

Article

Experiments of Lift-Bending Response on a Slender UAV Wing Structure with Control Surface under Extreme Flow Turbulence

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Abstract: The aeroelastic response of lightweight low-speed aircrafts with slender wings under extreme flow turbulence intensity is not well understood. Experiments on a commercial unmanned aerial vehicle (UAV) with a 3 m wingspan and aspect ratio of 13.6 were performed in a large open-return wind tunnel with extreme flow turbulence intensity of $\approx 10\%$. The wing bending displacement and the flow beneath the wing were measured by using laser-displacement sensors and tomographic particle image velocimetry (PIV) techniques, respectively. The unsteady lift produced by the wing was also measured by using a high-capacity load cell at an angle of attack of two degrees for three freestream velocities of 13.4 m/s, 17.9 m/s, and 26.8 m/s, representing the UAV's stall speed, a speed approximately equal to the cruise speed, and a speed considerably higher than the cruise speed, respectively. It was found that a high flow turbulence intensity with large integral length scales relative to the wing chord plays a dominant role in the large unsteady lift and wing displacements measured. The power spectral density (PSD) of the wing structural vibration shows that flow shedding from the wing and the integral length scales have a significant impact on the overall power inherent in the bending vibration of the wing. Computations of the vorticity isosurfaces in the flow measurement volume surrounding the aileron reveal a striking observation: an aileron deflection of 10° becomes less effective in producing additional spanwise vorticity, which is proportional to circulation and lift at 26.8 m/s since the freestream already has elevated levels of vorticity. A paradigm shift in design is suggested for light aircraft structures with slender wings operating in highly turbulent flow, which is to employ multiple control surfaces in order to respond to this flow and mitigate large bending or torsion displacements and the probability of structural failure.

Keywords: slender wing structures; structural dynamics; aerodynamics; high turbulence intensity; particle image velocimetry



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1. Introduction

The wing lift and structural bending displacement of a commercial UAV subjected to flow with a high turbulence intensity at transitional Reynolds numbers is investigated in this study through wind tunnel experiments. The Albatross electric-powered UAV used in this study has a 3 m wingspan with a wing aspect ratio of 13.6, which can be considered a slender wing [1]. Though there are several existing studies that describe the design and configurations of fixed-wing UAVs, little to no effort has been made to optimize the aerodynamic or structural dynamic performance of the vehicles from experimental data in highly turbulent flow [2]. Aircraft control laws are often developed in the absence of significant turbulence since flight tests are often conducted in remote test ranges and on days with benign atmospheric conditions [3]. The result of such low turbulence intensity conditions for UAV testing fails to provide sufficient excitation to evaluate the disturbance rejection capability of control systems. High aspect ratio wings exhibit aeroservoelastic

problems. Further work still needs to be conducted to identify aeroelastic instabilities that may occur on the control surfaces [4]. Experimental tests are required to provide valuable insight to reinforce the nonlinear aeroelastic behavior captured in various computational works developed and provide valuable insights into the physical phenomena uncovered in these numerical models. This paper aims to address these gaps, with the goal of studying the effect of a control surface (e.g., aileron) in extremely turbulent flow and suggest solutions that are likely to use multiple control surfaces on the aircraft structure including the wing.

Fixed-wing light aircrafts, which operate within the atmospheric boundary layer, encounter regular turbulence intensities in the range of $\approx 5\text{--}7\%$. The presence of turbulent winds has emerged as a significant impediment to achieving a successful flight [5]. This underscores the necessity of designing and studying methods to alleviate atmospheric turbulence loads. Fezans et al. [6] investigated the prediction of disturbance loads resulting from atmospheric turbulence for compensation through counteractive feedforward deflections of an aircraft's flight-control surfaces. Mohamed et al. [7] investigated a method for mitigating the effect of turbulence on fixed-wing microaerial vehicles (MAVs) by improving the sensing and response time of its on-board attitude control system. Ayele and Maldonado (2023) [8] modified the simplified Bernoulli–Euler beam model equation to include the fluctuating aerodynamic lift and hence the effect of the change in the wind direction (gust) and flow turbulence of the Martian atmosphere to compute the effective angle of attack and wing tip displacement of an inflatable wing robotic ground-aerial vehicle. Georgios et al. (2020) [9] show the strong dependency of aircraft structure flexibility between the selected turbulence model and aeroelastic response through a comparison of the load envelopes and spectral content. This is mainly due to the presence of large flow structures at low altitudes that have comparable dimensions to the vehicle, and which despite the relatively small wind speeds within the Earth boundary layer, result in overall high load events for slow-moving vehicles. The lifting potential of the wing depends on the nature of the airflow around its surroundings. However, the link between the aerodynamic derivatives responsible for lift production and the dynamics of the airflow characteristics is still under investigation [10]. In practical application areas, the adverse weather operation capabilities of UAVs are one of the challenges identified in using them to gather atmospheric data for weather-management systems [11].

A study by Maldonado et al. [12] showed that freestream turbulence with an intensity of $\approx 6.14\%$ substantially increases the lift coefficient and lift force over a fixed wind turbine S809 airfoil section at a Reynolds number of 2.08×10^5 , particularly in the stall region of the airfoil. Another study by Maldonado et al. [13] implemented active flow-control techniques with synthetic jets in a three-bladed rotor with a diameter of 2.58 m to mitigate blade structural vibration. The isolated rotor was operated inside a large laboratory without freestream turbulence. However, the three-dimensional unsteady nature of the flow and inherent bending motion vibration of a rotating rotor system operating at a rotor speed of 1000 revolutions per minute produced extreme wall-normal turbulence intensities of up to $\approx 26\%$ less than 1 mm from the blade tip surface. Synthetic jets were shown to delay flow separation by providing momentum to the boundary layer, which reduces the size of the separated recirculating flow region in the trailing edge region of the blade. In the process, the unsteady forcing of the blade, particularly in the blade tip region, is reduced, which mitigates the amplitude of the blade-bending vibration.

Since the early 1980s, experimental fluid mechanics has undergone a revolutionary development with research in particle image velocimetry (PIV) [14]. Three-dimensional particle-tracking velocimetry is a technique based on the reconstruction of single-particle trajectories over long sequences, and it allows an accurate evaluation of the Lagrangian properties [15] unlike the 3D PIV technique, which estimates the average velocity of particles in an Euler frame with the spatial correlation method [16]. In this research, flow measurement is done using the 'Shake-The-Box' (STB) particle tracking algorithm technique. The STB method represents an advanced particle tracking scheme that incorporates the recent advancements of both 3D PTV and tomographic particle image velocimetry [17],

which was first introduced in 2013. We employ a two-pulse STB particle tracking algorithm to capture volumetric flow measurements. The two-pulse STB confirms the capability to accurately reconstruct individual particle tracks despite the limited time-resolution information offered by two-frame recordings [18].

In this study, the goal is to understand how an extreme freestream turbulence intensity, $\approx 10\%$, impacts a commercial unmanned aerial vehicle (UAV) structure, and specifically how large fluctuating loads lead to the structural bending response and energy content of specific frequencies of a slender fixed wing. The objectives are to study the spectrum of UAV vibration and determine the power spectral energy (PSD) associated with the structural frequency, f_{struc} ; the shedding frequency, f_{shed} ; and the frequency due to the integral length scales in the flow, f_{L_∞} . An aileron on the UAV wing is deflected in order to measure the increase in the mean and fluctuating lift force as well as the bending deflection of the wing. This is the first step to understanding how the size and deflection angle, as well as the placement, of a control surface can be used to alleviate or counteract the large fluctuating loads imparted on the UAV by large-scale vortex flow structures. The length scales as well as the vorticity and turbulent kinetic energy of these flow structures are computed from volumetric particle image velocimetry (PIV) measurements. A cutting-edge LaVision PIV system was configured and adjusted to capture volumetric measurements through the application of LaVision's 'Shake-the-Box' (STB) particle-tracking algorithm. The 'shake-the-box' technique is employed in particle-tracking velocimetry (PTV) to improve the precision of tracking particles in three-dimensional space. It is expected that, ultimately, this work will lead to designing light aircraft structures such as UAVs that can maintain structural integrity and flight control in extreme wind conditions, such as in hurricanes, to enable real-time video feedback for search and rescue and damage assessment.

2. Experimental Setup

The research experiments were conducted at the Wall-of-Wind Experimental Facility (WOW-EF) located at Florida International University (FIU). This national shared-use facility is designated as part of the Natural Hazards Engineering Research Infrastructure (NHERI) network of facilities across the country [19]. The 12-fan WOW-EF is a large open-return wind tunnel with a 20 ft wide by 14 ft tall test section and wind field and is capable of producing wind speeds up to hurricane Category 5 (≈ 153 mph maximum). A flow-management section is located between the intake fans and the experimental test section (Figure 1a,b). The WOW facility is used to test failure modes of full-sized structures such as site-built or manufactured housing and small commercial structures. It has experimental capabilities of high-speed holistic testing at multiple scales, wind-driven rain simulation, and conventional boundary layer wind tunnel testing and full or large-scale aerodynamic/aeroelastic testing in simulated atmospheric boundary layer flows. An extreme turbulent flow profile was implemented in this study with ground spires fully exposed to the freestream, automated floor roughness plates fully extended to 90 degrees, and no roughness blocks on the concrete floor. The turbulent flow profile approximates a logarithmic velocity profile used to describe the atmospheric turbulent boundary layer and contains a turbulence intensity of about 10% measured with a TFI Cobra Probe sensor at the location of the UAV. The Cobra Probe is a multihole pressure probe that has the ability to simultaneously measure three unsteady orthogonal velocity components in subsonic flows. The probe is able to resolve the unsteady velocity components u' , v' , w' and compute the turbulence intensity due to its pressure transducers located in close proximity to the pressure-sensing ports. The particular Cobra Probes used have a four-hole pressure head with a diameter of 2.6 mm and 0.4 mm pressure tap holes. The probes contain 2 kPa pressure transducers, which provide a usable wind speed measurement range between 3 m/s and 80 m/s. The pressure measurements at each of the four holes were compared to the manufacturer's calibration data to acquire the fluctuating velocities and time-averaged freestream velocity to compute the turbulence intensity at the location of the UAV.

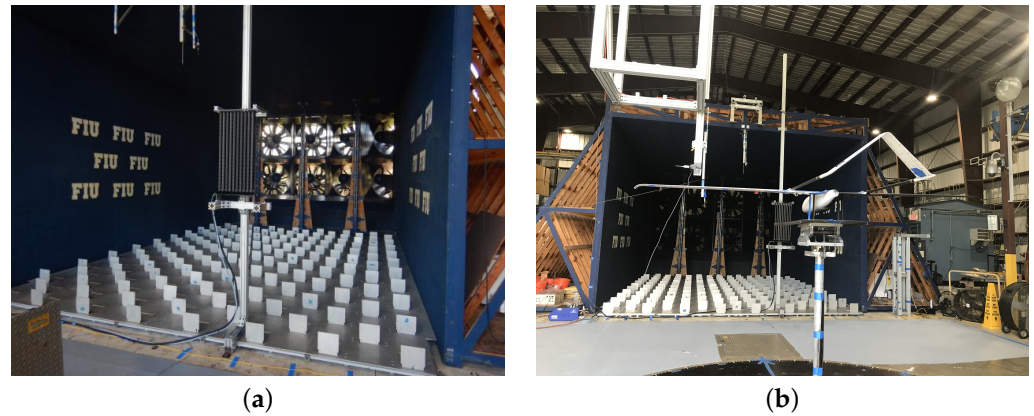


Figure 1. WOW-EF flow management and UAV setup. (a) Fully open vertical spire and ground plates. (b) UAV mounted on the test tower facing the oncoming flow.

The UAV structure (Figures 2 and 3) is manufactured from a carbon fiber and fiberglass composite creating a bare weight of 3.5 kg. The fuselage has dimensions of 0.74 m in length, 0.2 m in width, and 0.15 m in height. The wing contains an optimized 10% t/c thick airfoil with a slight forward-swept planform with a wingspan of 3 m and an aspect ratio of 13.6. The wing produces a significant lift-to-drag ratio between 28 and 30 at a cruise speed of 68 km/h. Other available performances and specifications of the Albatross UAV are stated in Table 1.

Table 1. Performance and specifications of the Albatross UAV.

Specifications		Performance	
Parameter	Value	Parameter	Value
MTOW	10 kg	Endurance	1–4 h (varies based on battery setup)
Wing span	3 m	Cruise speed	68 km/h
Fuselage dimensions	Length: 740 mm Width: 200 mm Height: 150 mm	Max speed	129 km/h
Landing gear system	Solid carbon fiber and aluminum mounting plate	Takeoff/landing distance	50–100 m
Power system	Electric	Propulsion	Electric
Max payload	4.4 kg	Glide ratio	30:1
Takeoff method	Catapult, Runway	Telemetry Range	2–40 km
Construction materials	Honeycomb composite, carbon fiber	Payloads	Modular and compatible with most cameras and sensors



Figure 2. Isometric drawing of the Albatross UAV.

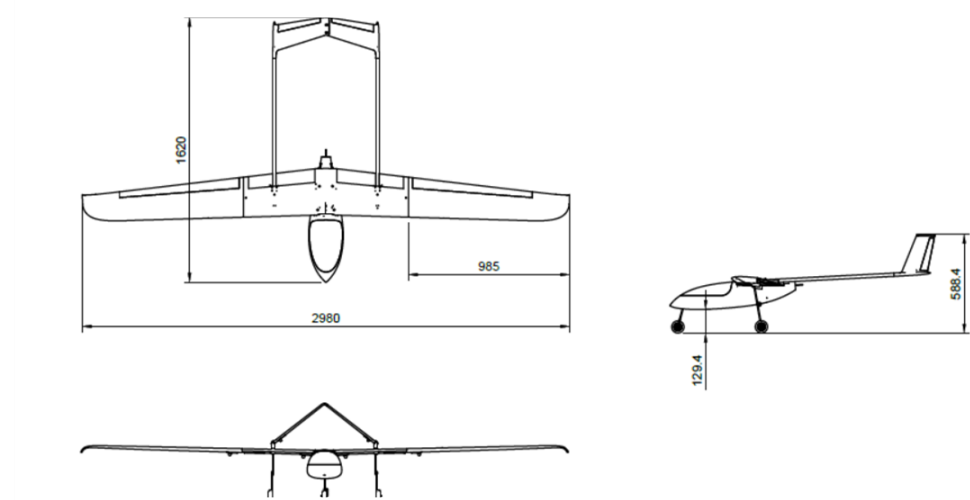


Figure 3. Dimension drawing of the top, front, and side view of the Albatross UAV (units are in mm).

An aluminum tower is designed and manufactured to test an Albatross UAV [1] as shown in Figure 1b. The tower is mounted on a turntable, and the UAV is mounted to the top of the tower via an adapter assembly with a manual adjustable angle of attack. A flat plate is used to isolate the flow and aerodynamic interference between the UAV and adapter as well as an ATI-IA Theta load cell mounted at the base of the tower to measure forces and moments. A state-of-the-art LaVision PIV system was set up and calibrated to acquire volumetric measurements by using LaVision's proprietary 'Shake-the-Box' particle-tracking algorithm. Four high-speed cameras were installed on the translation stage, and the laser optics were adjusted for 3D volumetric images. The laser volume was located around the right-wing aileron, which functioned as a control surface during these experiments. The right-wing panel and right side of the fuselage were painted flat black to improve the PIV image quality during the experiments. Figure 4a shows the PIV setup for UAV testing. A helium-filled soap bubble generator was installed near the exit of the WOW-EF flow-management section and upstream of the UAV. The laser optics were adjusted so that the laser volume was directed upward onto the bottom surface of the UAV's right-wing panel.

Load cell data were acquired at a sampling rate of 625 Hz for 60 s to match other data acquisition by using a National Instruments (NI, Austin, TX, USA) USB data-acquisition (DAQ) device and NI LabVIEW 2021 SP1 software. Three Acuity AR-700-50 laser-displacement sensors (Schmitt Industries Inc., Portland, OR, USA) were installed to measure deflections of the UAV's right wing during the experiments (Figure 5a). The laser-displacement sensors were located along the center of the wing chord with the first measurement point near the

wing's tip, the second measurement point near the wing's center, and the third measurement point near the wing's connection with the fuselage.

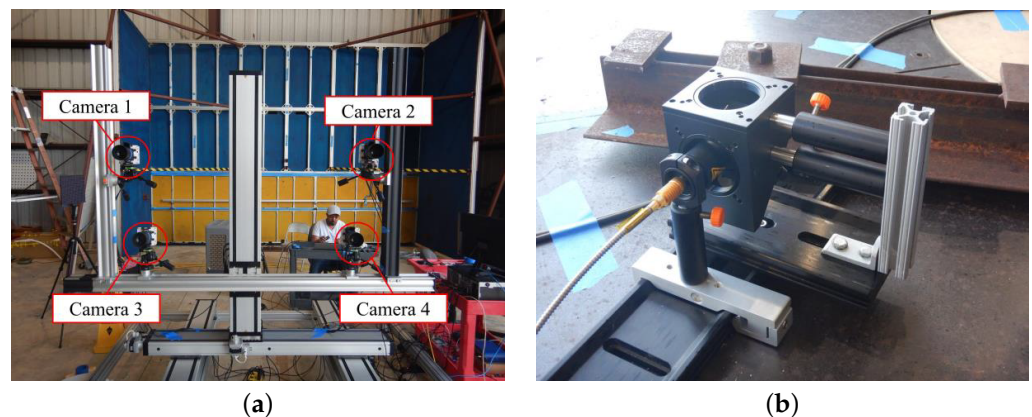


Figure 4. (a) Four high-speed PIV cameras mounted on the translation stage and (b) laser volume optics.

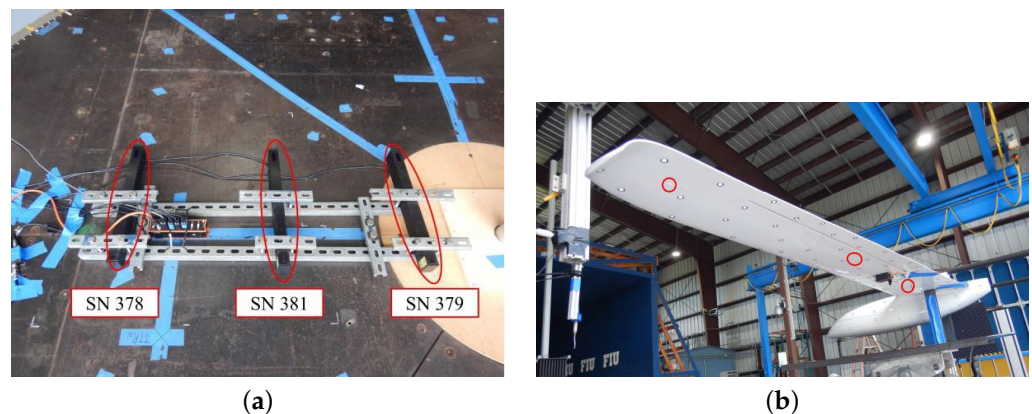


Figure 5. (a) Acuity AR-700-50 laser-displacement sensors mounted on WOW-EF turntable (note: sensor serial numbers are shown) and (b) laser-displacement measurement locations on the left-wing panel at locations $y/(b/2) = 0.236, 0.547, \text{ and } 0.926$.

Two TFI Cobra Probes were installed: one near the WOW-EF flow management exit to measure reference wind flow conditions during the experiments, and a second one (Figure 6a) just upwind of the UAV's left-wing panel to measure incoming flow conditions at the wing height. An RM Young 41342VF temperature sensor was relocated to a position near the second Cobra Probe to measure the air temperature impinging the wing.

The temperature sensor and the three laser-displacement sensors were wired into the Dewesoft 6xSTG DAQ device. To achieve data synchronization for the data-acquisition devices, an analog waveform generator (Figure 6b) was set up to generate a trigger pulse signal. The trigger pulse started PIV image acquisition, the Dewesoft DAQ device, and the Cobra Probe NI cDAQ device. Data from all devices were sampled at 625 Hz during the UAV experiments, with a sample size of 60 s for all sensors including the load cell and laser displacement and a sample size of 4.8 s for the PIV system. The sampling frequency was selected to be an order of magnitude greater than the Nyquist frequency, defined as two times the highest frequencies associated with the experiment in order to capture all of the important physics. In this case, the highest frequency measured was about 31.13 Hz due to the impact of the integral length scales on wing vibration. The PIV system operated in double-frame mode due to the WOW-EF wind speeds during the experiments.



Figure 6. (a) Temperature sensor and additional Cobra Probe near the UAV (suspended from gantry crane) and (b) servo control and data synchronization hardware.

To control the UAV aileron angle, an Arduino program developed for servo control was implemented to operate two standard hobby-grade servo motors (Figure 6b). The servo motors were secured to the underside of the UAV wing with 3D-printed mounting panels epoxied to the wing structure. Control horns were epoxied to the ailerons, and metal linkage rods were used to connect the servo arm to the control horn. The servos were powered by a DC power supply with the output set at 6.0V. Once the servos were installed on the UAV model, the Arduino program was used to control the servo position and achieve a downward deflection of the aileron at deflection angles δ_a of 0° , 5° , and 10° with respect to the wing chord line.

3. Wing Loading

3.1. Aerodynamic Lift Force

The UAV was tested at freestream velocities U_∞ of 13.4 m/s, 17.9 m/s, and 26.8 m/s at an angle of attack α of two degrees. The corresponding Reynolds number based on the mean aerodynamic chord of the wing is calculated to be 1.62×10^5 , 2.16×10^5 , and 2.92×10^5 , respectively, for the three test speeds. A brief time history of the lift force at wind speeds of $U_\infty = 26.8$ m/s and three aileron deflection angles $\delta_a = 0^\circ$, 5° , and 10° are presented in Figure 7. The aerodynamic lift is highly unsteady, reflecting the turbulent nature of the flow with a particularly high freestream turbulence intensity. The effect of the aileron is to increase the mean lift as the aileron deflection angle increases to $\delta_a = 5^\circ$ and 10° . Given the very large amplitude of the lift force, it becomes critical to study how this force impacts the UAV structure, in particular the bending motion of the wing and its structural frequency, f_{struc} , into a condition known as divergence.

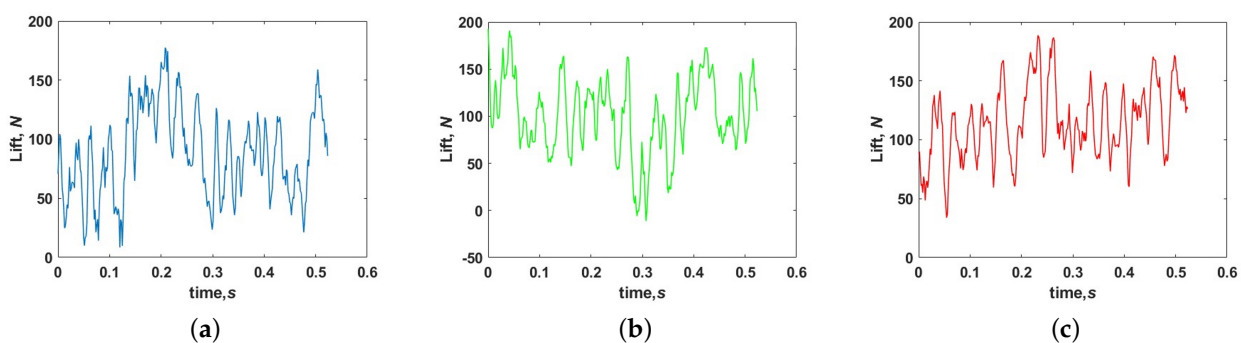


Figure 7. Lift force for the three aileron deflection angles. (a) $U_\infty = 26.8$ m/s, $\delta_a = 0^\circ$; (b) $U_\infty = 26.8$ m/s, $\delta_a = 5^\circ$; (c) $U_\infty = 26.8$ m/s, $\delta_a = 10^\circ$.

3.2. Power Spectral Density

The power spectral density of the force–time histories is computed in order to assess the most energetic frequencies associated with lift, L ; drag, D ; and the side force, Y . The nature of the turbulence produced by the WOW facility produces large length-scale vortices with vorticity about all three axes x , y , and z . The vorticity and turbulent kinetic energy in the flow contribute to a higher mean and unsteady forces as the vortices flow over the UAV structure. The PSD in terms of W/Hz is computed and plotted from the lift time histories for wind speeds $U_\infty = 13.4$ m/s, 17.9 m/s, and 26.8 m/s at aileron deflection angles $\delta_a = 0^\circ$, 5° , and 10° in Figures 8–10. The three primary PSD peaks in terms of increasing frequency are identified as the natural or structural frequency, f_{struc} ; shedding frequency, f_{shed} ; and integral length scale frequency, f_{L_∞} . The magnitude of the PSD peak and frequencies vary complexly with wind speed and whether computed from drag, lift, or the side force as indicated in Tables 2 and 3. The integral length scales in the streamwise direction for each test speed and aileron deflection angle were calculated from PIV data by using a two-point correlation method. The integral length scale is then equal to the area under the spatial auto-correlation function, $f(r, t)dr$, which is physically a measure of the minimum spatial separation at which the turbulent motion is uncorrelated with itself. The root mean square (RMS) and standard deviation (STD) of the forces suggest that the flow has a high degree of turbulence intensity and the turbulence is anisotropic.

Table 2. Natural frequency, RMS, and STD for the test wind speed and aileron deflection combinations.

Wind Speed (U_∞)	Aileron Deflection, δ_a	Structural Frequency (Hz), f_{struc}			Root Mean Square (N), RMS			Standard Deviation (N), STD		
		D	Y	L	D	Y	L	D	Y	L
13.4 m/s	0°	4.88	4.88	2.74	13.8	29.5	23.86	12.07	29.48	9.53
	5°	4.88	5.03	2.44	18.1	18.01	36.27	16.45	17.78	9.66
	10°	5.03	5.03	2.28	10.4	25.12	42.36	6.64	24.78	8.94
17.9 m/s	0°	5.03	5.03	5.03	19.84	39.6	45.89	14.65	39.59	19.61
	5°	4.88	4.88	2.74	27.56	52.21	59.55	23.7	52.2	18.09
	10°	5.03	5.03	7.02	19.7	48.65	68.7	12.12	48.61	19.3
26.8 m/s	0°	4.73	5.03	4.73	35.07	69.3	85.65	24.53	69.17	36.0
	5°	4.88	5.19	5.03	38.9	55.85	110.4	29.09	59.44	35.19
	10°	4.88	4.88	3.66	50.97	45.88	127.9	44.65	45.6	35.59

Table 3. Shedding frequency, frequency due to integral length scale based on lift measurement, and integral length scale at the location of the UAV for the test wind speeds and aileron deflection combinations.

Wind Speed, U_∞	Shedding Frequency, f_{shed}	Frequency Due to Integral Length Scale, f_{L_∞}			Integral Length Scale, L_∞ (m)		
		0°	5°	10°	0°	5°	10°
13.4 m/s	14.86	30.06	30.37	28.23	0.44	0.44	0.47
17.9 m/s	19.81	28.99	30.22	29.6	0.62	0.59	0.60
26.8 m/s	26.75	29.30	29.91	31.13	0.82	0.80	0.77

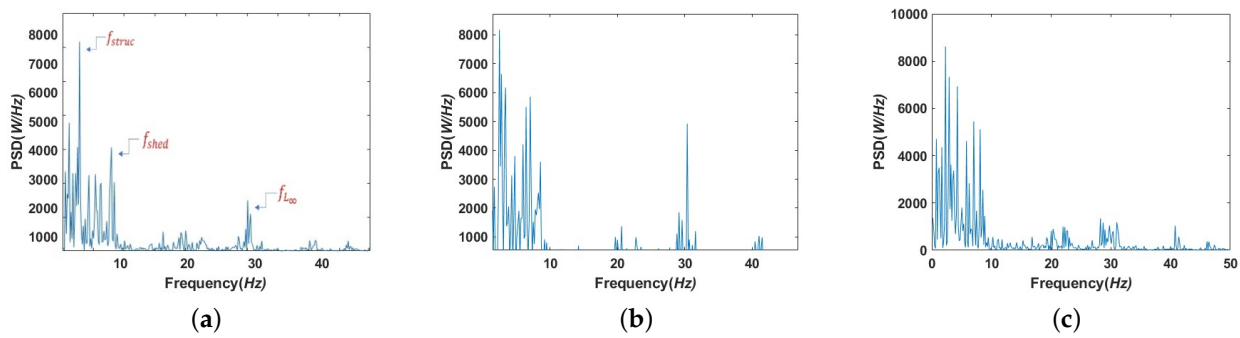


Figure 8. Power spectral density (PSD) for the three aileron deflection angles. (a) $U_\infty = 13.4$ m/s, $\delta_a = 0^\circ$; (b) $U_\infty = 13.4$ m/s, $\delta_a = 5^\circ$; (c) $U_\infty = 13.4$ m/s, $\delta_a = 10^\circ$.

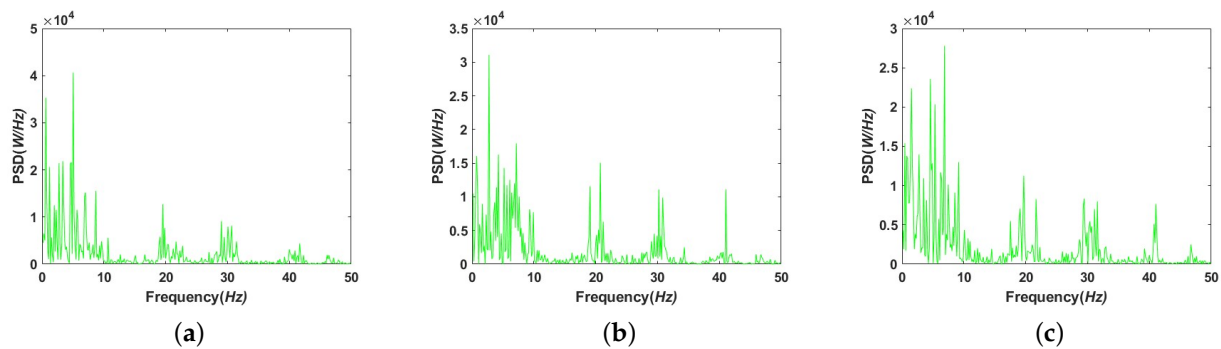


Figure 9. Power spectral density (PSD) for the three aileron deflection angles. (a) $U_\infty = 17.9$ m/s, $\delta_a = 0^\circ$; (b) $U_\infty = 17.9$ m/s, $\delta_a = 5^\circ$; (c) $U_\infty = 17.9$ m/s, $\delta_a = 10^\circ$.

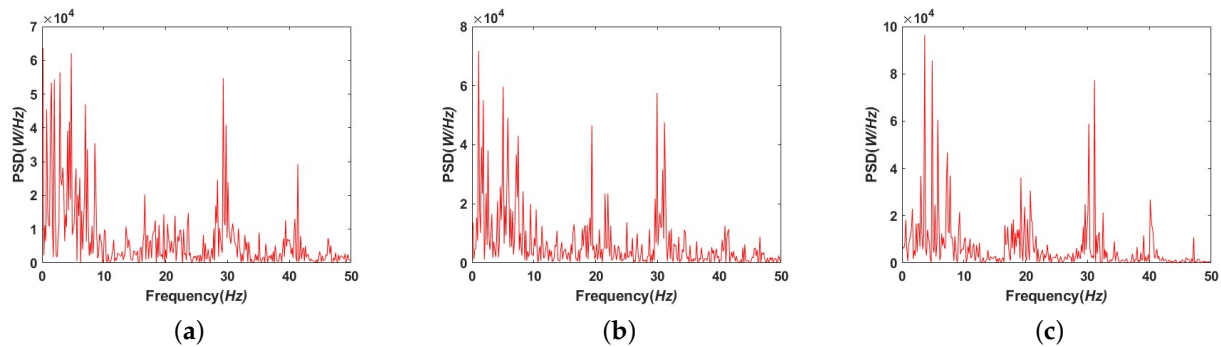


Figure 10. Power spectral density (PSD) for the three aileron deflection angles. (a) $U_\infty = 26.8$ m/s, $\delta_a = 0^\circ$; (b) $U_\infty = 26.8$ m/s, $\delta_a = 5^\circ$; (c) $U_\infty = 26.8$ m/s, $\delta_a = 10^\circ$.

3.3. Wing Bending Displacement

Wing displacement in the bending mode is measured by using three Acuity AR-700-50 laser-displacement sensors placed along the center of the wing chord, $x/c = 0.50$. The spanwise location of the sensors is placed at $y/(b/2) = 0.236, 0.547$, and 0.926 , considered to be at the root, middle, and tip region, respectively, of the wing half-span, $b/2$. Figures 11–13 show the time histories and moving average of the three-point deflections for wind speeds $U_\infty = 13.4$ m/s, 17.9 m/s, and 26.8 m/s at aileron deflection angles $\delta_a = 0^\circ, 5^\circ$, and 10° . We can observe that vertical wing displacement, measured in inches from its state of equilibrium (no wind speed), is highly nonlinear with the spanwise position $y/(b/2)$. The wing displacement fluctuates about a mean of just above zero cm at $y/(b/2) = 0.236$ for all wind speeds and aileron deflection angles.

At a position of $y/(b/2) = 0.547$, the wing is displaced upwards and oscillates about a higher mean and RMS, which increases as a function of the wind speed and aileron

deflection. The bending displacement of the wing reaches a mean of ≈ 2.5 cm for the case at $U_\infty = 26.8$ m/s and $\delta_a = 5^\circ$. At these same conditions, the displacement at the tip of the wing, $y/(b/2) = 0.926$, reaches a mean of ≈ 6.5 cm, which highlights the nonlinear nature of wing bending displacement.

The extreme nature of the structural dynamics of the wing and the probability of structural failure is evident from the very high amplitudes of wing displacement at the wing tip for $U_\infty = 26.8$ m/s. Compared to the equilibrium position (0 cm), the unsteady displacements reach up to ≈ 14 cm, with a mean of about ≈ 7.5 cm with $\delta_a = 10^\circ$. The increase in the mean displacement between $\delta_a = 0^\circ$ and $\delta_a = 10^\circ$ is ≈ 2.5 cm, which is considerable. The significance is that the aileron, and by extension any control surface wetted to the flow, can be used to either provide additional loading and displacement as shown here, or if deflected in the opposite direction, can be used to *unload* the wing or other structure and act as a disturbance ‘rejector’ to significantly reduce structural displacements that lead to aeroelastic instabilities or failure.

In order to gain more insight into the relative energy content of the structural vibration of the wing at the different spanwise locations, $y/(b/2)$, the PSD peak of the structural frequency f_{struc} is plotted in Figure 14. The PSD function is logarithmic with vibration, and therefore the increases in the power of f_{struc} between $y/(b/2) = 0.236, 0.547$, and 0.926 are much greater than the increases in the mean and RMS displacement. The PSD magnitudes are summarized in Table 4 for the cases at different wind speeds, aileron deflections, and wing locations. The maximum PSD of 137.54 W/Hz occurs for the wing tip vibration tested at $U_\infty = 26.8$ m/s and $\delta_a = 0^\circ$. Aileron deflection has a considerable effect on the PSD magnitude; however, there is no clear correlation, and this is likely due to the stochastic nature of the turbulence and vortex structures as they impact the aileron. It is clear, however, that the wing displacement amplitude in the wing tip region, particularly at higher speeds, attains exceedingly high magnitudes of power that can likely cause failure in the structure if the wing operates in this type of flow with an extreme turbulence intensity for an extended period of time.

Table 4. Power spectral density (PSD) peak of the structural frequency f_{struc} .

Wind Speed (U_∞)	Aileron Deflection (δ_a)	Tip ($y/(b/2) = 0.926$)	Mid ($y/(b/2) = 0.547$)	Root ($y/(b/2) = 0.236$)
13.4 m/s	0°	23.74	2.56	0.05
	5°	21.43	2.42	0.03
	10°	13.93	1.61	0.05
17.9 m/s	0°	60.63	7.87	0.26
	5°	46.23	6.93	0.60
	10°	112.25	14.38	0.33
26.8 m/s	0°	137.54	17.21	0.36
	5°	74.86	10.94	0.34
	10°	135.70	19.30	0.26

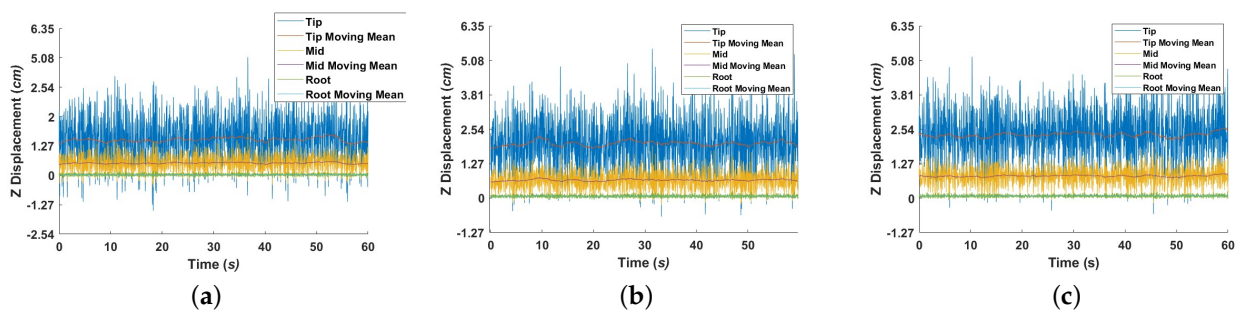


Figure 11. Wing bending displacement for the three aileron deflection angles. (a) $U_\infty = 13.4$ m/s, $\delta_a = 0^\circ$; (b) $U_\infty = 13.4$ m/s, $\delta_a = 5^\circ$; (c) $U_\infty = 13.4$ m/s, $\delta_a = 10^\circ$.

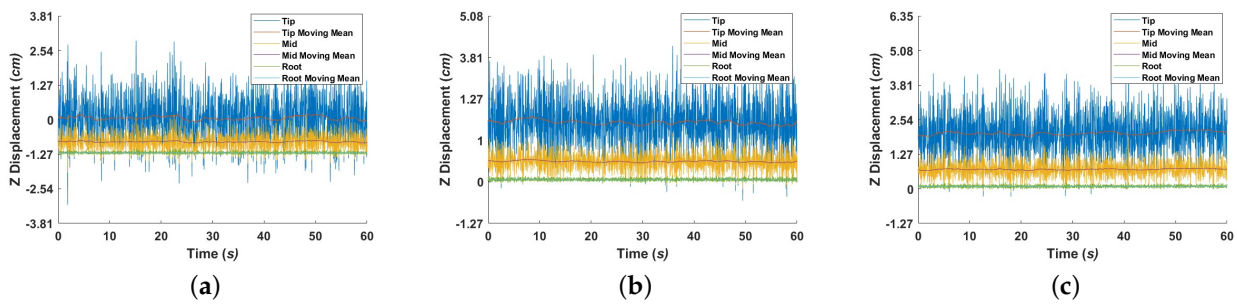


Figure 12. Wing bending displacement for the three aileron deflection angles. (a) $U_\infty = 17.9$ m/s, $\delta_a = 0^\circ$; (b) $U_\infty = 17.9$ m/s, $\delta_a = 5^\circ$; (c) $U_\infty = 17.9$ m/s, $\delta_a = 10^\circ$.

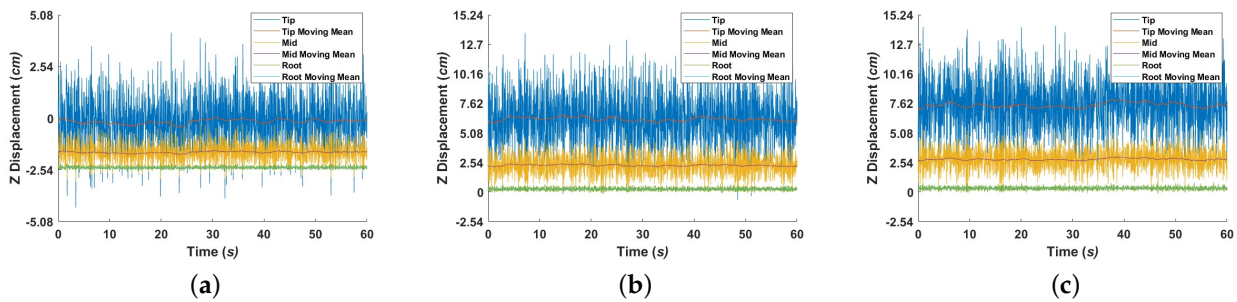


Figure 13. Wing bending displacement for the three aileron deflection angles. (a) $U_\infty = 26$ m/s, $\delta_a = 0^\circ$; (b) $U_\infty = 26.8$ m/s, $\delta_a = 5^\circ$; (c) $U_\infty = 26.8$ m/s, $\delta_a = 10^\circ$.

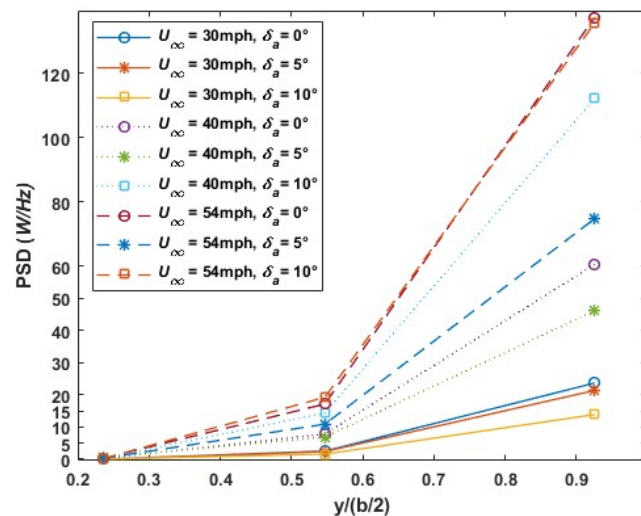


Figure 14. Power spectral density (PSD) of the structural frequency for the test speeds and aileron deflection angles.

4. Flow Measurement Methodology

The primary instrument used for the UAV experiments was the WOW-EF tomographic particle image velocimetry (tomo-PIV) system from LaVision. Four Phantom VEO-L series high-speed cameras were employed for 3D PIV measurements to capture the flow on the right-wing panel at half-span on the aileron. High measurement resolution is achieved through Nikon AF-S Nikkor 300 mm lenses (Nikon Corporation, Tokyo, Japan) with 527 nm filter. The four PIV cameras were installed on the translation stage in the west part of the WOW-EF building near the turntable. The high-speed laser optics were adjusted to 3D volumetric hardware and were directed upward onto the bottom surface of the UAV's wing. The laser light volume was positioned to illuminate the region of interest on the UAV wing, and the cameras were focused by using a 309-15 calibration target. Pretest and

post-test calibration is performed to ensure accurate and reliable measurement results, as shown in Figure 15. Trial tests were conducted to check the bubble seeding density, and the position of the seeder was adjusted in the wind field to improve the density. The analog waveform generator was integrated into the data-acquisition setup to synchronize the start time of all data-acquisition devices. All PIV data were acquired with LaVision's proprietary integrated image acquisition and processing software, DaVis 10.2.

For volumetric recording, four cameras with double-frame and two-pulses capability were used with each image consisting of eight frames. The time between the double-frame images dt was varied between 45 and 75 μs depending on the test speed, and the sample duration was 4.8 s at a sampling rate of 625 Hz. Helium-filled soap bubbles with a size of approximately 1 mm are used with an optimal seeding density for the best Shake-the-Box measurement.

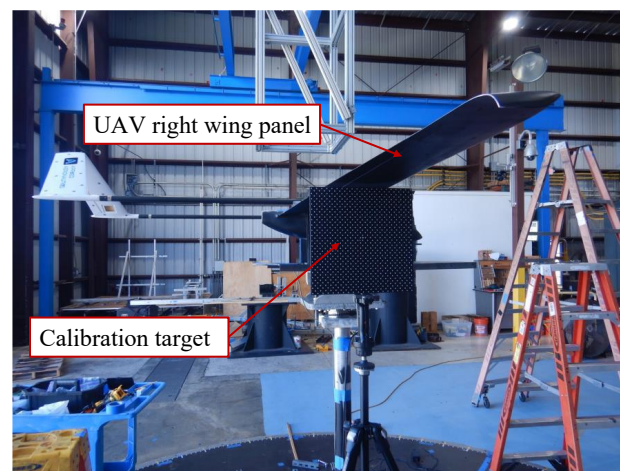


Figure 15. Side view of the UAV setup during the PIV calibration process.

A combination of three different wind speeds and three angles of aileron deflection were tested with 3000 images captured for each case. Image preprocessing is performed for the raw camera images for further analysis. Volume self-calibration is performed to remove any residual calibration disparities. This is performed by repeatedly going through the calculations of disparity vector maps and making corrections to the mapping function until the remaining disparity is below 0.1 voxel in all subvolumes. To allow for the precise reconstruction of the virtual camera images from 3D particle positions, the optical transfer function (OTF) is calculated after volume self-calibration. The calculation of the OTF is an important step for Shake-the-Box (Figure 16) before finally calculating particle tracks from the preprocessed images. Velocity from the STB track data has been converted to a regular grid resulting in an averaged field. Tracks in the vicinity of a grid point have been used to calculate the velocity at a point. The contribution of a track to this grid point is weighted by the distance of the track from the grid point using a Gaussian weighting function [20]. Velocity has been calculated for each particle using the particle track data using finite difference between the particle positions from the two time steps for this double pulse recording. Once velocity is known for each particle, polynomial regression is used to calculate velocities for grid points.

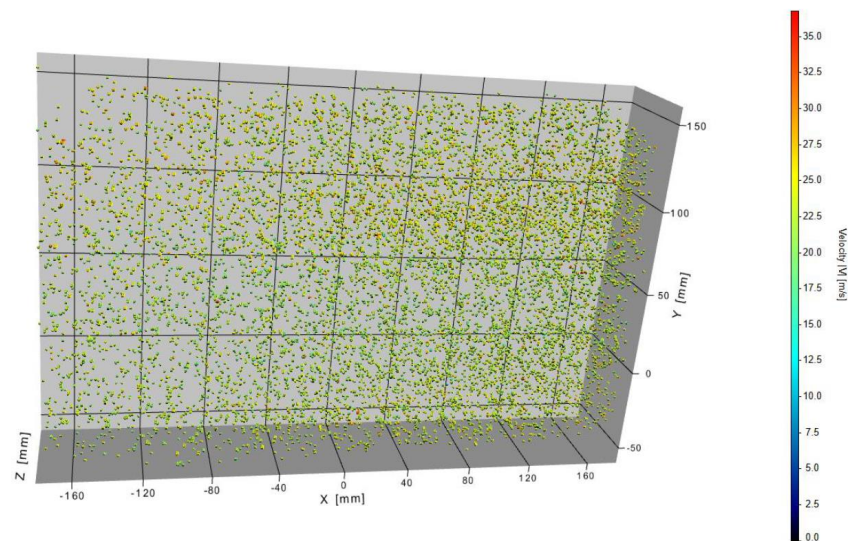


Figure 16. Particles identified in the Shake-the-Box measurement method; flow is along the $-X$ direction.

5. Time-Averaged Flow Field

The time-averaged streamwise flow velocity U on the underside of the UAV wing is presented as planes of velocity fields in Figures 17 and 18 for a freestream velocity $U_\infty = 13.4$ m/s and aileron deflection angles $\delta_a = 0^\circ$ (baseline flow) and 10° . The first velocity field at $x = 150$ mm (plane 1) is located at the leading edge of the wing. Planes 2 and 3 are located 100 mm and 205 mm downstream of the leading edge, respectively. The trailing edge of the wing and aileron is positioned at $x = -100$ mm, creating a chord length of 0.25 m. Finally, the last measurement plane 4 located at $x = -155$ mm is just 55 mm downstream of the aileron in order to capture its effect on the flow. Note that the hinge or rotating point of the aileron coincides at $x = -50$ mm, which is close to the location of plane 3 at $x = -55$ mm. The chord length of the aileron is therefore 50 mm. The pressure or bottom surface of the wing is aligned along an $x-z$ plane defined by $y \approx 150$ mm. For the baseline flow (Figures 17a and 18a,b), the velocity fields for the portion of the flow underneath the wing from $y = 100$ mm to 150 mm show a noticeable and gradual increase in velocity from the leading edge ($U \approx 12$ m/s) to the trailing edge, which tends to the freestream velocity value of 13.4 m/s. However, when the aileron is deflected, represented in the velocity fields of Figures 17b and 18c,d, there is a substantial reduction in the velocity represented by light blue contours ($U \approx 13$ m/s) to yellow–orange contours ($U \approx 12$ m/s) below the aileron hinge area (plane 3 at $y \approx 100$ –140 mm), which is indicative of a rise in the pressure coefficient as expected. The flow downstream of the aileron quantified in plane 4, however, shows scattered pockets of higher momentum flow (blue contours), which are likely caused by vortex shedding as the flow rolls away from the trailing edge of the aileron. When the freestream velocity is doubled to 26.8 m/s, represented by the velocity fields of Figure 19b, the streamwise velocity contours along the underside of the wing are similar to the lower freestream velocity. However, downstream of the aileron, in Figures 19b and 20d, plane 4 and the velocity fields indicate a reduced velocity magnitude, respectively, which suggests the production of stronger negative vorticity about the spanwise z axis from the shed vortex structures. Vorticity transport in the flow and in the vicinity of the flap will be analyzed further. The highly turbulent nature of the flow with a turbulence intensity T_∞ of approximately 10% is appreciated by the large fluctuations in the streamwise velocity within each measurement plane and as it flows from the wing leading edge to behind the trailing edge.

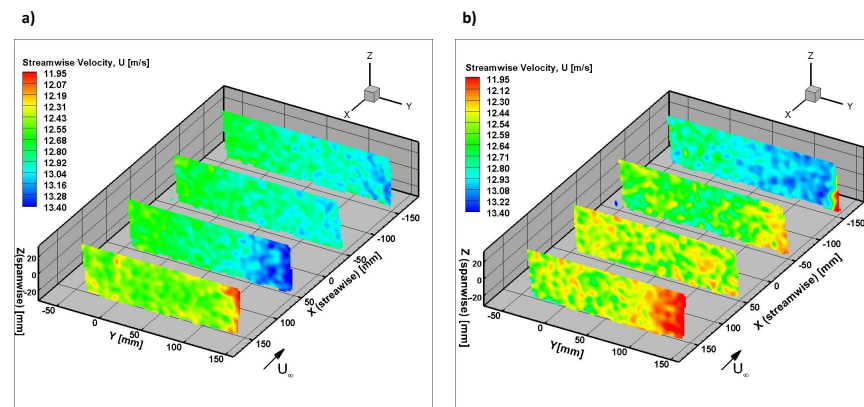


Figure 17. Time-averaged streamwise velocity U in the flow volume at $U_\infty = 13.4$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

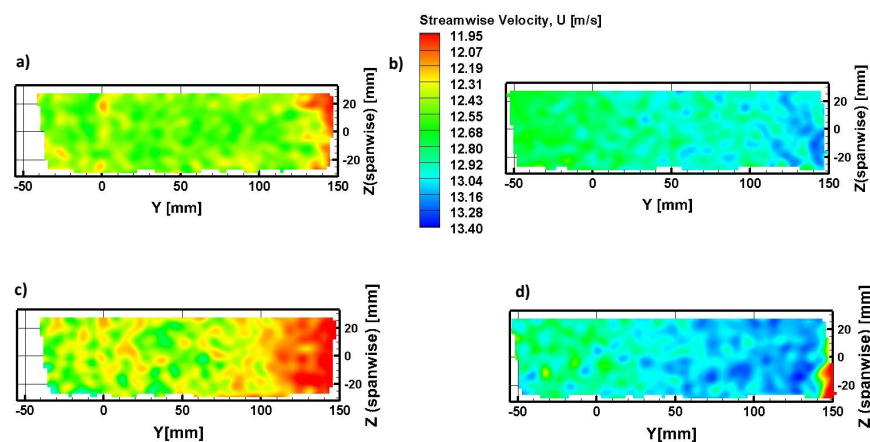


Figure 18. Time-averaged streamwise velocity U at $U_\infty = 13.4$ m/s for (a) plane 1 (at $x = 155$ mm) with aileron deflection, $\delta_a = 0^\circ$; (b) plane 4 (at $x = -155$ mm) with $\delta_a = 0^\circ$; and (c) plane 1 with $\delta_a = 10^\circ$ and (d) plane 4 with $\delta_a = 10^\circ$.

The aileron, when deflected down, increases the effective camber of the wing section, thus increasing the lift per unit span L' produced by the wing section. The aileron deflection also vectors the flow so as to produce downward momentum (along the $-y$ axis), where its time rate of change inside a control volume that encompasses the wing section can be shown to be equivalent to the change in lift produced by deflecting the flap. The downward velocity magnitude V fields at $U_\infty = 13.4$ m/s are plotted in Figures 21 and 22. For the baseline flow, the V component underneath the wing in plane 2 ($x = 50$ mm) to plane 3 ($x = -55$ mm) decreases significantly in regions from $V \approx 0.61$ – 0.75 to $V \approx 0.26$ – 0.37 . Downstream of the aileron, when $\delta_a = 0^\circ$, the downward velocity increases again to $V \approx 0.80$, which is consistent with a small downward redirection of the flow as a result of the cambered airfoil on the wing. The high level of the flow turbulence in the V velocity is apparent by comparing the drastic changes in velocity from the inlet to the outlet of the flow volume at $x = 155$ mm to -155 mm. It is hypothesized that the significant unsteady structural displacement of the wing in the bending mode (quantified in Figures 11–13) induces a separate unsteady vertical velocity component in the direction of wing motion close to the surface of the wing. However, this is not evident from the time-averaged PIV velocity fields, which by definition are not phase-averaged to the natural or structural frequency of the wing.

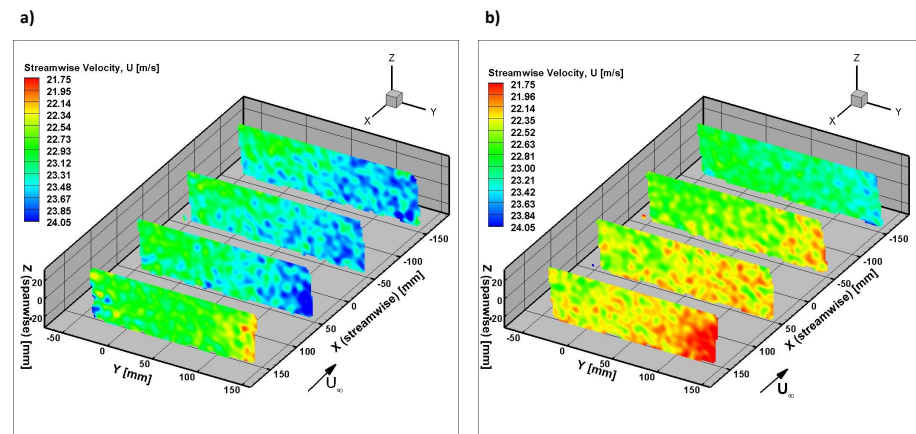


Figure 19. Time-averaged streamwise velocity U in the flow volume at $U_\infty = 26.8$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

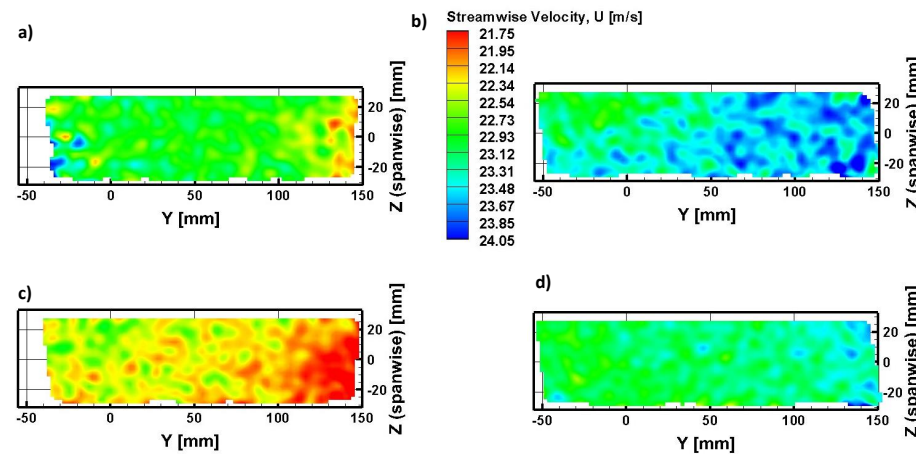


Figure 20. Time-averaged streamwise velocity U at $U_\infty = 26.8$ m/s for (a) plane 1 (at $x = 155$ mm) with aileron deflection, $\delta_a = 0^\circ$; (b) plane 4 (at $x = -155$ mm) with $\delta_a = 0^\circ$; and (c) plane 1 with $\delta_a = 10^\circ$ and (d) plane 4 with $\delta_a = 10^\circ$.

The vorticity in the flow below the wing was computed and must be considered in terms of the turbulent length scales and energy cascade. It is noted from the outset that the UAV and measurement volume is located far downstream, approximately 13 m, from the Wall-of-Wind facility fans where the turbulent flow field is first produced. The flow then passes through a conditioning section with fully open spires and ground plates to generate a wind shear profile and additional length scales with high turbulence intensity. Initially, predominantly energetic large-scale structures up to the integral length scale assumed to be on the order of the WOW fan diameter ($L_\infty \sim 2$ m) are produced by the fans. As the flow travels downstream, these large structures undergo vortex stretching and break down into smaller structures with less kinetic energy due to the effects of viscous shear stress and dissipation. The turbulent flow measured constitutes a snapshot of how the flow has evolved during this process. From the vorticity fields presented in the next figures, it is clear that the turbulence has ‘cascaded’ into small-scale structures or finer-scale turbulence from what is generated close to the fans.

The time-averaged spanwise vorticity ω_z contours contained in the measurement volume are presented in Figure 23 for $U_\infty = 13.4$ m/s and aileron deflection $\delta_a = 0^\circ$ and 10° . The nature of the baseline turbulent structures and vorticity in Figure 23a from $x = 155$ mm to -155 mm is fairly homogeneous. When the aileron is deflected, vortex shedding produces a collection of larger vortex structures with predominantly positive vorticity immediately behind the aileron in the area formed by $x = -100$ mm to 155 mm

and $y = 125$ mm to 150 mm. The aileron in essence increases the circulation around the wing section, which translates into more vorticity production with the largest vortex length scales that are proportional to the chord length of the aileron or flap. It is estimated from Figure 23b behind the aileron that the largest length scales are on the order of 40–50 mm, which is in fact approximately the chord length of the aileron.

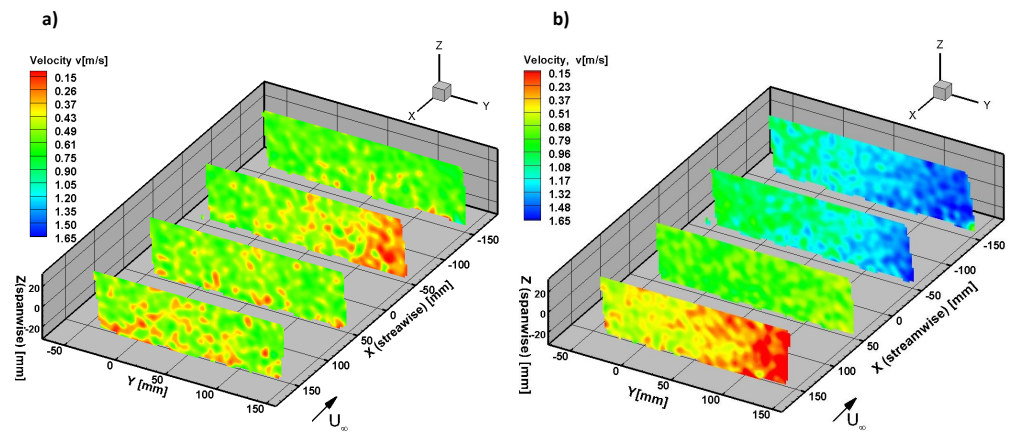


Figure 21. Time-averaged vertical velocity V in the flow volume at $U_\infty = 13.4$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

Isosurfaces of the time-averaged total vorticity $\omega = \nabla \times \vec{V}$ at $U_\infty = 13.4$ m/s for the measurement volume are presented in Figure 24. Elevated values of the total vorticity compared to the spanwise vorticity are shown throughout the baseline flow in Figure 24a. The vortex structures are fairly evenly distributed, and the length scales vary in size between the smallest scales ~ 5 mm and the largest approaching ~ 50 mm. The effect of aileron deflection is clearly visible in the larger size and strength of the vortices downstream of the aileron. The vorticity in the flow in this region reaches a maximum of $\omega \approx 290$ /s. The mean vorticity throughout the flow is somewhere in the midrange of the contour bar equivalent to $\omega \approx 145$ /s. Isosurfaces of the total vorticity along the $x - y$ midplane of the measurement volume along $z = 0$ at the same freestream velocity are presented in Figure 25. The makeup and distribution of vortex structures may be easier to visualize in a two-dimensional plane and indicate that the turbulence is virtually indistinguishable between the baseline flow and when the aileron is deflected if the surface of the aileron is perpendicular to the $x - y$ plane.

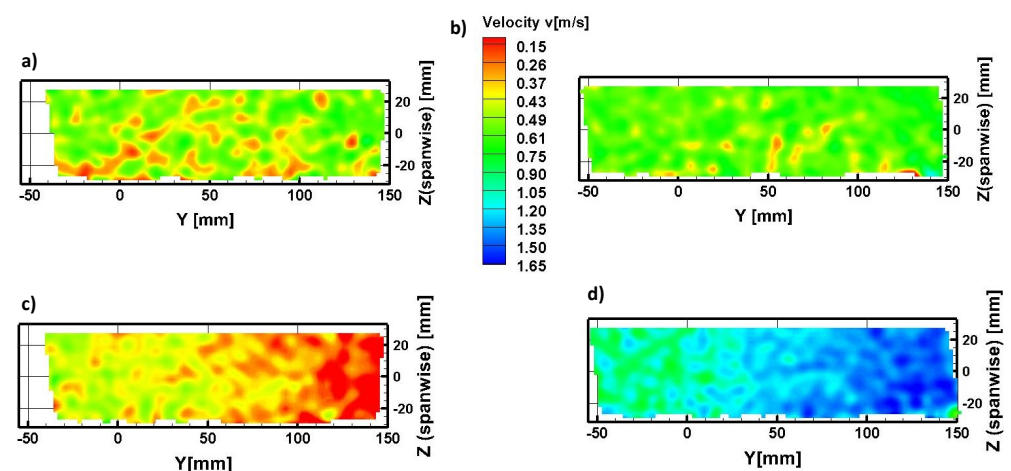


Figure 22. Time-averaged vertical velocity V at $U_\infty = 13.4$ m/s for (a) plane 1 (at $x = 155$ mm) with aileron deflection, $\delta_a = 0^\circ$; (b) plane 4 (at $x = -155$ mm) with $\delta_a = 0^\circ$; and (c) plane 1 with $\delta_a = 10^\circ$ and (d) plane 4 with $\delta_a = 10^\circ$.

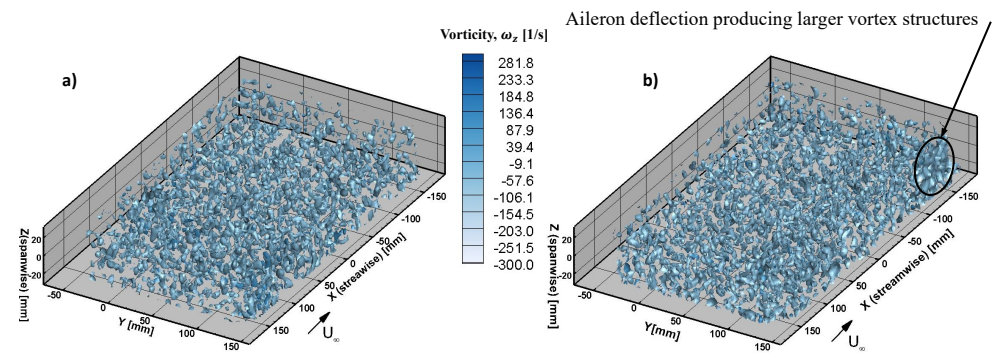


Figure 23. Isosurfaces of time-averaged spanwise vorticity ω_z at $U_\infty = 13.4$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

The next set of results in Figures 26 and 27 are volumetric plots of isosurfaces of the time-averaged spanwise vorticity ω_z and total vorticity ω of the flow when the freestream velocity is doubled to $U_\infty = 26.8$ m/s. The range of the length scales of the turbulence is similar; however, the upper and lower level of $\pm\omega$ doubled. In the case of spanwise vorticity, a maximum vorticity of $\omega_z \approx 563$ /s is reached at various points in the flow, with a mean vorticity throughout the flow that is positive. When the aileron is deflected, the ω_z isosurfaces downstream of the aileron show no appreciable increase in vorticity as was observed previously when $U_\infty = 13.4$ m/s. At the higher freestream velocity, the total vorticity of the isosurfaces shows an increase in the maximum vorticity equal to $\omega \approx 594$ /s as well as a higher mean vorticity due to stronger velocity gradients in the total vorticity expression $\nabla \times \vec{V}$. The deflection of the aileron does not appreciably produce different length scales or additional total vorticity.

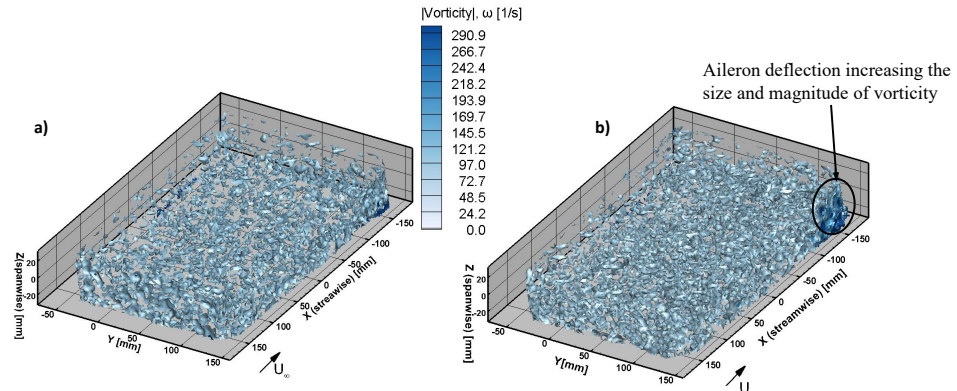


Figure 24. Isosurfaces of time-averaged total vorticity ω at $U_\infty = 13.4$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

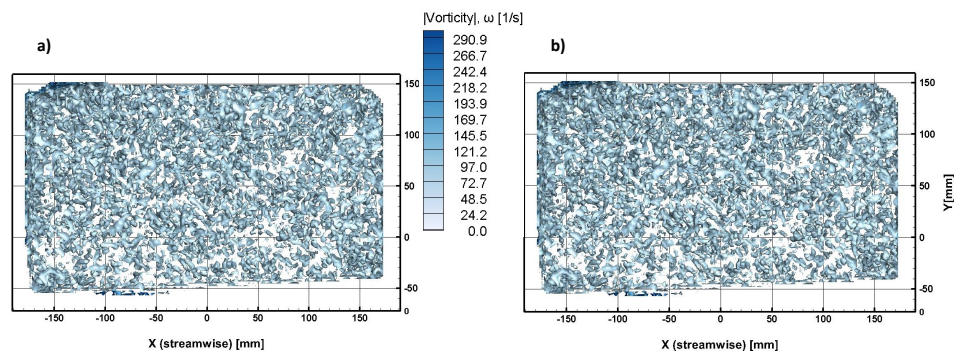


Figure 25. Isosurfaces of time-averaged total vorticity along the $z = 0$ plane ω at $U_\infty = 13.4$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

Table 5 and Figure 28 display the mean and RMS values of the lift force for the test wind speeds and aileron deflections. At the lower velocity of $U_\infty = 13.4$ m/s, the mean lift force nearly doubles from 21.88 N to 41.4 N when the aileron is deflected to 10° . However, when the freestream velocity is doubled to 26.8 m/s, the aileron produces only a 59% increase in the lift force, indicating a decrease in the effectiveness of the aileron.

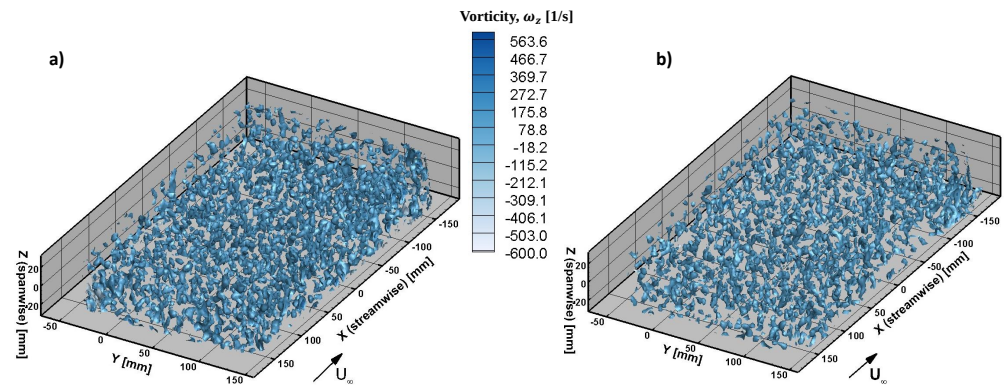


Figure 26. Isosurfaces of time-averaged spanwise vorticity ω_z at $U_\infty = 26.8$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

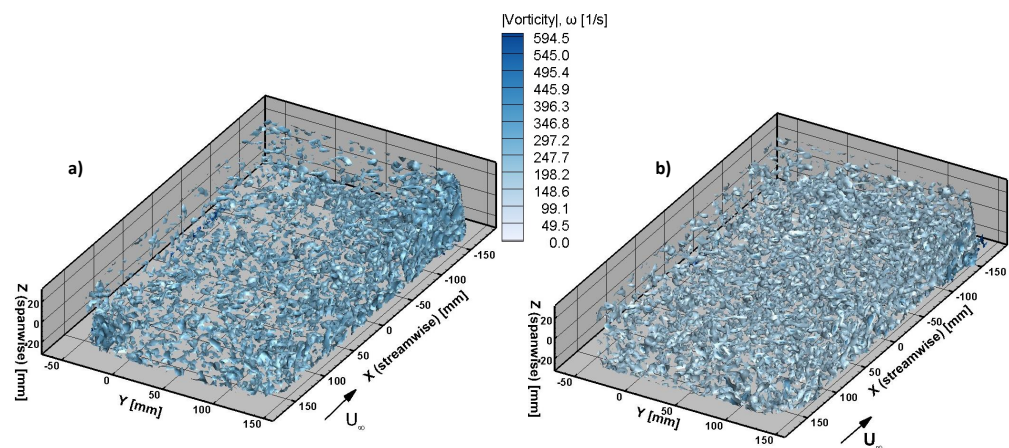


Figure 27. Isosurfaces of time-averaged total vorticity ω at $U_\infty = 26.8$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

Table 5. Mean and RMS of the lift force and wing tip displacement.

Wind Speed, U_∞	Aileron Def., δ_a	Lift, Mean (N)	Lift, RMS (N)	Wing Tip Disp. (cm)
13.4 m/s	0°	21.88	23.8	1.40
26.8 m/s	0°	77.72	85.6	5.08
13.4 m/s	10°	41.4	42.4	2.54
26.8 m/s	10°	123.5	127.9	7.62

The time-averaged turbulent kinetic energy k in the flow volume is presented in Figures 29 and 30 for both free stream velocities. This quantity is a measure of the turbulent energy inherent in the flow through the variances in the velocity components as follows:

$$k = \frac{1}{2} \left(\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2} \right) \quad (1)$$

where u' , v' , and w' are the streamwise, wall-normal, and spanwise fluctuating velocity components, respectively. The effect of aileron deflection is to increase the concentration of turbulent kinetic energy in the vicinity and downstream of the aileron. As mentioned previously, the aileron is an active surface that acts as a circulation and vortex-production

mechanism that increases velocity fluctuations. For the baseline flow in Figure 29a in the area downstream and below the trailing edge in plane 4, the region of blue and green contours represents turbulent kinetic energy in the range of $k \approx 3$ to 3.6 (m/s)^2 . With aileron deflection shown in Figure 29b, the orange–red contours on the right corners of planes 3 and 4 (slightly upstream and downstream) of the aileron show enhanced levels of turbulent kinetic energy in the range of $k \approx 4\text{--}8 \text{ (m/s)}^2$. However, further below the aileron for $y < 100 \text{ mm}$ in plane 4, there is a large blue-contour region of low- k flow with pockets of higher turbulent kinetic energy. This may be due to the high Reynolds stresses of the vortical flow shed from the aileron, which promotes breaking up into smaller dissipated vortices further down below the aileron. The flow with a higher freestream velocity of $U_\infty = 26.8 \text{ m/s}$ displays a smaller orange–red contour region, where $k \approx 15\text{--}18 \text{ (m/s)}^2$ when the aileron is deflected. Based on this observation, there is a less significant increase in turbulent kinetic energy compared to the baseline flow when the aileron is deflected at considerably higher freestream velocity.

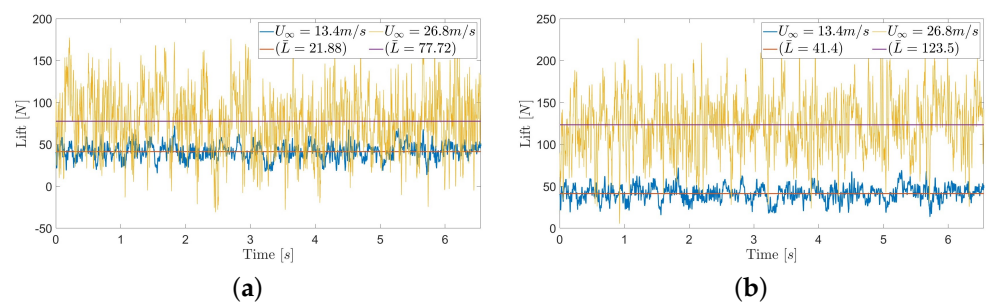


Figure 28. Mean and RMS of lift force. (a) $U_\infty = 30$ and 60 mph , $\delta_a = 0^\circ$; (b) $U_\infty = 30$ and 60 mph , $\delta_a = 10^\circ$.

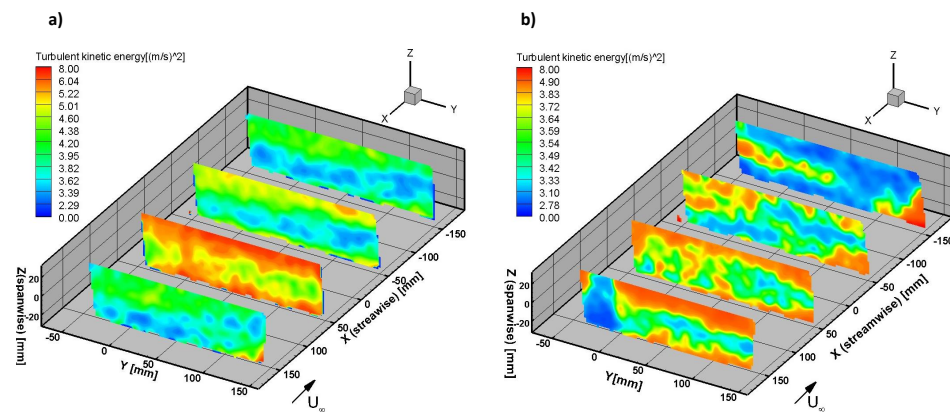


Figure 29. Turbulent kinetic energy k at $U_\infty = 13.4 \text{ m/s}$ for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

This outcome supports the results of the time-averaged total vorticity, where the same behavior was found: flap deflection produces less additional vorticity if the flow already has elevated vorticity due to the doubling of the freestream velocity. As a consequence of the diminishing spanwise vorticity, which contributes most significantly to the development of the wing trailing vortex sheet (where its intensity is proportional to lift production), there is less additional lift produced by the aileron. This leads to the main theory of this study: in flow with extreme turbulence intensity, in order to compensate for control surfaces that are less effective in varying lift loads on a fixed-wing aircraft, there is a need for larger and/or more control surfaces on the wing in order to respond to and mitigate large structural displacements of the wing and maintain flight control. Moreover, a second point to this theory is that a control surface becomes less effective in producing lift and control moments if the length scales of the largest vortex structures in the flow are on the order of the control surface chord length or larger.

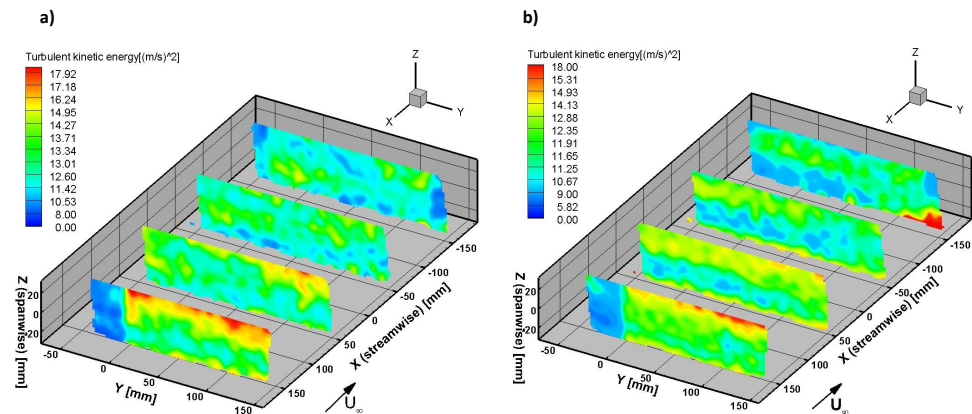


Figure 30. Turbulent kinetic energy k at $U_\infty = 26.8$ m/s for (a) aileron deflection, $\delta_a = 0^\circ$ and (b) $\delta_a = 10^\circ$.

6. Concluding Remarks

Light aircraft structures such as commercial UAVs with slender (a high aspect ratio) fixed wings are not designed to operate in flight with extreme flow turbulence intensities of $\sim 10\%$ and above, representative of the flow conditions replicated in these experiments or during a hurricane. High levels of turbulent kinetic energy are imparted on the UAV structure from the flow. This elevates the power spectral density up to ≈ 137 W/Hz at $U_\infty = 26.8$ m/s for both $\delta_a = 0^\circ$ and 10° , which is inherent in the unsteady wing bending motion. The wing structure should be reinforced with additional spars and/or higher-strength materials in order to reduce the stress and strain of the structural components, which is directly related to the wing displacements measured. The RMS of the wing tip displacement at $U_\infty = 13.4$ m/s was computed as 1.40 cm and increased to 5.08 cm at $U_\infty = 26.8$ m/s without aileron deflection ($\delta_a = 0^\circ$), representing a factor of 3.6 increase. However, when the aileron was deflected to $\delta_a = 10^\circ$ comparing the same flow speeds, there was only a factor of 3.0 increase from 2.54 cm to 7.62 cm.

A similar phenomenon was discovered in the mean lift produced. For the baseline flow without aileron deflection, the lift increased from 21.88 N to 77.72 N when the freestream velocity was doubled, a factor of 3.3 higher, which does not represent conventional understanding from the relation $L \propto U_\infty^2$. The claim that aileron deflection becomes less effective at producing lift when there is already a much higher level of total vorticity in the flow by doubling the freestream velocity is supported by the data. The mean lift was increased from 41.4 N to 123.5 N at $\delta_a = 10^\circ$, representing only a 3.0 factor increase in the lift. The aileron effectiveness in producing lift was also compromised at $\delta_a = 5^\circ$ but to a lower degree.

In order to design next-generation UAVs capable of controlled flight in extreme flow conditions, we must consider a paradigm shift in aircraft design: this involves implementing a considerable number and combination of control surfaces such as ailerons, flaps, and spoilers throughout the wing and likely adding new active surfaces on the sides of fuselage in order to produce stronger rolling and directional/yaw moments to maintain flight control in highly turbulent flow. The additional control surface actuators and material to reinforce the structure will increase the takeoff weight of such an aircraft and negatively impact its range and climb performance. However, this loss in performance can be ameliorated or altogether eliminated by increasing the surface area of the wing and thrust/ power rating of the engine to maintain the same wing loading and thrust-to-weight ratio. Certain conceptual design guidelines may be established for UAVs operating in extreme wind conditions, beginning with increasing the structure factor (defined as the empty weight of an aircraft divided by its takeoff weight) in order to account for what may be a ≈ 10 – 15% increase in structural weight. From an automatic sensing, feedback, and control surface actuation standpoint, it is likely that these processing demands can be met with modern control systems. Future research will focus on studying the effect of control surface size, placement, and location on the wing or fuselage, and real-time actuation to measure the

structural response to turbulence and unsteady loads. These types of structurally resilient and flight-stable UAVs that are capable of operating in real time during a hurricane are critical for first-response efforts and to build resilient communities.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

D	Drag Force
DAQ	Data acquisition
DC	Direct Current
FIU	Florida International University
L	Lift force
NHERI	Natural Hazards Engineering Research Infrastructure
NI	National Instruments
OPT	Optical transfer function
PIV	Particle image velocimetry
PSD	Power spectral density
PTV	Particle-tracking velocimetry
RMS	Root mean square
STB	Shake-the-Box
STD	Standard deviation
UAV	Unmanned aerial vehicle
WOW-EF	Wall-of-Wind Experimental Facility
Y	Side force

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