



Surface Flow Visualization via Tuft-Tracking on Transonic Truss-Braced Wing Configuration

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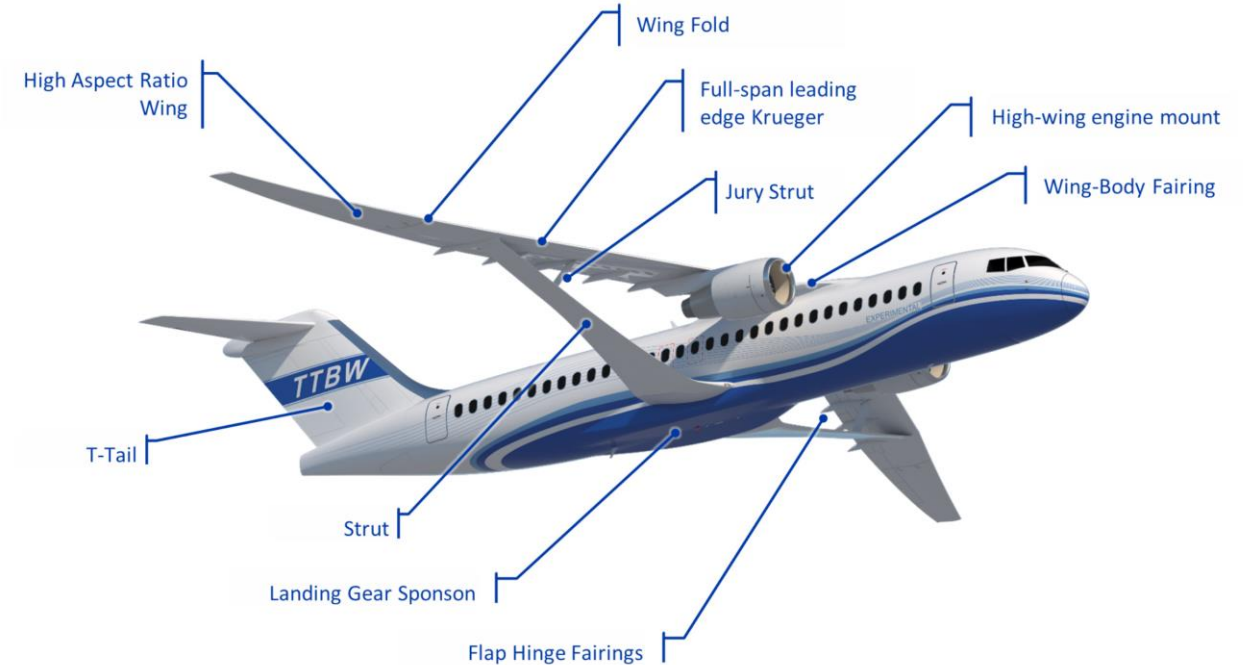
- Transonic Truss-Braced Wing (TTBW)
- Experimental Setup
- Tuft Flow Analysis – Prior Work
- Frame-by-Frame Tuft Tracking (FFTT) Procedure
- CFD Overview
- Experimental/CFD comparisons
- Conclusions and Future Work

Configuration of Interest: TTBW



Transonic Truss-Braced Wing (TTBW)

- The TTBW was developed during the Subsonic Ultra Green Aircraft Research (SUGAR) project, an ongoing NASA/Boeing collaborative effort to advance commercial subsonic aircraft with a goal of reduced noise, emissions, and energy/fuel consumption to **increase efficiency**, environmental compatibility, and economic impact.
- The aerodynamic efficiency of the aircraft stems from its **high aspect ratio (AR = 19.55)** wings.
- The increase in aspect ratio requires **additional support** to compensate for the elevated wing-root bending moment, thus the need for the **truss-bracing** from which the aircraft derives its name.



SUGAR TTBW Mach 0.80 Configuration [1]

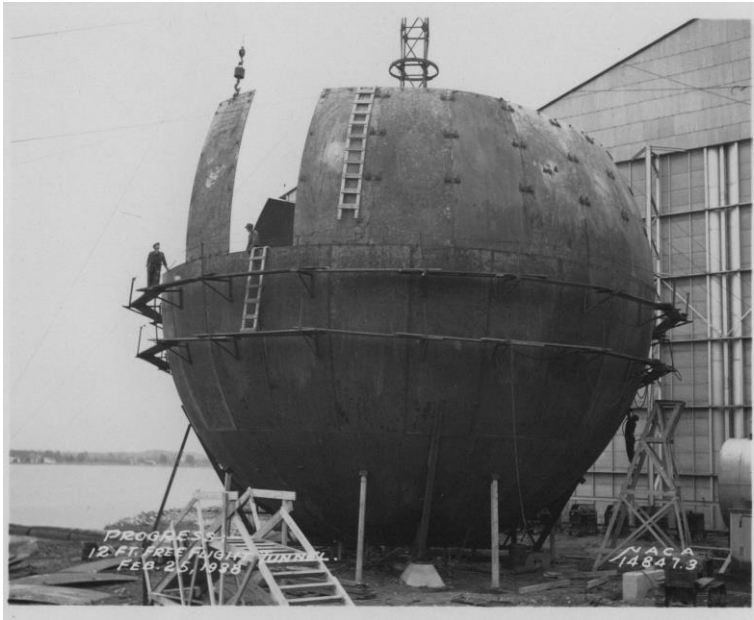
[1] Harrison, N. A., Hoffman, K., Lazzara, D. S., Reichenbach, E. Y., Sclafani, A. J., and Droney, C. K., "Subsonic Ultra Green Aircraft Research: Phase IV Final Report–Volume I Mach 0.80 Transonic Truss-Braced Wing High-Speed Design Report," 2023

Experimental Setup

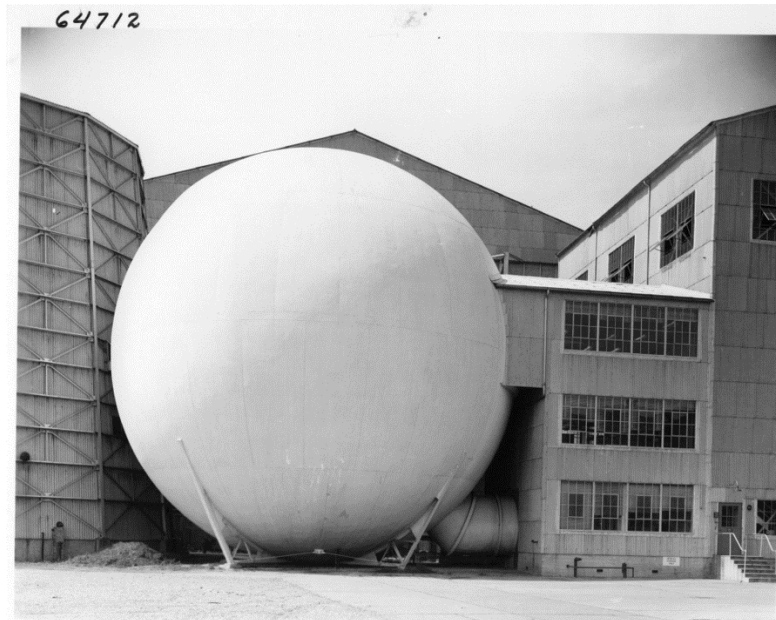


Experiments conducted at the NASA Langley 12-Foot Low-Speed Tunnel

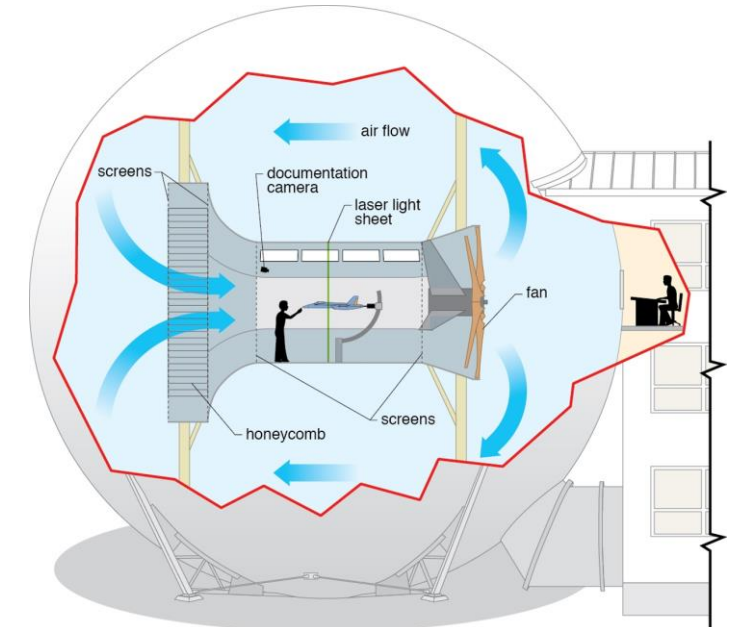
- Began operations in 1939, originally designed to explore aircraft stability and control characteristics using free-flight testing techniques.
- Driven by a 6-bladed, 15.8-foot diameter fan. For data presented in this paper, the testing was conducted at $Q = 4$ psf, corresponding to a freestream velocity of roughly 60 ft/s.



Tunnel exterior during construction (1938). [NASA]



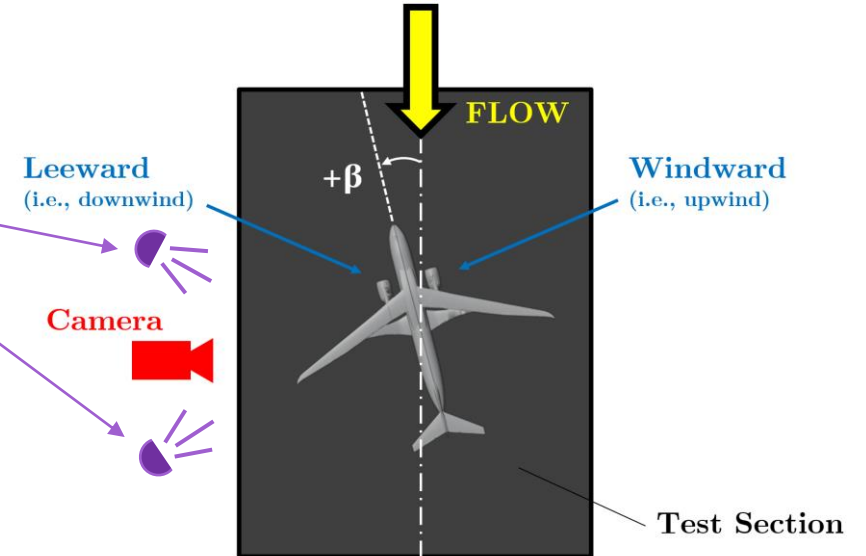
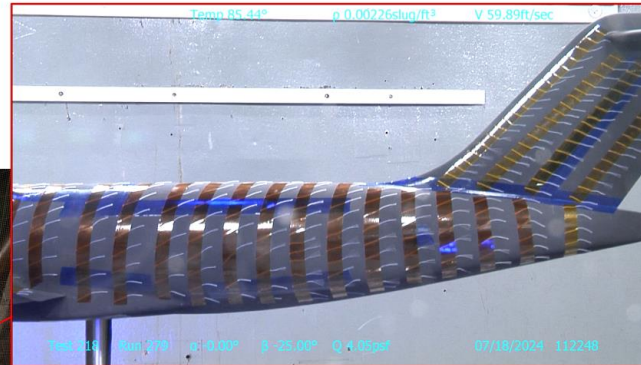
Tunnel exterior, LaRC building 644 (date unknown). [NASA]



Cutaway diagram of tunnel. [NASA]

Experimental Setup

- 4%-Scale Full Span SUGAR TTBW with $\bar{c} = 4.41"$ tested at $Re = 0.136 \times 10^6$ and $M = 0.052$.
- Aerodynamic tufts applied to the model for flow visualization made of polyester/cotton sewing thread and attached via strips of Kapton tape.
- The model painted matte black to reduce glares and **Ultra-Violet (UV) lights** were used to enhance tuft-model contrast.

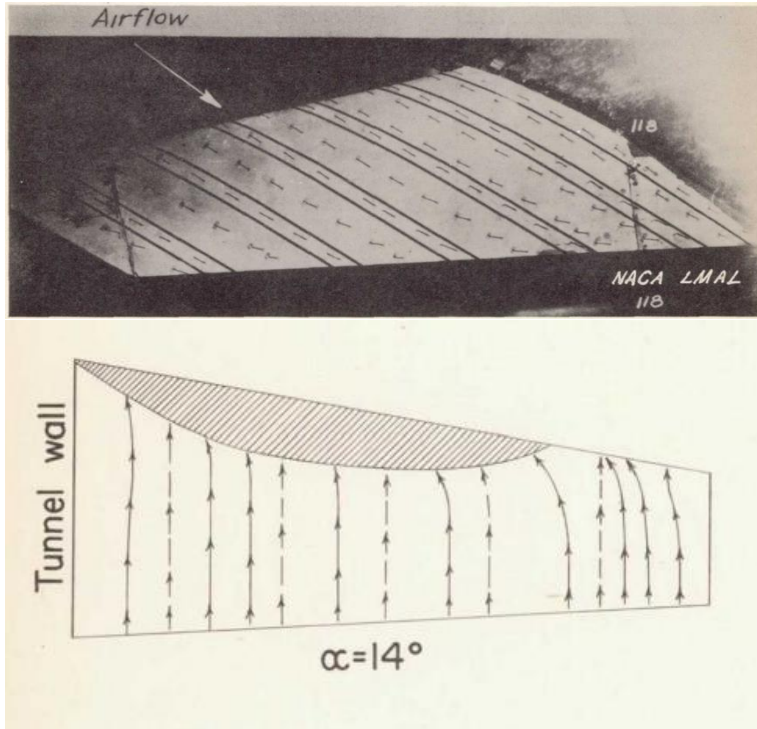


Single camera on side used to obtain videos for tuft motion analysis.

Tuft Flow Analysis – Prior Work

Traditional

- Qualitative analysis of tuft behavior in a variety of environments has been done for 80+ years.
- Lack of quantitative information.



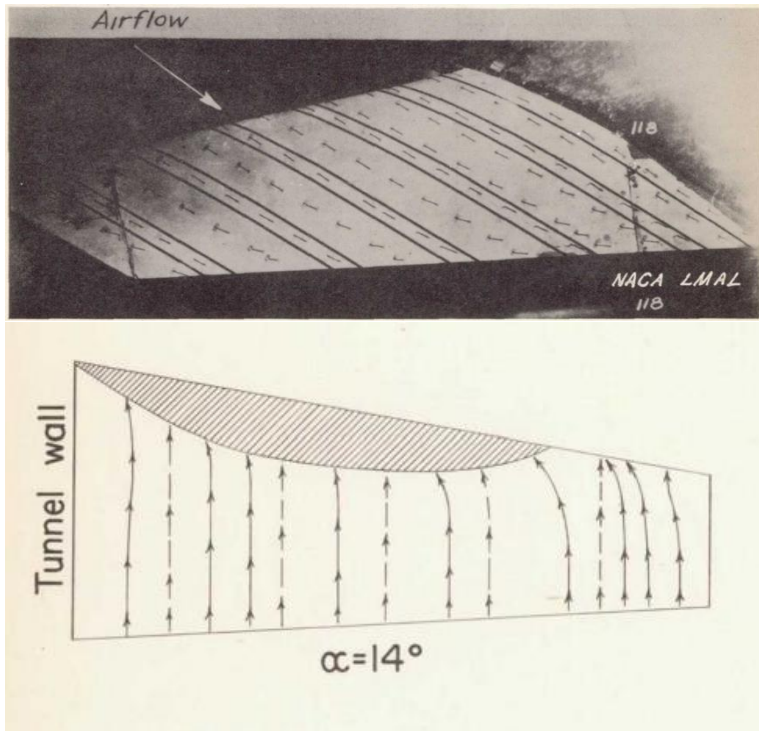
[2] Hieser, G., "Tuft Studies of the Flow Over a Wing at Four Angles of Sweep", NACA Research Memorandum No. L7C05a, 1947.

Modern

Tuft Flow Analysis – Prior Work

Traditional

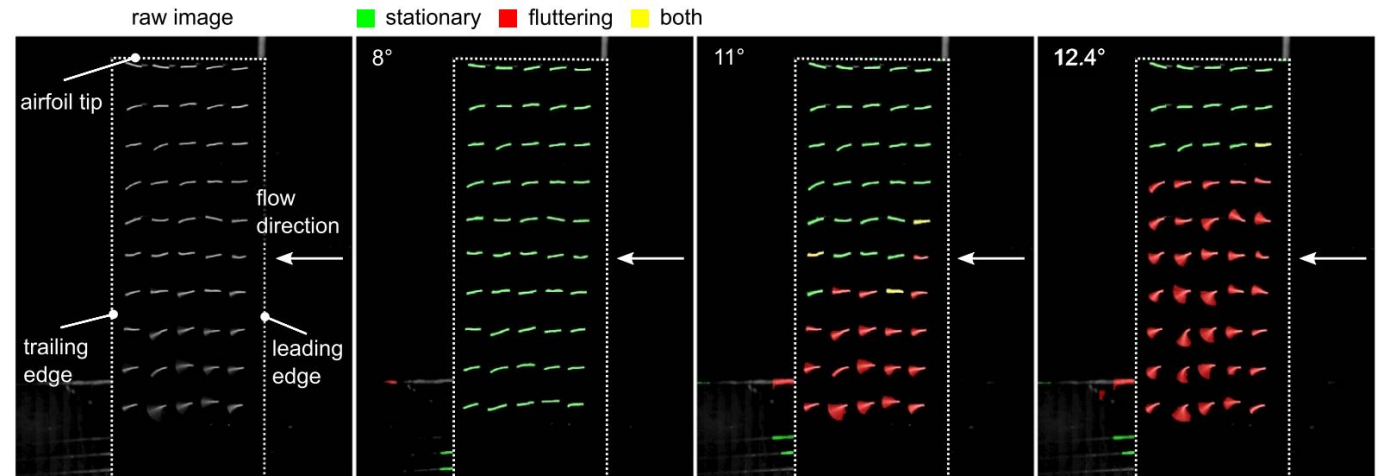
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Modern

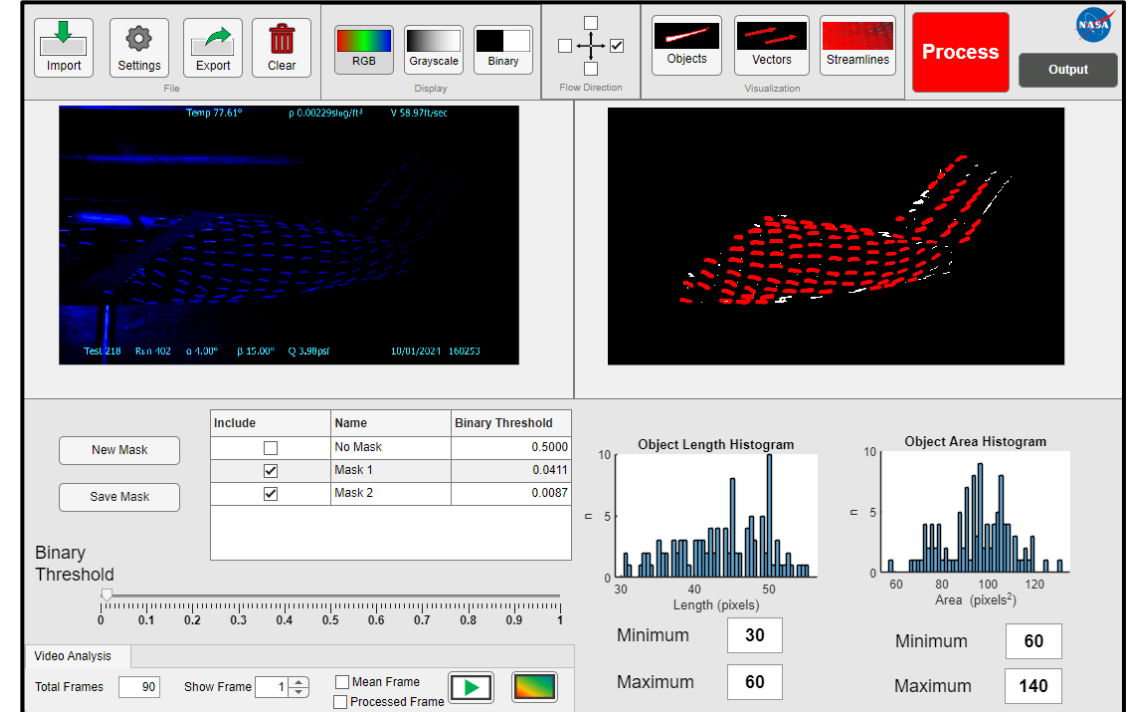
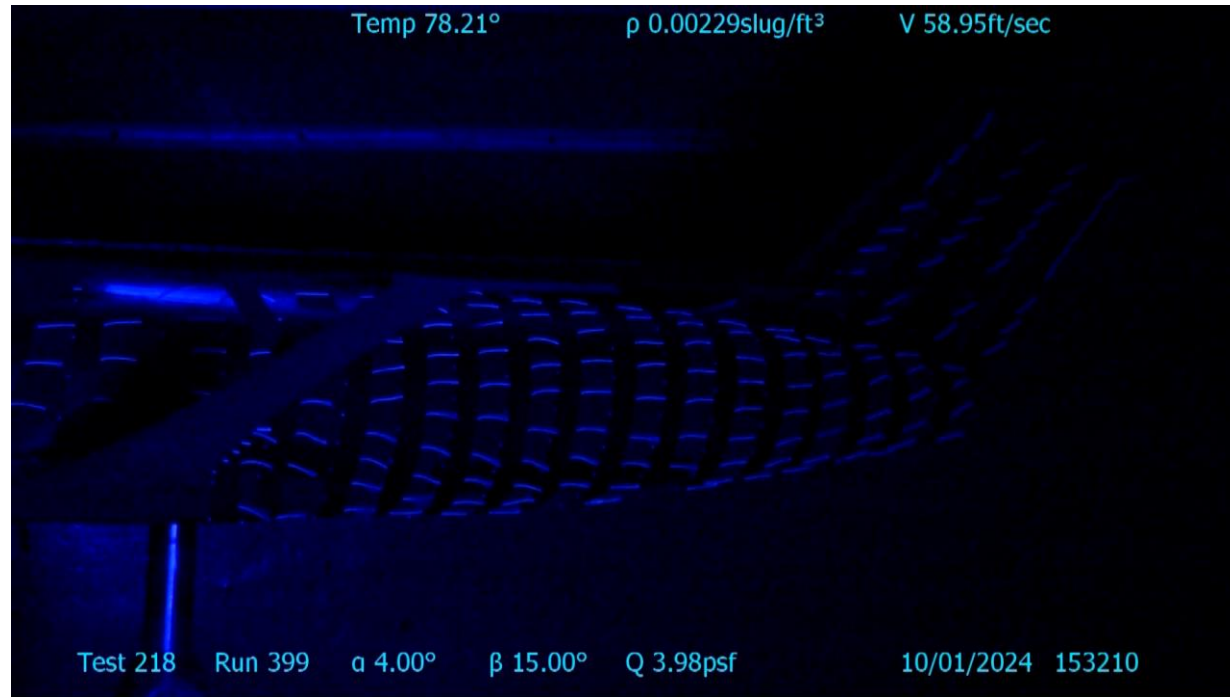
- Modern approach relies on improvements in camera quality and computing power/statistical analysis.
- Literature is full of methods to extract quantitative information from surface tufts.
- Cutting edge applications utilize machine learning to understand tuft behavior.
- Higher-end methods rely on near perfect lighting conditions to track the tufts.



[3] Tsalicoglou, C., and Rösger, T., “Deep learning-based instance segmentation of particle streaks and tufts,” Measurement Science and Technology, Vol. 33, No. 11, **2022**, p. 114005.

Frame-by-Frame Tuft Tracking Method

What makes this method unique?



1. Useful for data in wind tunnel environment with **inconsistent lighting** conditions.

2. Streamlined process for **rapid analysis** of **large amounts of experimental data**.

Frame-by-Frame Tuft Tracking Method



Aerodynamic tufts can provide information on the surface of the model in regard to: **flow-directionality** and **regions of unsteadiness**.

The proposed method of tuft analysis seeks to understand these **assuming 2-Dimensionality within the video frame**; the process can be split into a pre-processing and post-processing element.

Pre-processing

- Utilizes built-in MATLAB functions to identify tufts on the model regardless of lighting conditions.
- Saves information on masking, binarization thresholds, and object size filters.

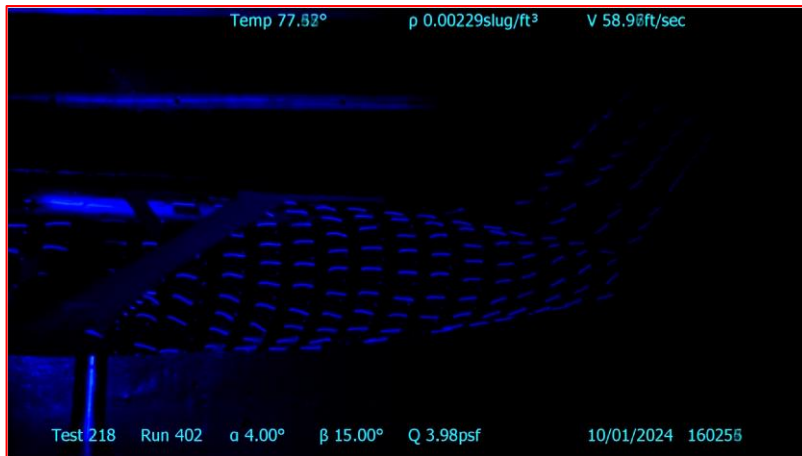
Post-processing

- Organizes tuft location information into matrices and analyzes each frame of an input video.
- Qualitative enhancement of output images showing **streamlines, vectors, and unsteady regions**.

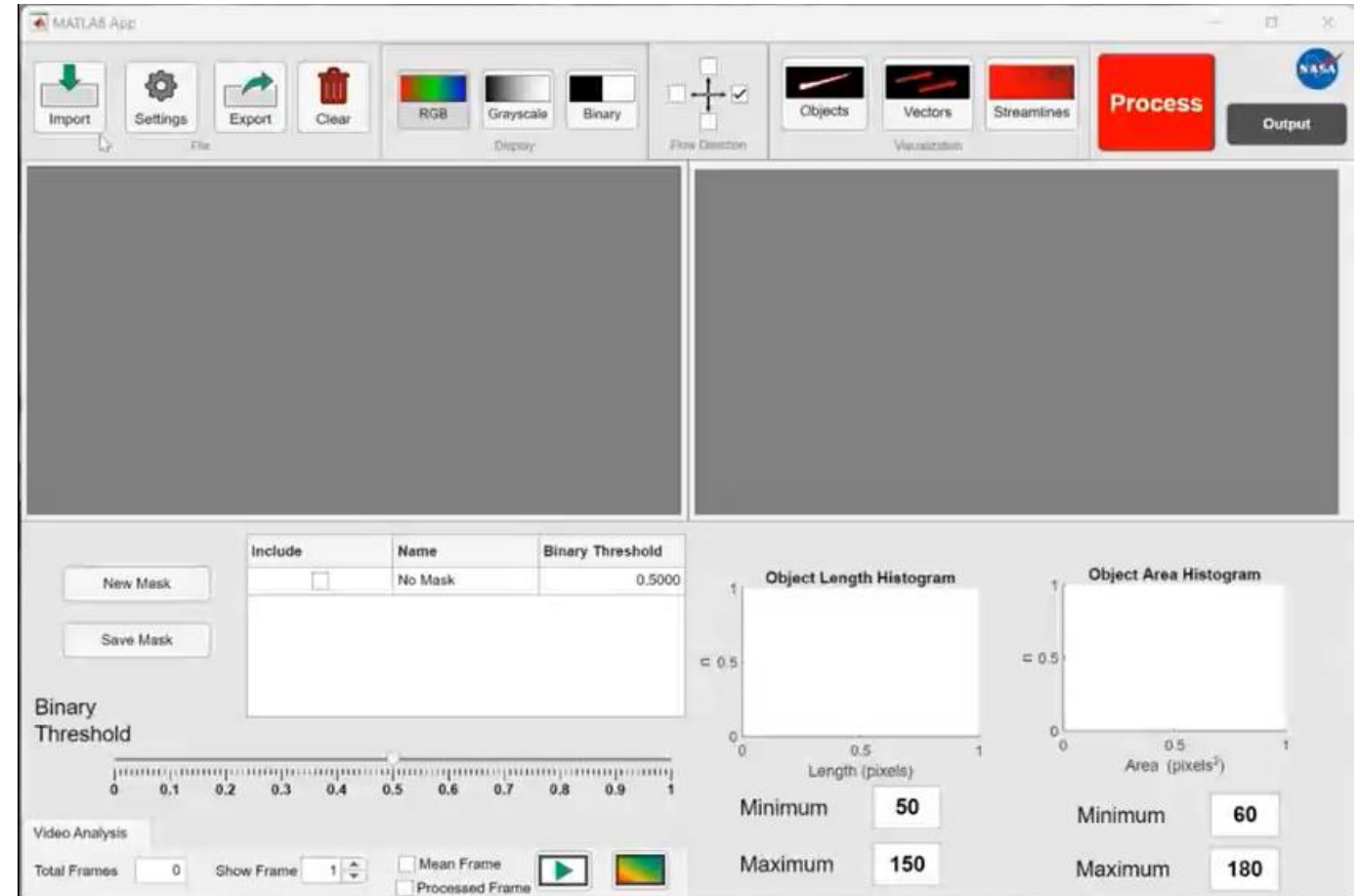
Load in Video

Step 1: Load in all frames of video.

- Display the mean frame or toggle through single frames.



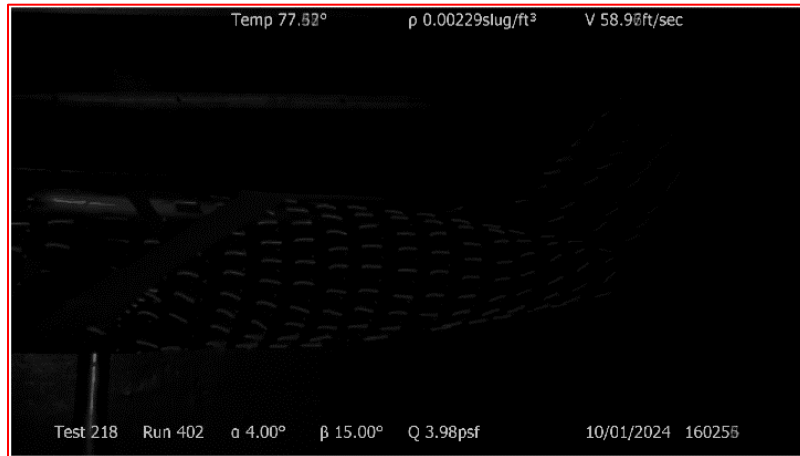
example mean frame.



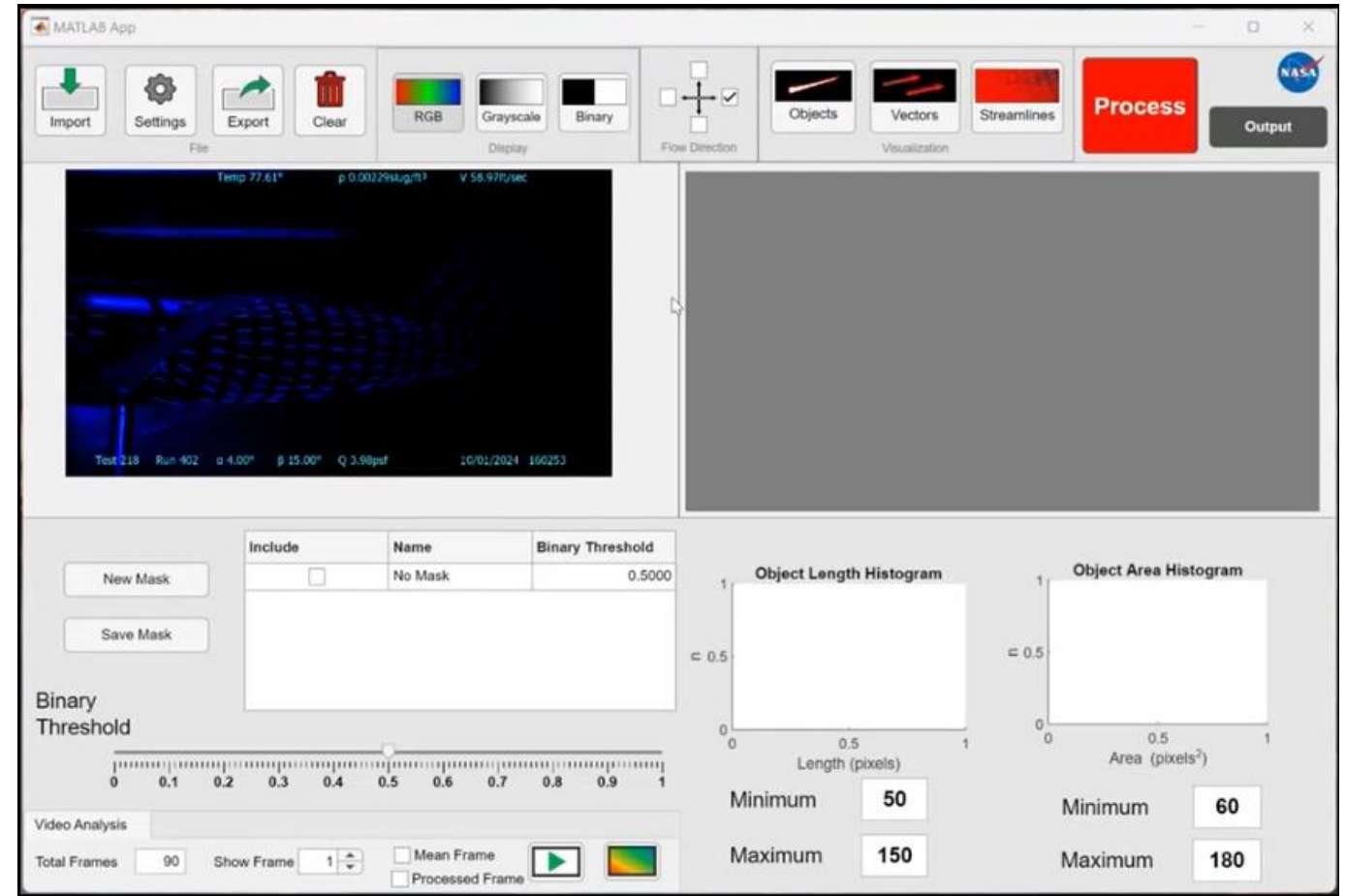
Convert to Grayscale

Step 2: Convert frame to grayscale. `[rgb2gray]`

- Notice how you can barely see anything (especially the tufts) in the frame.



Mean frame converted to grayscale.

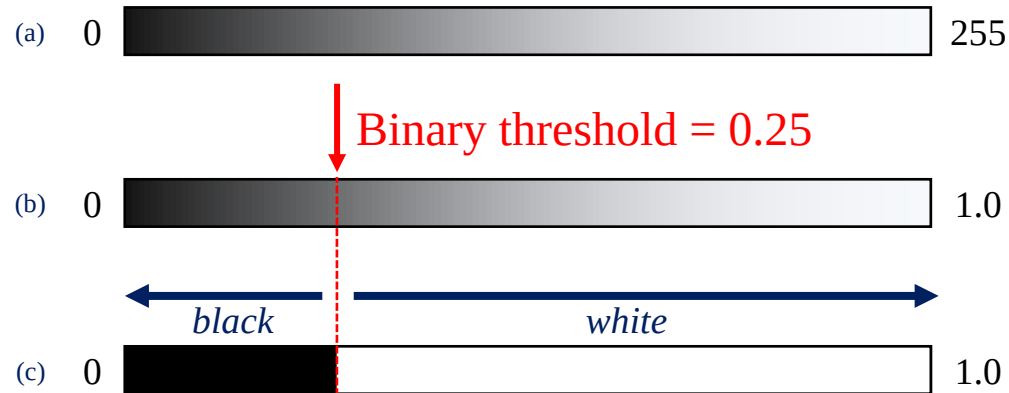


Convert to Binary

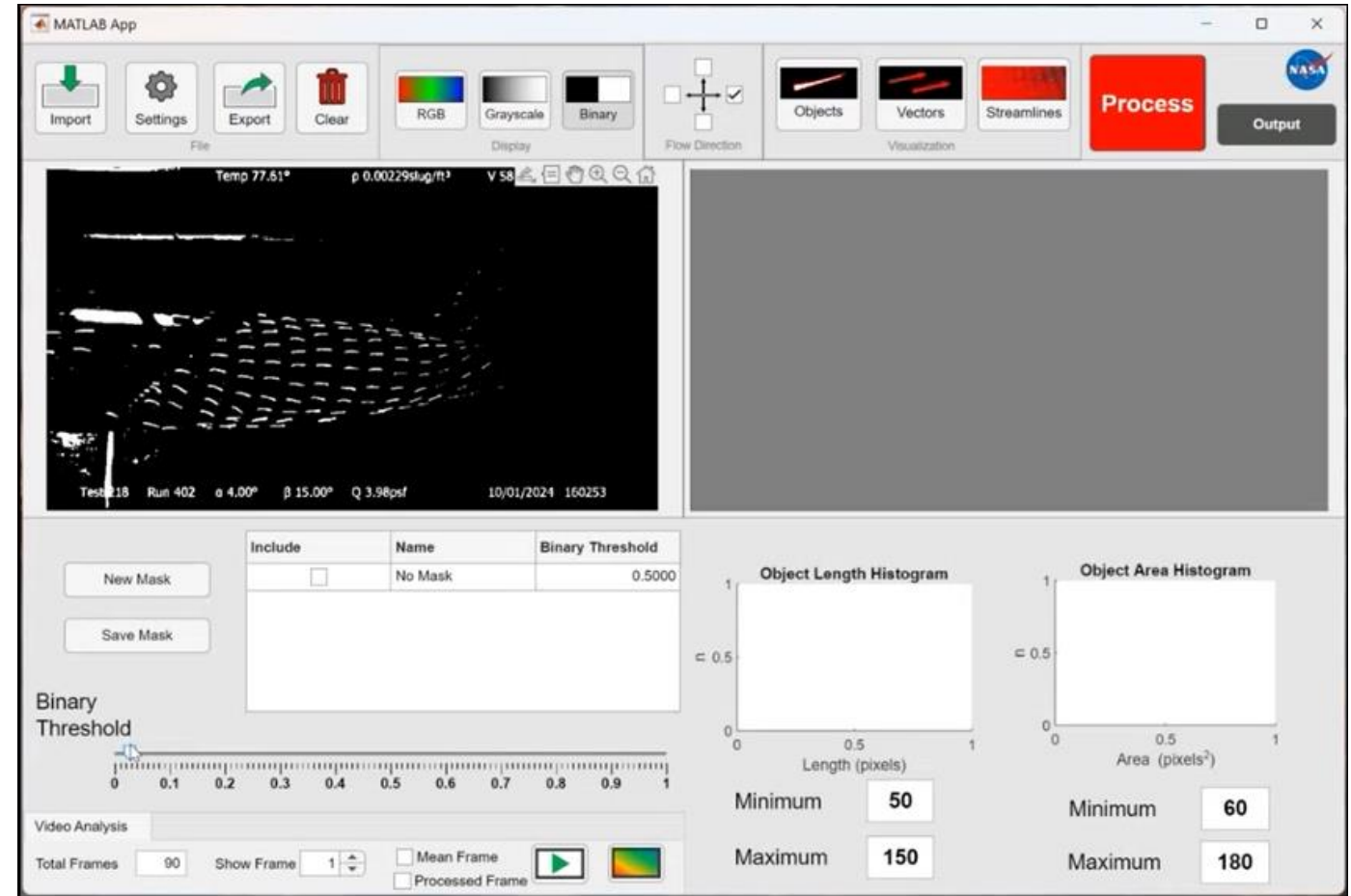
Step 3: Convert grayscale frame to binary. [**imbinarize**]

- Adjust threshold as necessary to observe tufts.

The converted grayscale image has pixels whose values are between 0 and 255 (a). The pixel values are normalized (b), and a threshold is set (c).



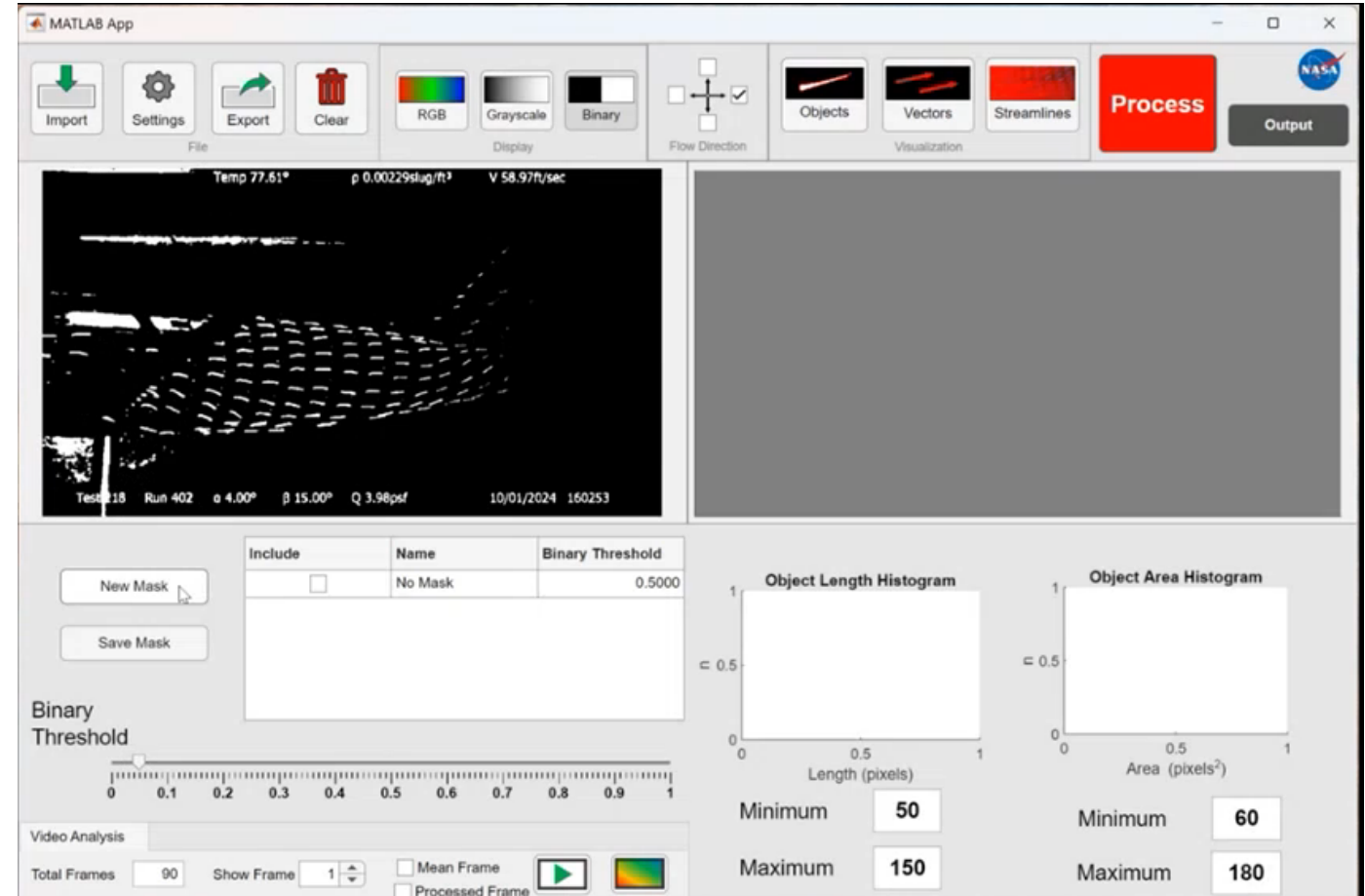
All values above threshold converted to white, all below converted to black.



Apply Masks

Step 4: Apply masks to regions of interest. [[images.roi.Polygon](#)]

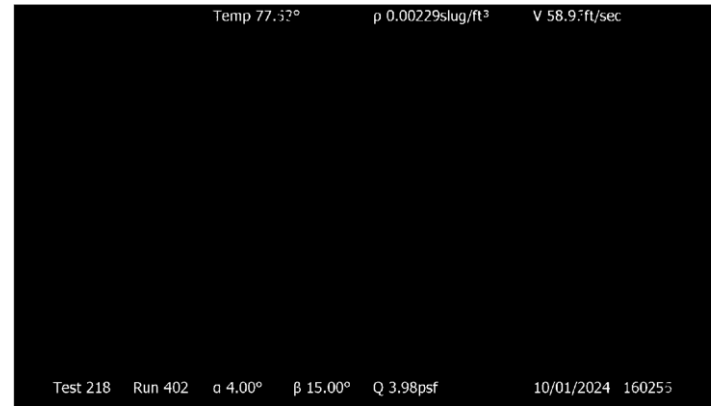
- Masks are hand drawn around regions with similar lighting, a binarization threshold is chosen to observe all the tufts within the masked region.



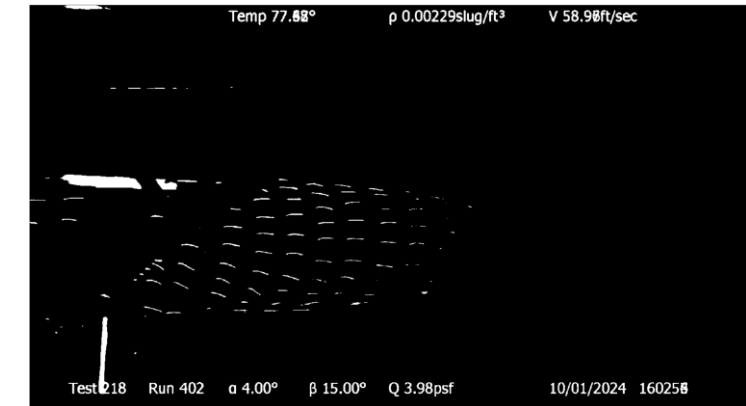
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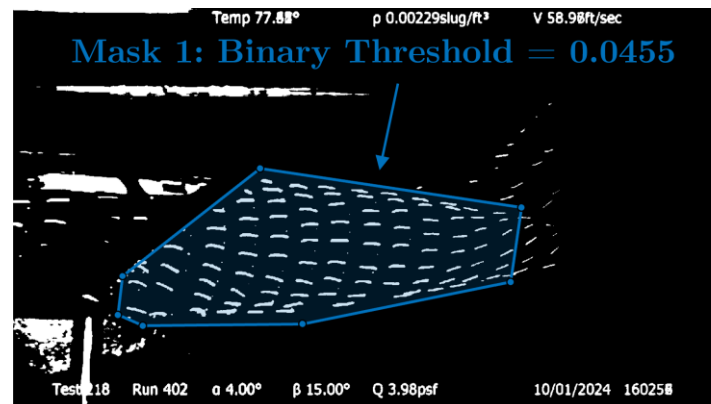
- Masks are hand drawn around regions with similar lighting, a binarization threshold is chosen to observe all the tufts within the masked region.
- Examples shown on the right for observing the fuselage tufts (c) and vertical tail tufts (d).



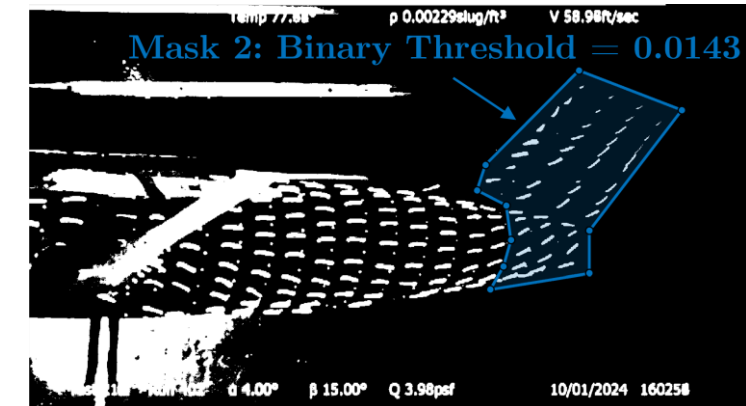
(a) Binary threshold = 0.50



(b) Binary threshold = 0.10



(c) Binary threshold = 0.0455

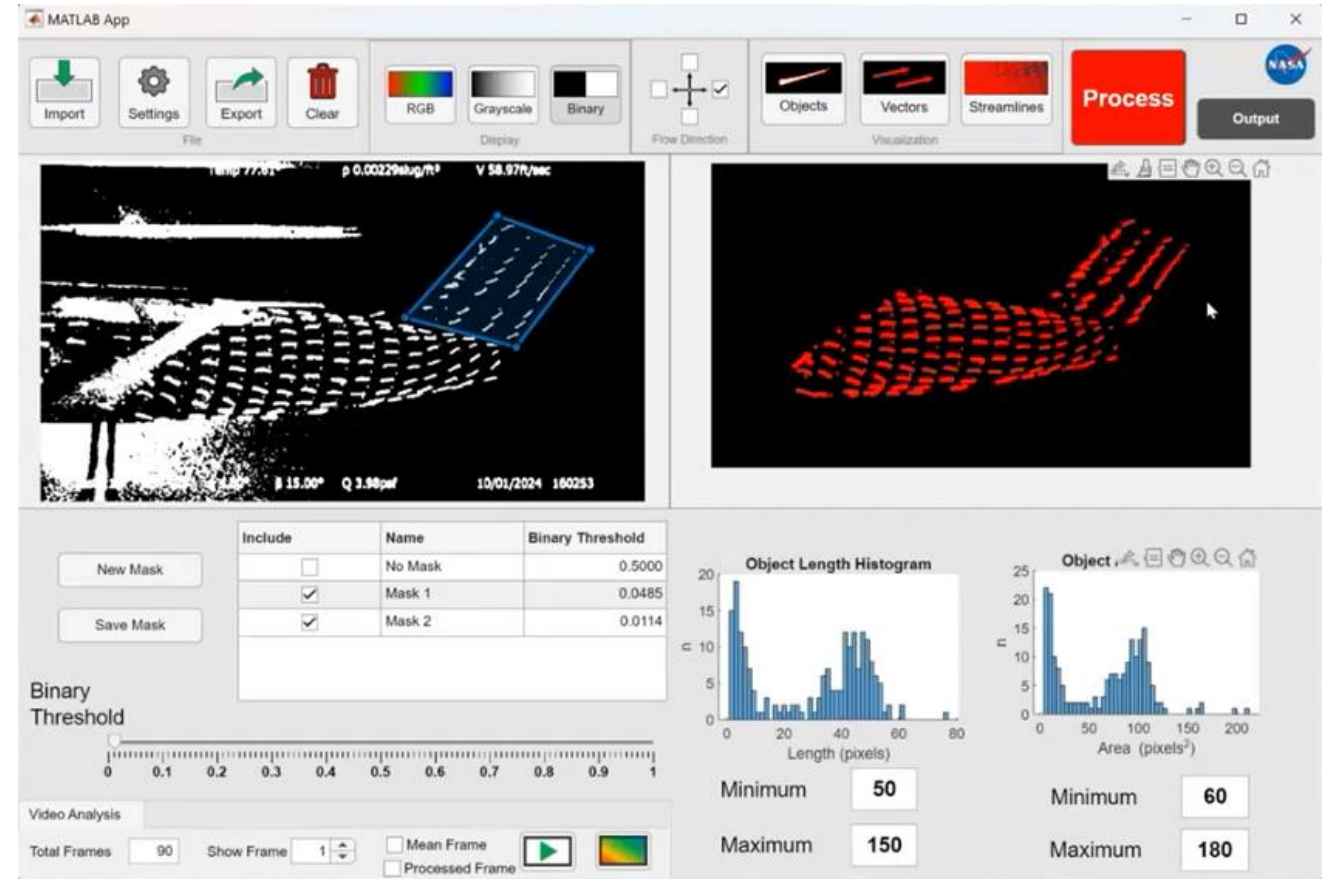
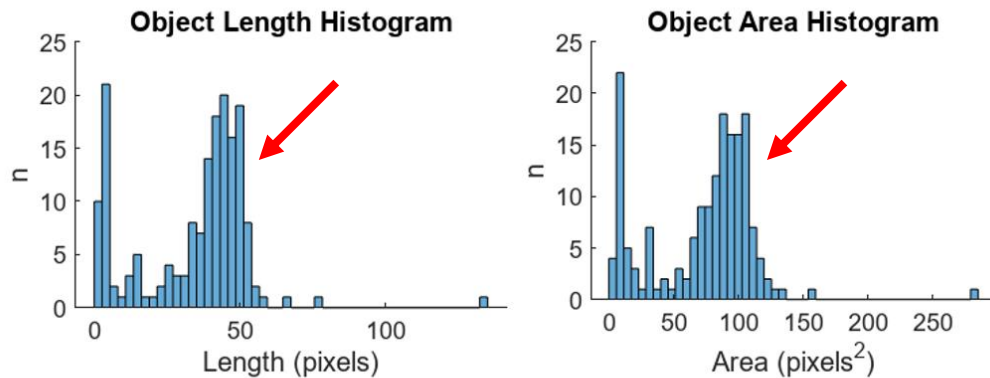


(d) Binary threshold = 0.0143

Identify Objects and Filter

Step 5: Identify objects within masked regions. [**bwboundaries**]

Step 6: Filter objects based off length and area to observe only tufts.



Tufts length and area are often a normal distribution amongst all the identified objects.

Identify Root and Tail Compute Angle

Step 7: Tuft root identified as the pixel with the minimum *x-coordinate* value.

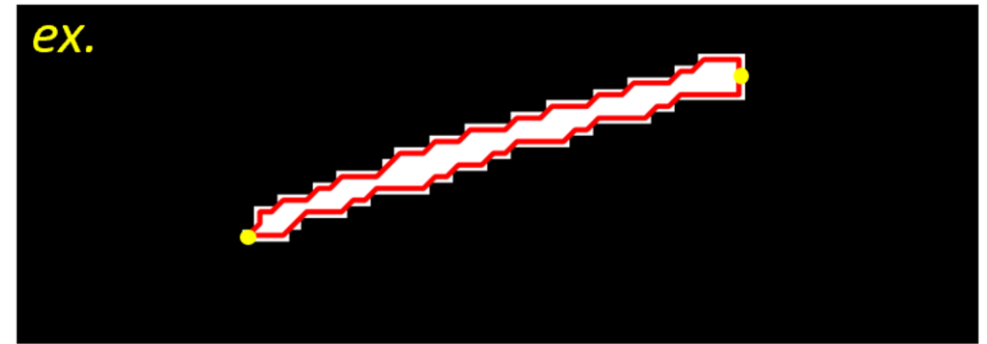
Step 8: Tail defined as the pixel with the maximum Euclidian distance away from the root within the same object (Equation 1).

$$(1) \quad (x1, y2) = MAX(\sqrt{(x_c - x1)^2 + (y_c - y1)^2})$$

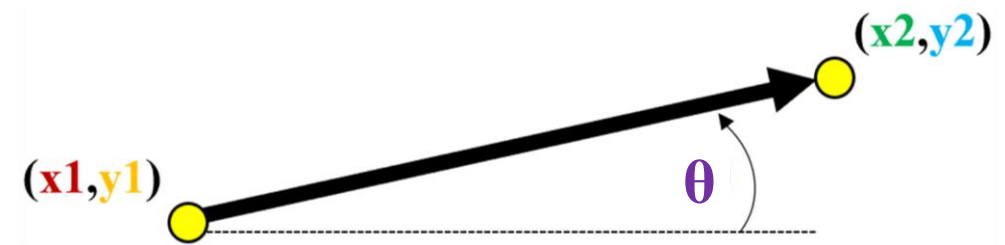
Candidate (x,y) coordinates

Step 9: Compute angle (θ) from root and tail coordinates (Equation 2).

$$(2) \quad \theta = \tan^{-1} \left(\frac{y2 - y1}{x2 - x1} \right)$$

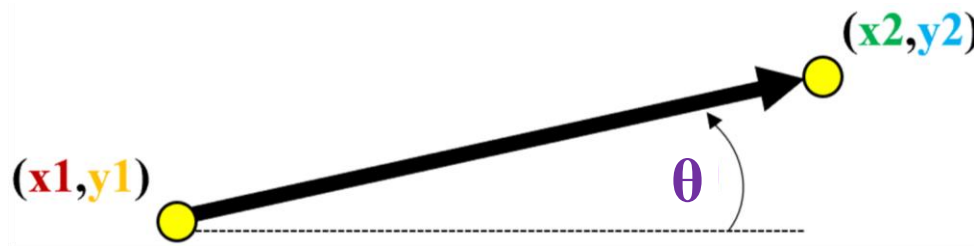


Object identified to be a tuft.

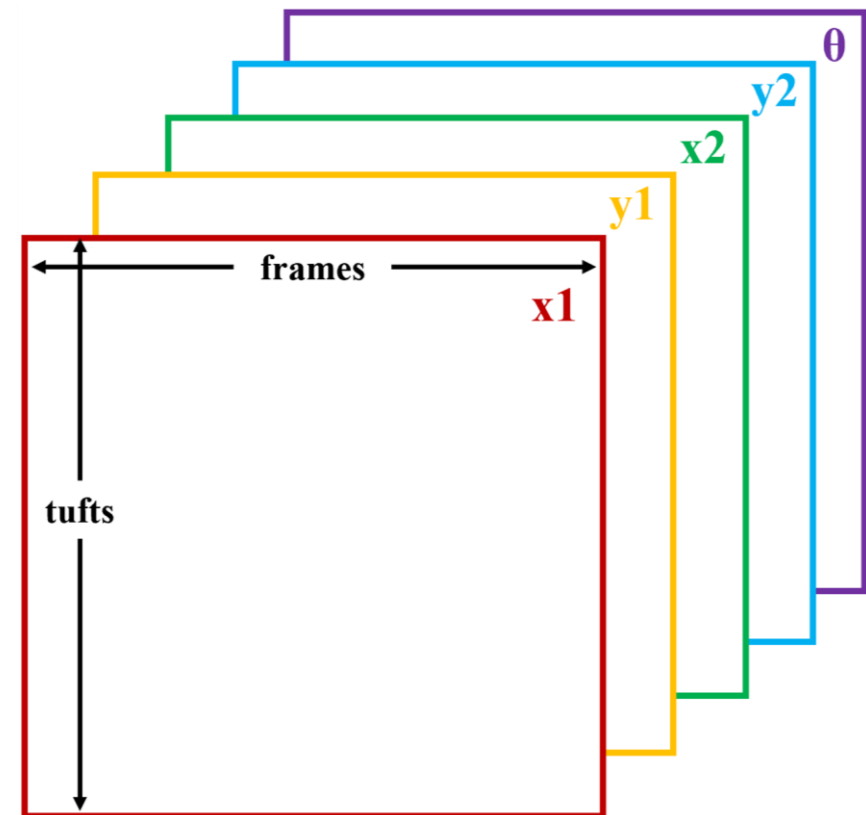


Root, tail, and angle of tuft determined.

Step 10: Organize data into matrices and apply analysis to all frames of video.



- Mean tuft tail positions across all frames informs **flow directionality**.
- Root-mean-square (rms) of tuft angle across all frames informs **regions of unsteadiness**.

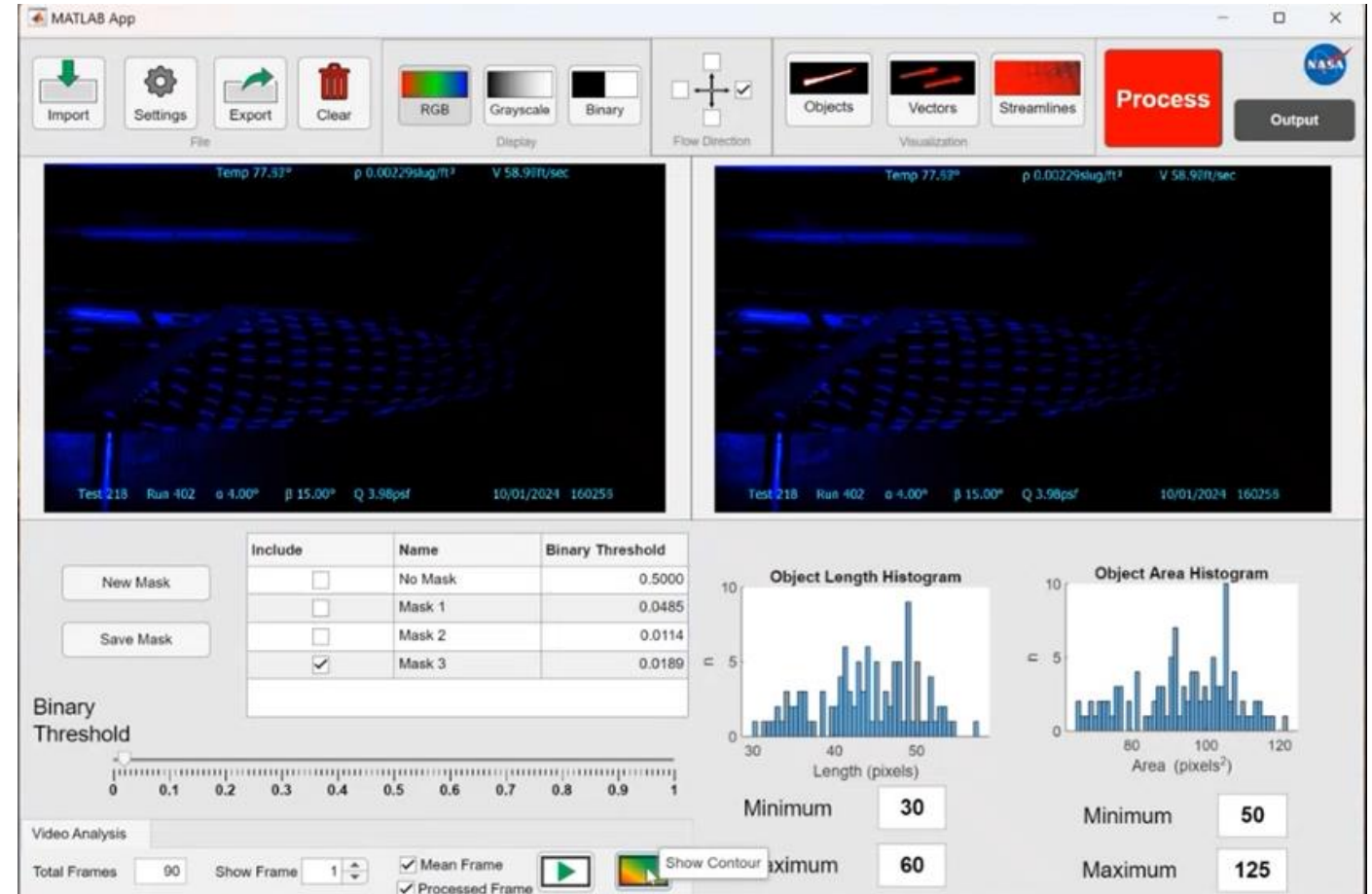
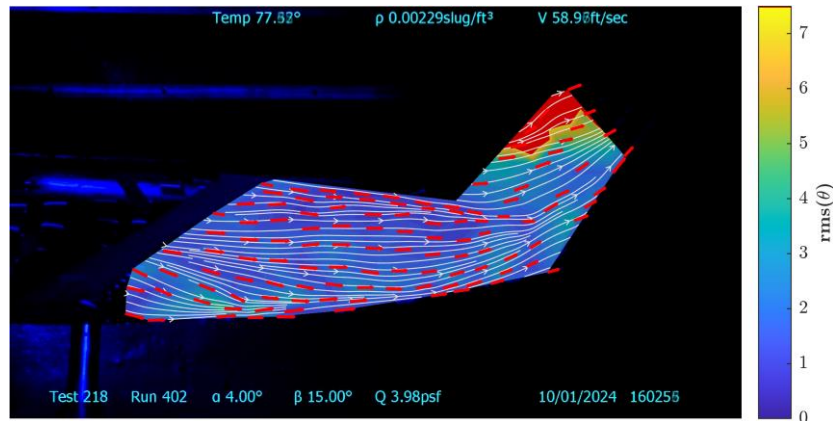


Qualitatively Enhanced Output Images



Post-processing

- Streamlines/mean vectors seek to show **flow directionality**.
- rms contours seek to show **regions of unsteadiness**.



Pre-Processing

1. Import Video.
2. Convert to grayscale.
3. Convert to binary, adjust binarization level as needed.
4. Apply masks to regions of interest.
5. Identify objects within masked regions.
6. Filter out non-tuft objects.
7. Identify tuft root.
8. Determine instantaneous tuft tail.
9. Compute instantaneous tuft angle.
10. Organize data and apply analysis to all frames.

Post-processing

Qualitatively enhance images with:

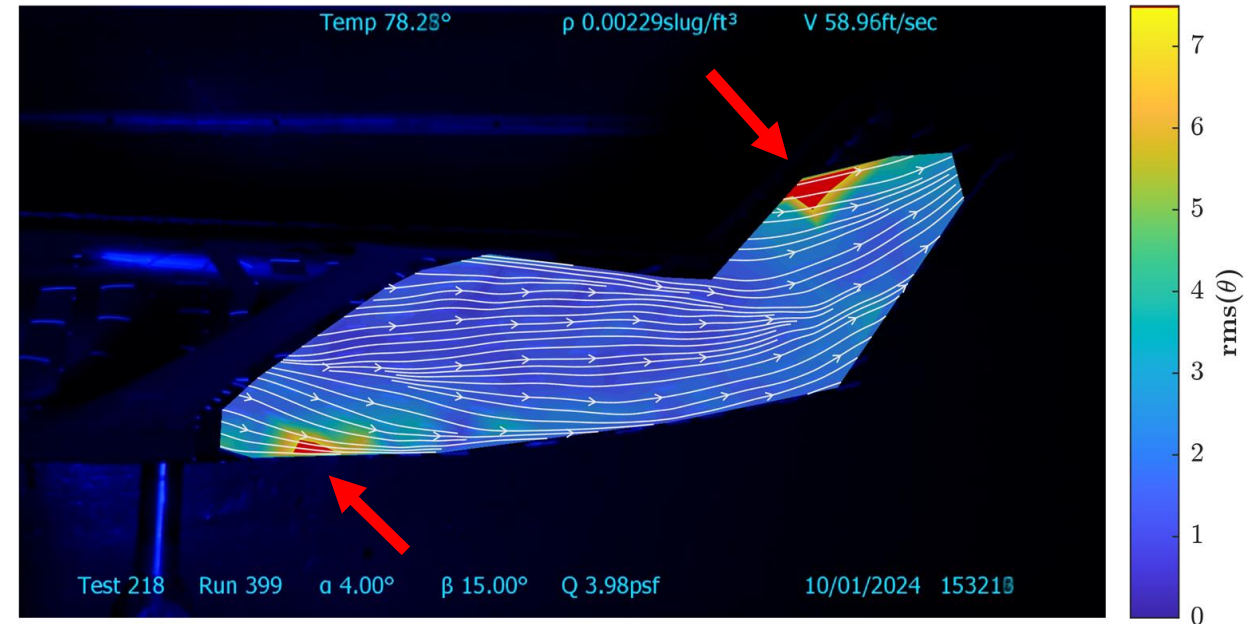
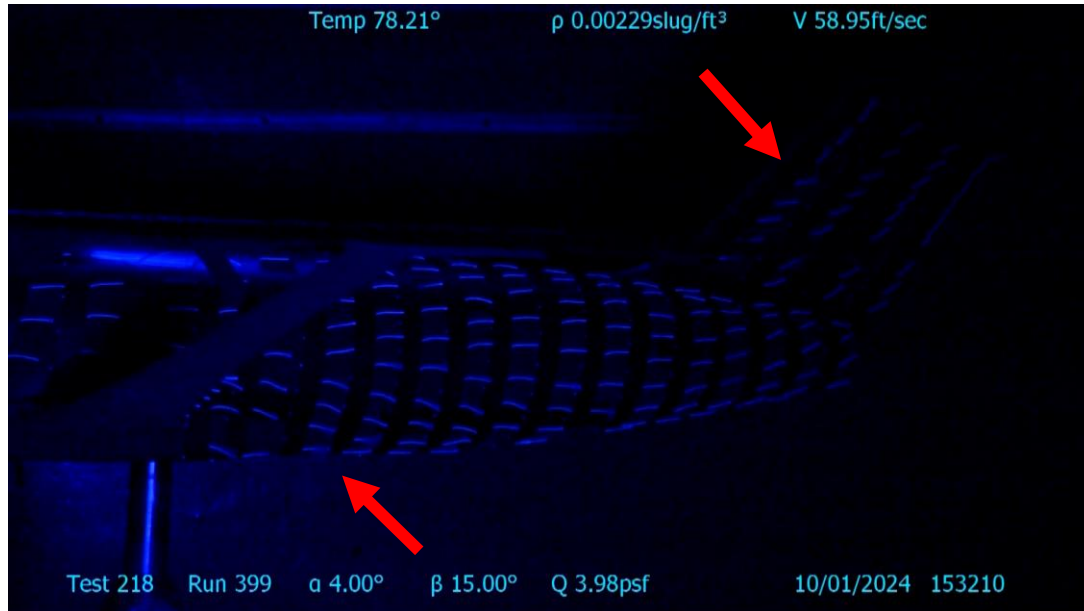
1. Streamlines.
2. Contours of rms.
3. Tuft vectors.

This process assumes 2-D tuft behavior in the image plane.

Streamlines and Contours



$$\alpha = 4^\circ, \beta = 15^\circ$$



- FFTT method accurately captures the **regions of unsteadiness** with rms contours. 
- Streamlines from mean tuft positions capture the **flow directionality**. 

FFTT results are compared with relevant CFD runs on the TTBW geometry.

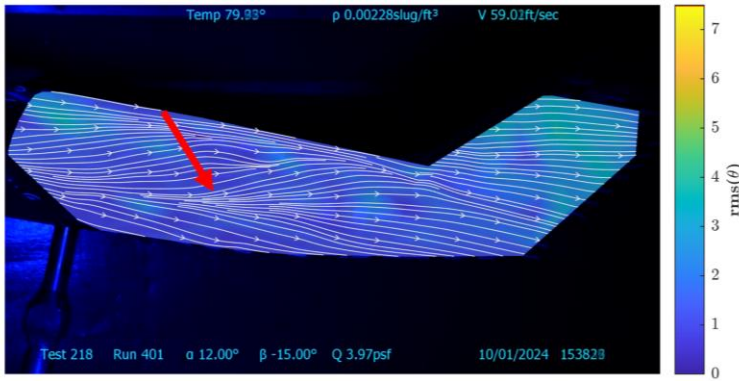
- RANS simulations carried out using USM3D-ME.
- 50.28 million cell unstructured grid generated using HeldenMesh.
- Steady-state TTBW configurations simulated using the SA-Neg-QCR-2000 turbulence model with rotation and curvature corrections.
- All test cases performed at $Re = 0.136 \times 10^6$ and $M = 0.052$ (matching experimental conditions).

CFD Flow Conditions		
Angle of Attack (α)	4°	12°
Angle of Sideslip (β)	0°, 15°	0°, 15°

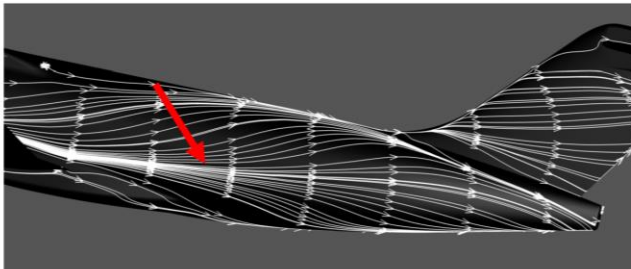
FFTT-CFD Comparisons

$$\alpha = 12^\circ$$

$$\beta = -15^\circ$$

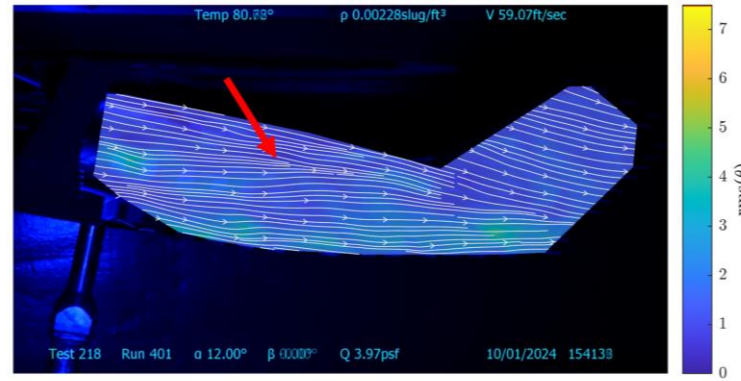


(a) Experimental streamline and rms of $\theta(t)$ contour from experimental FFTT methods.

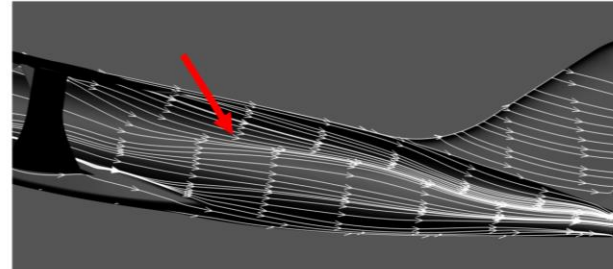


(b) CFD streamlines.

$$\beta = 0^\circ$$

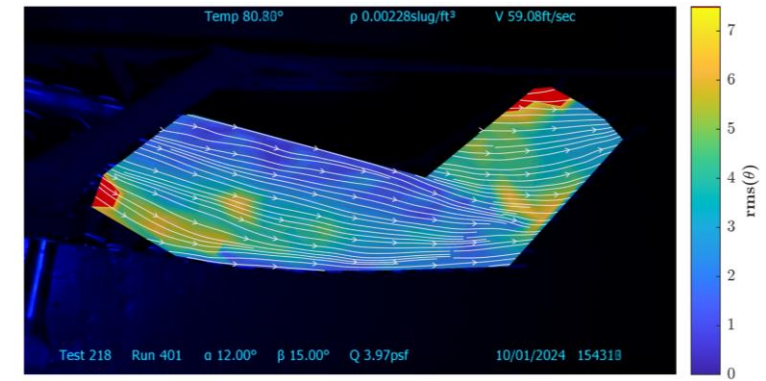


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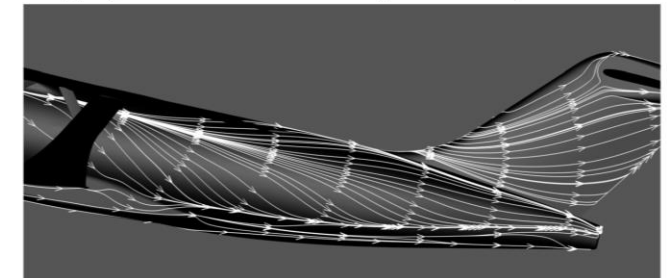


(b) CFD streamlines.

$$\beta = 15^\circ$$



(a) Experimental streamline and rms of $\theta(t)$ contour from experimental FFTT methods.

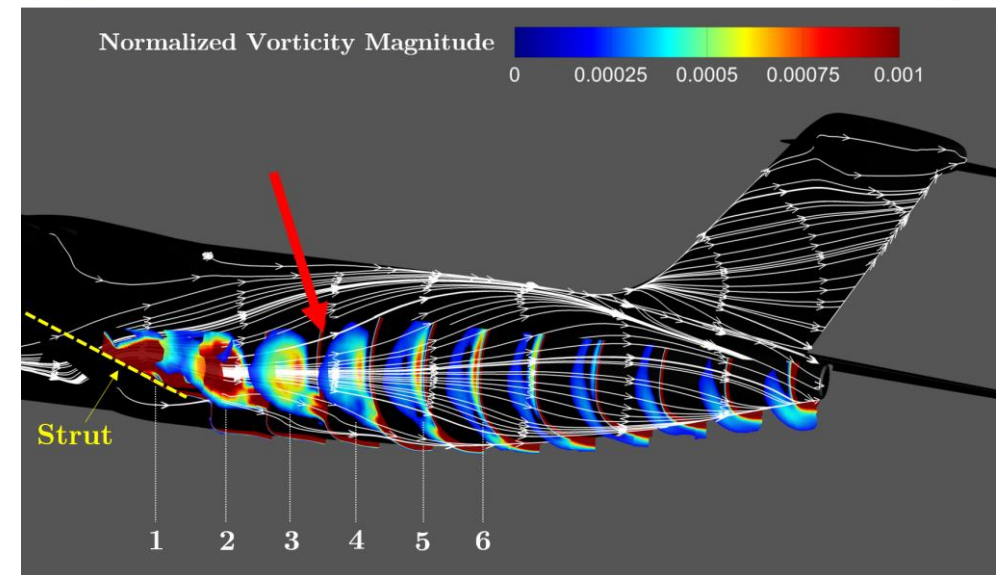
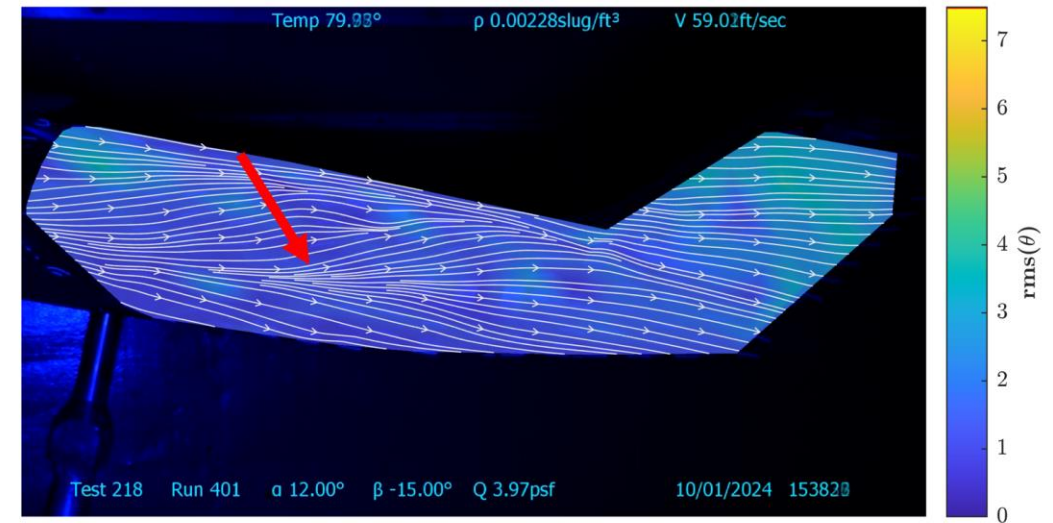
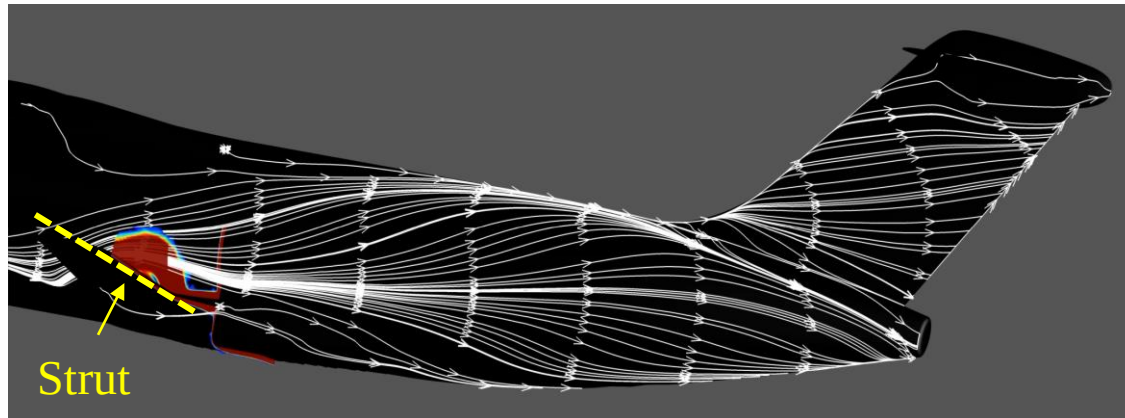


(b) CFD streamlines.

- Similar flow features observed between experimental FFTT method and CFD.

Unique TTBW Flow Feature

- Diverging streamline pattern observed both experimentally and via simulation at high (15°) negative sideslip (windward side).
- RANS simulations do not provide time-accurate information but do allow us to observe off body phenomena.
- Vortical structures that form on the TTBW strut impinge on the fuselage and cause this divergent streamline pattern.
- **The experimental FFTT methods were able to accurately capture this unique TTBW flow feature.**



Conclusions

- New **method for analyzing the motion of aerodynamic tufts** is presented.
- The method, Frame-by-Frame Tuft Tracking (FFTT) utilizes **multiple masks with varying binarization levels** to account for imperfect lighting in a wind tunnel environment.
- Simple mathematical framework relies on built-in MATLAB functions; GUI allows for **rapid processing of large datasets with varying light conditions**.
- FFTT method was applied to the TTBW geometry and was able to **capture flow directionality and regions of unsteadiness**. Comparisons were made with relevant CFD test runs that further validated the accuracy of the method.

Future Work

- Refinement of MATLAB interface for release to public as a low-cost flow visualization tool.
- Improvements to tuft-tracking process to account for 3-Dimensionality of model/flow-field.