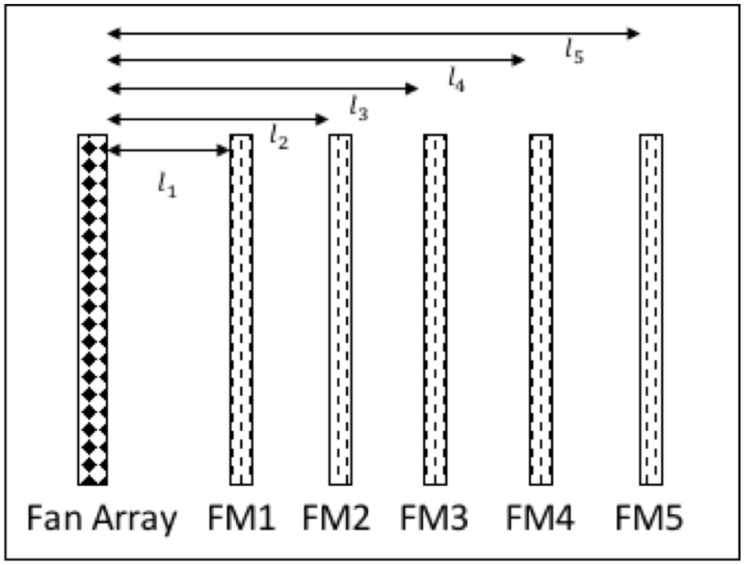


Figure A.6: Diagram view of flow manipulator (FM) placement at set downstream locations ($l_{1,2,..,5}$) relative to the fan array.

Honeycomb + Auxiliary Manipulators:

The influence of honeycomb on eliminating transverse velocities is well documented for single-source wind tunnels. To understand the effect of honeycomb on FAWT, an analysis similar to J. L. Lumley (1964) is undertaken. A comparison of downstream development of turbulence intensity with and without a honeycomb is given in fig. A.7. Because flow variability is oftentimes prioritized over flow quality for FAWT builds, it is recommended that the honeycomb be implemented flush against the array as the primary flow manipulator with auxiliary manipulator(s) slotted downstream of that, as necessary, to further reduce turbulence. From a convenience stand-point (especially for larger builds), placing the honeycomb flush to the array provides the support and access to mounting structure necessary for secure installation, regardless of configuration.

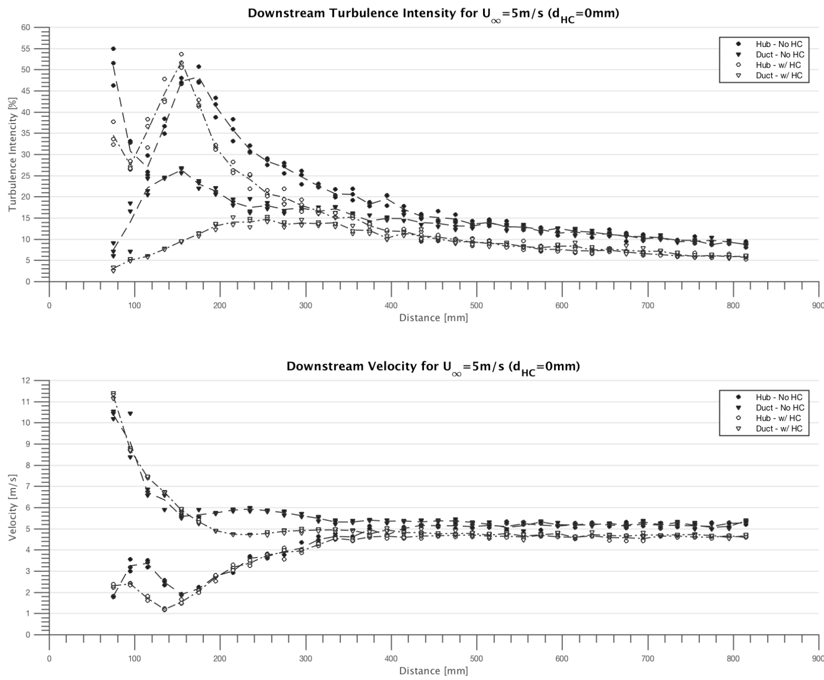


Figure A.7: Effect of honeycomb on downstream development of uniform flow.

A summary of viable flow manipulator configurations is presented in table A.2 to aid in the selection of auxiliary manipulators for a desired turbulence intensity. Representative trends are showcased graphically in fig. A.8 for the addition of auxiliary manipulators, in particular the addition of perforated plates and/or screens downstream of the honeycomb. A reference configuration of a fan array with no flow manipulators is denoted as “REF". The majority of the configurations tested slot a honeycomb into “FM1" while auxiliary flow manipulators are typically installed further downstream. The typical order tested is honeycomb (HC) followed by perforated plate(s) (PP) followed by screen(s) (S).

Table A.2: Flow manipulator configurations. *honeycomb*: HC, *perforated plate*: PP, *screen*: S.

Config.	$FM1$	$FM2$	$FM3$	$FM4$	$FM5$
E	HC	PP	PP	S	S
L	HC	PP	PP	S	-
K	HC	PP	S	-	-
H	HC	PP	PP	-	-
G	HC	PP	-	-	-
J	HC	-	-	-	-
REF	-	-	-	-	-

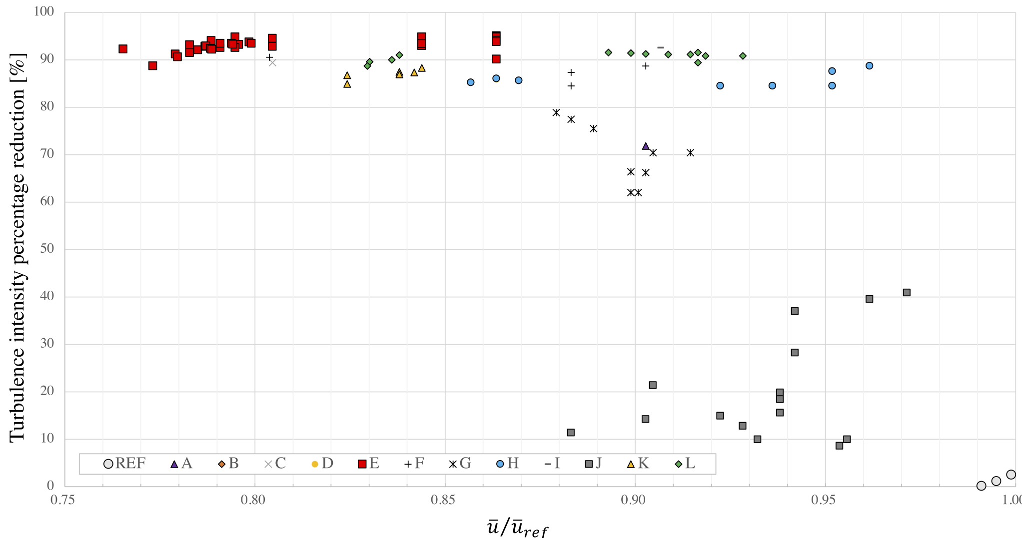


Figure A.8: Effectiveness of various flow manipulator configurations at reducing turbulence intensity.

Ideally, turbulence intensity is reduced while maintaining freestream velocity. Therefore, it is desirable to select a flow manipulator configuration tending toward the upper right portion of fig. A.8. Some viable configurations are highlighted in table A.3.

Table A.3: Turbulence intensity and velocity reduction for various flow manipulator configurations. Dimensional units for $l_{1,2,..,5}$ are in inches.

Config.	l_1	l_2	l_3	l_4	l_5	**TI %**	$\bar{u}/\bar{u}_{ref}$
E	2	6	7	13	21	**0.35**	0.86
L	2	6	7	13	-	**0.60**	0.89
K	9	13	15	-	-	**0.83**	0.84
H	2	6	7	-	-	**0.99**	0.86
G	2	6	-	-	-	**2.25**	0.91
J	2	-	-	-	-	**5.10**	0.94
REF	-	-	-	-	-	**7.11**	1.00

Flow Variety

The primary utility of FAWT is in the multifariousness of flow generation. As previously discussed, this subclass of wind tunnel implementation is primed to be utilized for free-flight dynamic stability and controllability testing of flyers of interest, though statically-mounted testing is obviously possible, as are other more traditional use cases. It is vitally important to understand the capabilities of fan array flow generation prior to fully exploring strategies for the aerodynamic testing of free-flying flyers. A hierarchical overview of the types of flows able to be generated by FAWT is given in fig. A.9.

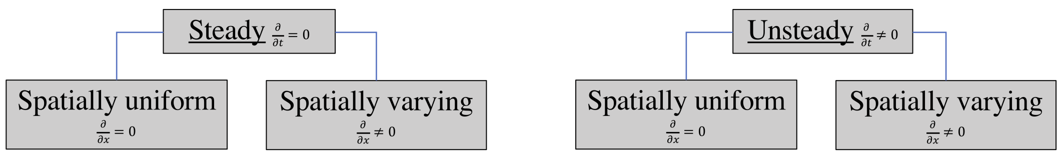


Figure A.9: Types of flows able to be generated by FAWT.

Table A.4: Description of techniques and analysis for flow characterization.

Measurement Device	**Technique**	**Description of Analysis**
Hot-wire anemometer	manually traversed	coarse spatial interpolation, fast temporal averaging
Five-hole pitot system	(semi-) manually traversed	fine spatial interpolation, slow temporal averaging
Particle Image Velocimetry	position laser sheet at ROI	ensemble average of 15 Hz double-pulse image sets

The measurement devices, techniques, and analyses utilized in the subsequent example datasets is summarized in Table A.4. For steady flows (both uniform and non-uniform), single-point and rake measurement apparatuses are sufficient to properly capture flow evolution. Particle image velocimetry (PIV) is able to visualize steady flowfields, discretely oscillatory flow behavior (when phase-averaged), and instantaneous snapshots of unsteady behavior while continuous measurements of unsteady flows prove more challenging for current technologies. As such, discussion and visualizations below deal solely with steady flows.

Steady Flows

The majority of effort in flow characterization thus far has been applied toward steady flows. Since the test envelope for FAWT begins immediately downstream of the source fans and/or flow-manipulators, the streamwise development is typically the first section of interest. For first insights, a vertical centerline streamwise 2D plane is measured. For both uniform and non-uniform flows, this viewpoint allows for quick apprehension of the spatial limits of the flow generated as well as a general sense of the downstream development. After analyzing the streamwise plane, a set of suitable downstream locations are selected based on the type of experiment to be run. At this point, the data for 2D spanwise planes of interest are acquired to help visualize the horizontal (and vertical) extent of the generated flow.

Flow Type #1: Steady, spatially-uniform

This is the default use case of conventional wind tunnels. In subsonic flight regimes, this flow modality well-simulates the motion through the inviscid free atmosphere or through the homogeneously turbulent inertial sublayer depending on the level of turbulence intensity. It is desired to condition the flow to acceptable levels of uniformity across the test section through flow manipulation. In each FAWT build at Caltech and JPL, honeycomb is used to eliminate the fan swirl. In cases where freestream turbulence intensities should better match background turbulence of the ABL, grids and screens are excluded. Grids and screens may also be excluded as a matter of convenience on larger builds where they may not be practical to install. When further flow manipulation is required, a filing cabinet style enclosure is attached to the array. All implementations are considered open-circuit, open-jet wind tunnels beyond the mixing region. Two streamwise planar example datasets acquired on different resolution FAWT using a five-hole probe system were shown in section 2.2 (see fig. 2.4 and fig. 2.6). Turbulence intensity distributions from traverses using a standard single hotwire are given in fig. A.10.

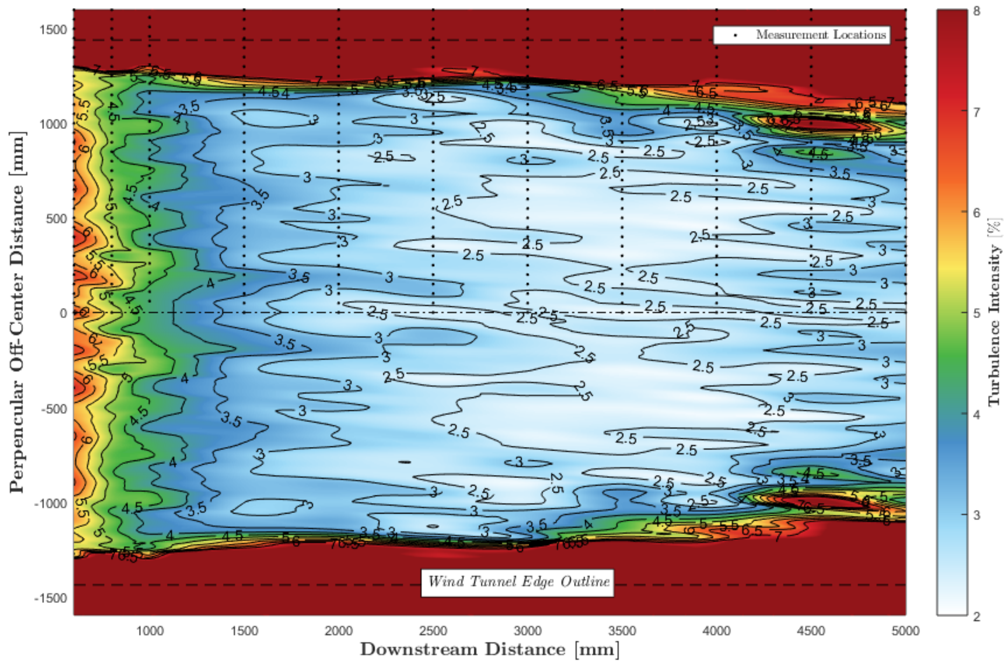


Figure A.10: The turbulence intensity distribution of a $d/L = 0.03$ resolution dual-layer array at nominal freestream velocities.

Flow Type #2: Steady, non-uniform (irrotational)

A steady non-uniform input distribution may or may not generate flowfields that are irrotational. For the cases where there are no inflection points in the mean velocity profile, a time-averaged measurement technique alone is justified. Extracting velocity profiles along lines of interest from these datasets is straightforward. This is oftentimes useful to enhance intuition of spatially-varying flows that are not immediately obvious from a contour plot alone. An illustrative example is a vertical gradient shear flow. Figure A.11 showcases the streamwise velocity contour plot alongside the spatial evolution of velocity profiles. For flow patterns that are rather non-uniform and directionally variant, probe-based techniques may not be suitable and two-dimensional particle image velocimetry (2D-PIV) can be utilized instead if the space permits. The primary example dataset is a steady vortex generation from an enclosed configuration FAWT with side fan units installed, shown in fig. A.12.

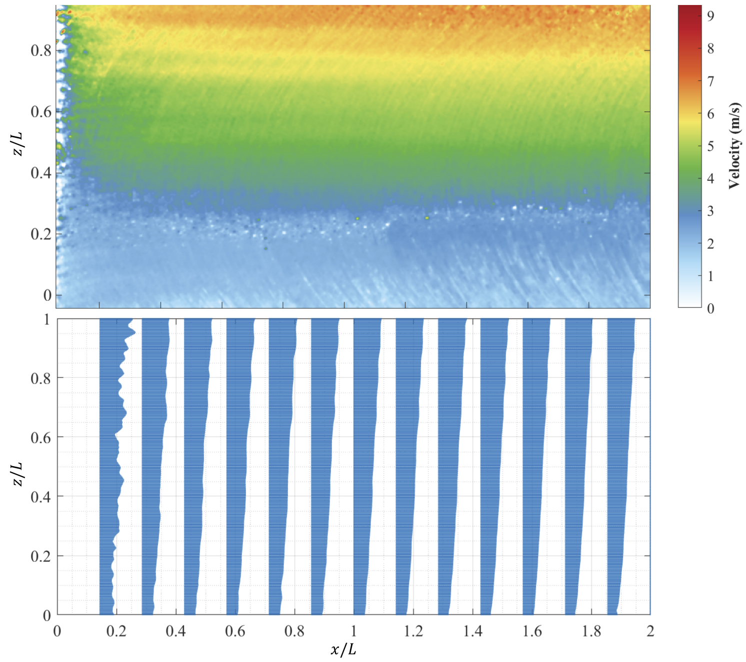


Figure A.11: Spatial development of a gentle vertical gradient shear flow. Contour shear velocity profiles (above) with corresponding velocity profiles (below) for a centerline streamwise measurement plane of a $d/L = 0.03$ resolution array. The maximum velocity is 7.5 m/s incremented piecewise per fan down to the idle velocities of the fan units, 2 m/s.

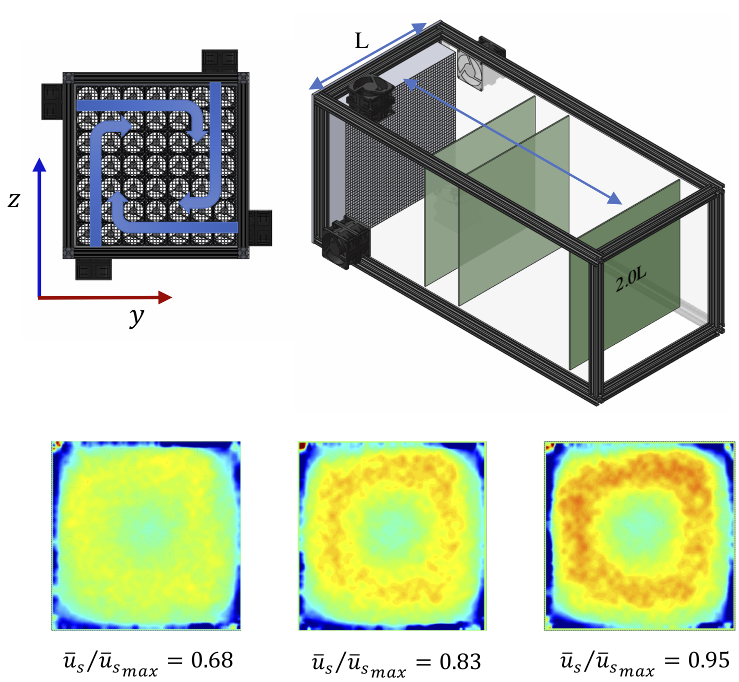


Figure A.12: Spanwise vorticity plots derived from particle image velocimetry measurements at $x/L = 2.0$ with varying side fan velocities $\bar{u}_s$.

A.4 Main facilities with FAWT implementations

The 25-ft Space Simulator at JPL

A specially designed FAWT was developed for integration into the Jet Propulsion Laboratory (JPL) 25-ft Space Simulator during an experimental campaign in 2018 to enable forward flight simulation of Ingenuity on Mars. Significant sub-scale testing of the fan units was completed prior to full-scale implementation to ensure performance under low-density conditions at relevant velocities to simulate desired Ingenuity flight characteristics. These tests were necessary to investigate forward flight vehicle dynamics and inform flight controller gain settings in a simulated non-terrestrial environment well-before (successfully) tackling Martian flight conditions for the very first time on April 19, 2021, marking the first ever powered controlled extraterrestrial flight by an aircraft. For details on this particular build, the reader is referred to Veismann et al. (2021).

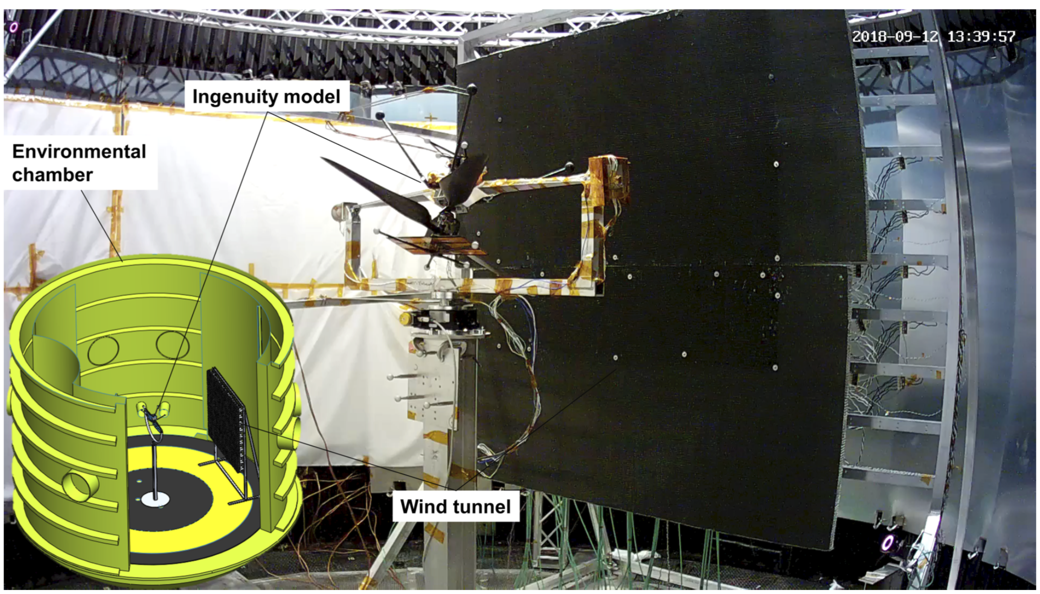


Figure A.13: FAWT within the 25-ft Space Simulator chamber at the Jet Propulsion Laboratory (JPL). A full-scale model of Ingenuity is seen fix-mounted (upside-down) in front of a bank of $21 \times 21 \times 2 = 882$ individual fan units stacked in two layers with a metallic honeycomb affixed to the outlet plane.

CAST at Caltech

At the Center for Autonomous Systems and Technologies (CAST) at Caltech, considerable effort has been made to better understand and further define the role of autonomous flyers, crawlers, rollers as extensive and extensible tools to humanity. Vital to the success of this goal is creating the proper contextual environment from which both humans and machines can explore, iterate, and otherwise learn.

Figure A.14: A bipedal walker in the foreground interacting with a flock of flyers in the surround against the backdrop of the CAST fan array.

The Aerodrome within CAST is home to the first real weather fan array wind tunnel, an open-air and continuously measurable flight environment geared toward the emerging fields related to (hybridized) autonomous flyers. The four-story tall flight arena is outfitted with two U-shaped tiers of infrared motion capture cameras able to identify objects of interest with up to 100 micron resolution.

Figure A.15: FAWT within the Aerodrome in CAST.