ReadMe
HVAB Shadowgraphy Data

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September 2023

The following text is largely extracted from Norman et al., "Fundamental Test of a Hovering Rotor: Comprehensive Measurements for CFD Validation," Vertical Flight Society's 79th Annual Forum & Technology Display, West Palm Beach, FL, USA, May 16-18, 2023.

This document summarizes the test conditions during which shadowgraphy images were acquired, a description of the image processing, a description of the spreadsheets containing the coordinates of the tip vortices for each of the test conditions, and plots of the vortex positions.

<u>Shadowgraphy Test Conditions</u>
Table 1 provides a summary of shadowgraphy test conditions. The table includes cross-references to the Run and Point numbers.

Table 1. Shadowgraphy test contions.

Run	Pt	Mtip	COLL (Nom)	CT_B2_AVG	Avg Lag (deg)
50	13-39	0.650	8	0.00580	-1.55
50	40-53	0.650	10	0.00784	-2.18
50	54-67	0.650	12	0.00993	-3.20
50	68-80	0.650	14	0.01200	-4.51
52	8-20	0.675	8	0.00579	-1.54
52	21-33	0.675	10	0.00780	-2.25
52	34-47	0.675	12	0.00991	-3.27
52	48-60	0.675	14	0.01196	-4.54
54	8-22	0.600	8	0.00598	-1.61
54	23-36	0.600	10	0.00799	-2.24
54	37-50	0.600	12	0.01008	-3.27
54	51-64	0.600	14	0.01218	-4.50

Shadowgraphy images were acquired from 0-3360 deg azimuth at intervals of 15 deg at an image acquisition rate of one image every 12 revolutions. The resultant rate of 1.74 Hz (rotor speed of 1250 rpm (20.83 Hz) divided by 12) was a trade-off between the time needed to acquire 100 images at 25 (0-360 deg, 15 deg increments) azimuth positions and the desire to keep the test run to a reasonable duration.

<u>Image Processing</u>
The goal of the image processing was to characterize the radial contraction and axial positions of the vortices - with respect to the blade tips - as a function of wake azimuth angle (or wake age). The challenge was to extract only the outermost extent of the wake trajectory; for example, in Fig.1, four tip vortices are visible on each side of the wake.

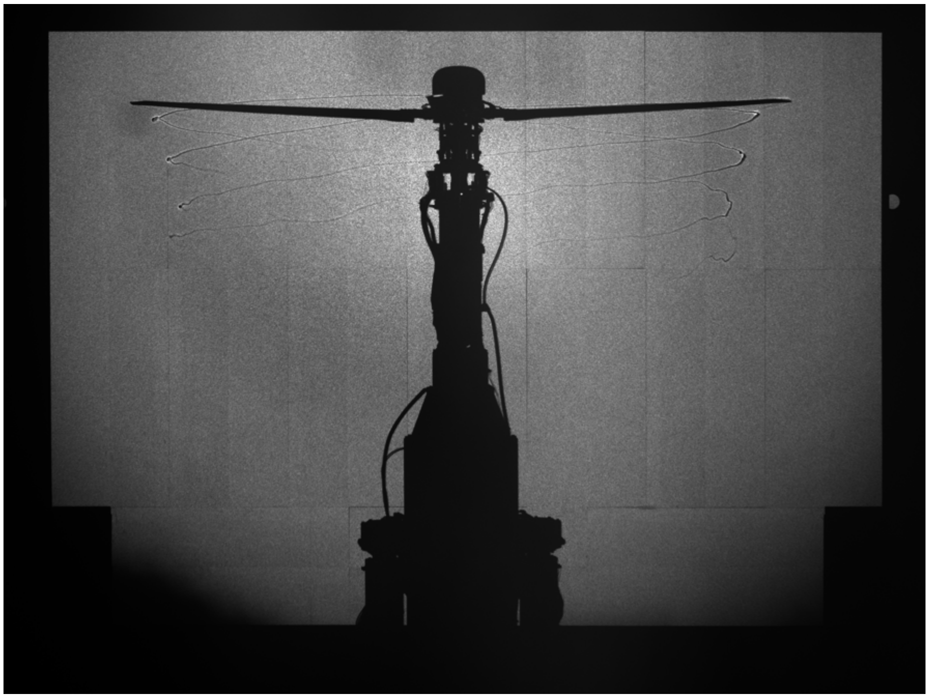

Figure 1. Typical shadowgraphy image, M_{tip}=0.65 and θ_0=12°.

The vortices move– due to flow environment and blade motion – from one image to the next image. Manual extraction of the tip vortex location using a point-and-click digitizer is always an option, but not practical for processing thousands of images. Instead, a technique was developed using a grayscale gradient (GSG) approach.

Figure 2 represents a section of a typical shadowgraphy image. The image is in grayscale, meaning that each pixel has a value between 0 (black) and 255 (white).

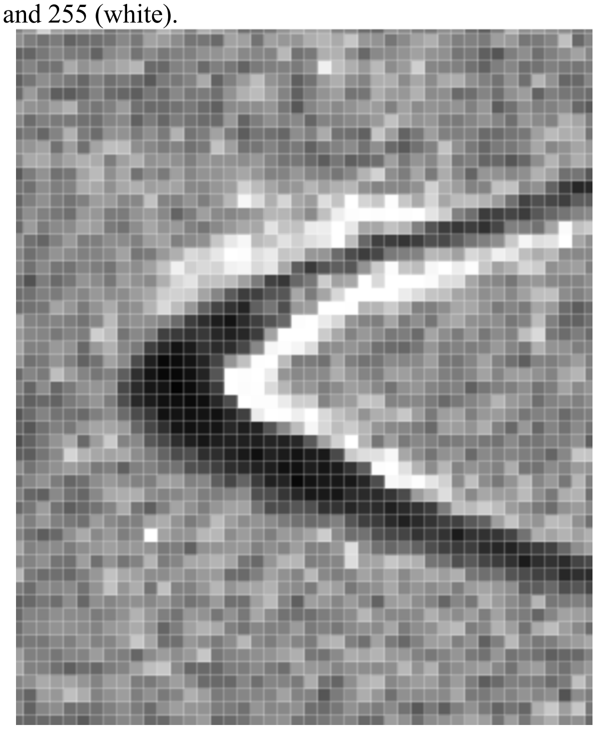

Figure 2. Enlarged view of small region of a sample 2x2 binned shadowgraphy image showing a blade tip and a 90° wake age vortex. Note the cross-section of the vortex is 12-15 pixels.

The GSG method interrogates the image by marching along each row of the image search area and for each pixel location, computes a grayscale gradient value G(i,j) defined in the Equation 1 below:

$$G(i,j) = abs(g(i,j) - g(i-1,j)) + abs(g(i+1,j)-g(i,j)) \qquad \text{Eqn. (1)}$$

where g is the pixel grayscale value and (i,j) represent the (column,row) coordinate of the image. G(i,j) will be largest near the location of the outermost extent of the tip vortex trajectory.

Figure 3 shows a sample result of implementing the GSG method for the left side of a shadowgraphy image, such as Fig. 1.

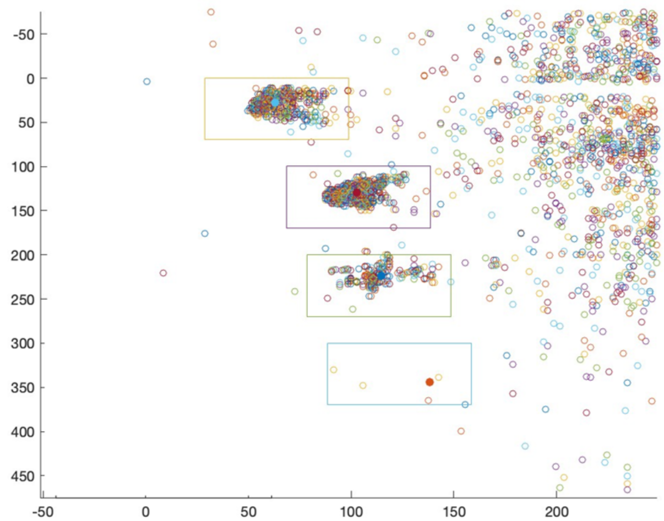

Figure 3. Pixel locations with high grayscale gradient (G(i,j)) values are plotted. The three clusters of symbols represent tip vortex locations. The solid symbol is the centroid computed from the G(i,j) values within the rectangles.

The symbols shown in the plot identify pixel locations that meet a user-specified threshold for the value of G(i,j). The threshold value was determined iteratively to eliminate outliers and low values of GSG. Since the general locations of the tip vortices were known, a rectangular region large enough to capture the clusters shown in Fig. 3 was defined for each of the eight vortices – four on each side of the wake. No more than four blade passages of the wake were observed and sometimes, as in Fig. 3, the fourth vortex was not identified by the GSG method. Within each of the eight rectangular regions, centroids (x- or i-direction and y- or j-direction) based on the value of G(i,j) and the pixel location (i,j) were computed. In Fig. 3, the centroid is identified as a solid symbol within the cluster of open symbols. Further data processing is required to convert the vortex positions to blade coordinates (z/R and r/R) and to determine the wake ages of each vortex.

Conversion to blade coordinates requires knowledge of the center of rotation as well as the relative location of the blade tips in pixel space. The center of rotor rotation was determined by manually identifying the center of the rotor shaft. The blade tip locations for the left and right side of the image were manually identified using the imageJ application (Version 1.53, https://imagej.nih.gov/ij/). For each Mtip and collective pitch combination, the blade tip pixel coordinates were selected using point-cand-click for the blade azimuth settings of 0 and 15 degrees (100 images per azimuth setting). From these tip locations, the minimum and maximum pixel locations in the radial direction were determined and a tip-to-tip pixel value was defined as the rotor diameter. The radial locations of the blade tip for the left and right side of the image were then determined from the rotor diameter and the center of rotation. The rotor diameter was determined to be 1587.89 pixels.

The determination of wake age starts with the rotor azimuth at which the shadowgraphy laser is triggered and then adjusted to account for the blade lag and the assumption that the tip vortex is formed at the blade trailing edge. The average blade lag of all four blades is determined from the measured root lag data acquired at each condition. The angle between the quarter-chord line and the blade trailing edge, referenced from the lag hinge, is 3.72 deg in the lag direction. The largest adjustment is due to the camera seeing a foreshortened view of the rotor disk edge because the camera is not infinitely far from the rotor – see Fig. 4. This view results in corrections of -5.38 deg and 5.38 deg that are applied to the azimuth location of vortices on the left and right sides, respectively, of the image.

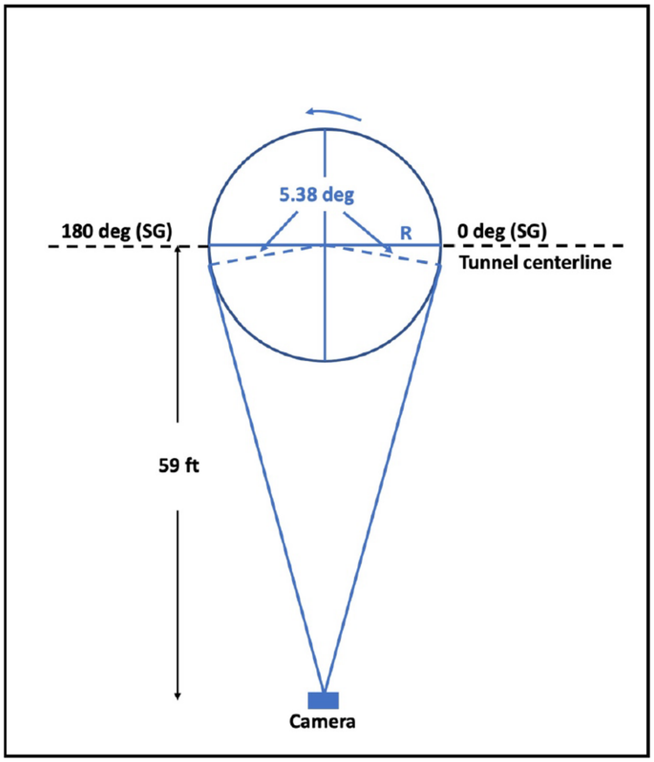

Figure 4. Planview of shadowgraphy camera view of rotor disk and resulting correction (5.38°) to wake age.

To summarize, the corrections to the wake ages of the vortices on the left and right sides of each shadowgraphy image are:

Correction to wake age (left side of image) = camera offset + average lag angle + chord offset   Eqn. (2)

Correction to wake age (right side of image) = -camera offset + average lag angle + chord offset   Eqn. (3)

<u>Description of Spreadsheet Data: R50-52-54-SG-Data_24Sep2023.xlsx</u>

The spreadsheet - contains 4 sheets. The first three sheets – R50M650, R52M675, R54M600 – each have four tables and each table has the following format:

R50M650TH08				
Wake age (deg)	**r/R**	**r/R STDEV**	**z/R**	**z/R STDEV**

The **Wake age** is the corrected wake age, **r/R** is the non-dimensional radial coordinate of the tip vortex, referenced to the rotor radius R (R =1587.89 /2 = 793.95 pixels), the **standard deviation of r/R**, the vertical coordinate **z/R** is the non-dimensional vertical coordinate of the tip vortex, referenced to the rotor radius R, and the **standard deviation of z/R**. Only centroids that were computed using at least 50 samples were included in the tables. For example, in Fig. 3, the 4th vortex location is computed from a few samples so would not be included in the tables.

The 4th sheet of this spreadsheet contains predicted r/R and z/R coordinates using the Landgrebe model (Landgrebe, A. J., "The Wake Geometry of a Hovering Helicopter Rotor and Its Influence on Rotor Performance," Journal of the American Helicopter Society, Volume 17, Number 4, October 1972, pp. 3-15(12). DOI: 10.4050/JAHS.17.4.3). The parameters used to compute the coordinates are also provided in the 4th sheet.

Plots of Vortex Positions

As shown in Fig. 1, tip vortices are visible on the left and right sides of the rotor. Ideally, the wake would be axisymmetric that is, the rate of wake contraction and vertical descent of the tip vortices would be the same at every azimuth plane. The data provided in the spreadsheet (R50-52-54-SG-Data_24Sep2023.xlsx) does not identify whether the vortex location was extracted from the left (180 deg azimuth) or the right side (0 deg azimuth) of the image. Norman et. al (2023) shows the tip vortex locations for R50M650TH12 and discusses possible sources of the wake asymmetry revealed for this condition.

The tip vortex locations of the 12 conditions provided in the spreadsheet are plotted in Figs. 5-10. The Landgrebe model is included in each plot. All 12 conditions show that for similar wake ages, the tip vortices extracted from the left (180 deg azimuth) side of the images are offset from tip vortices extracted from the right side (0 deg azimuth) of the images.

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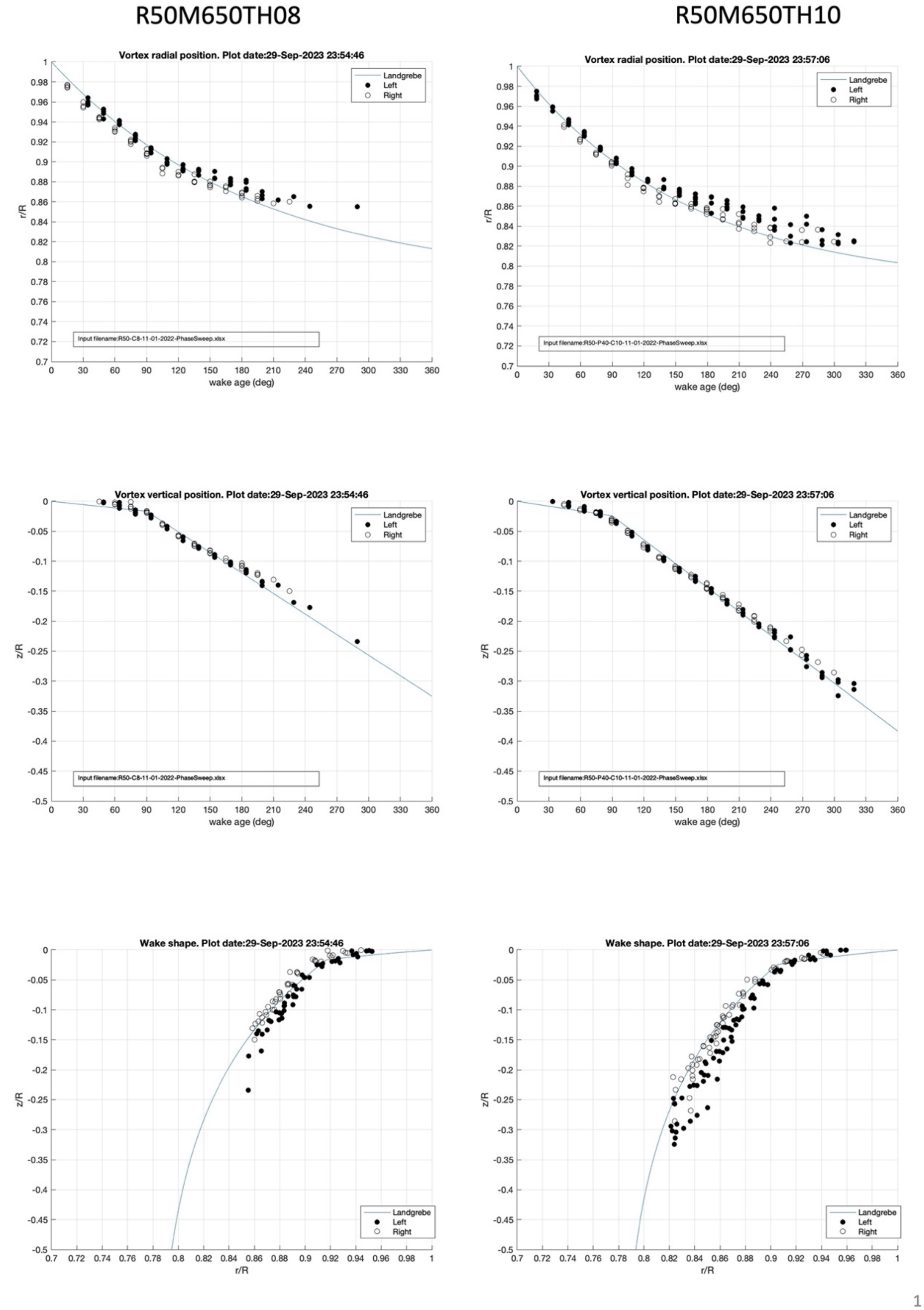

Figure 5. Non-dimensional radial and vertical positions of tip vortices: Mtip = 0.65, Collective pitch = 8, 10 degrees.

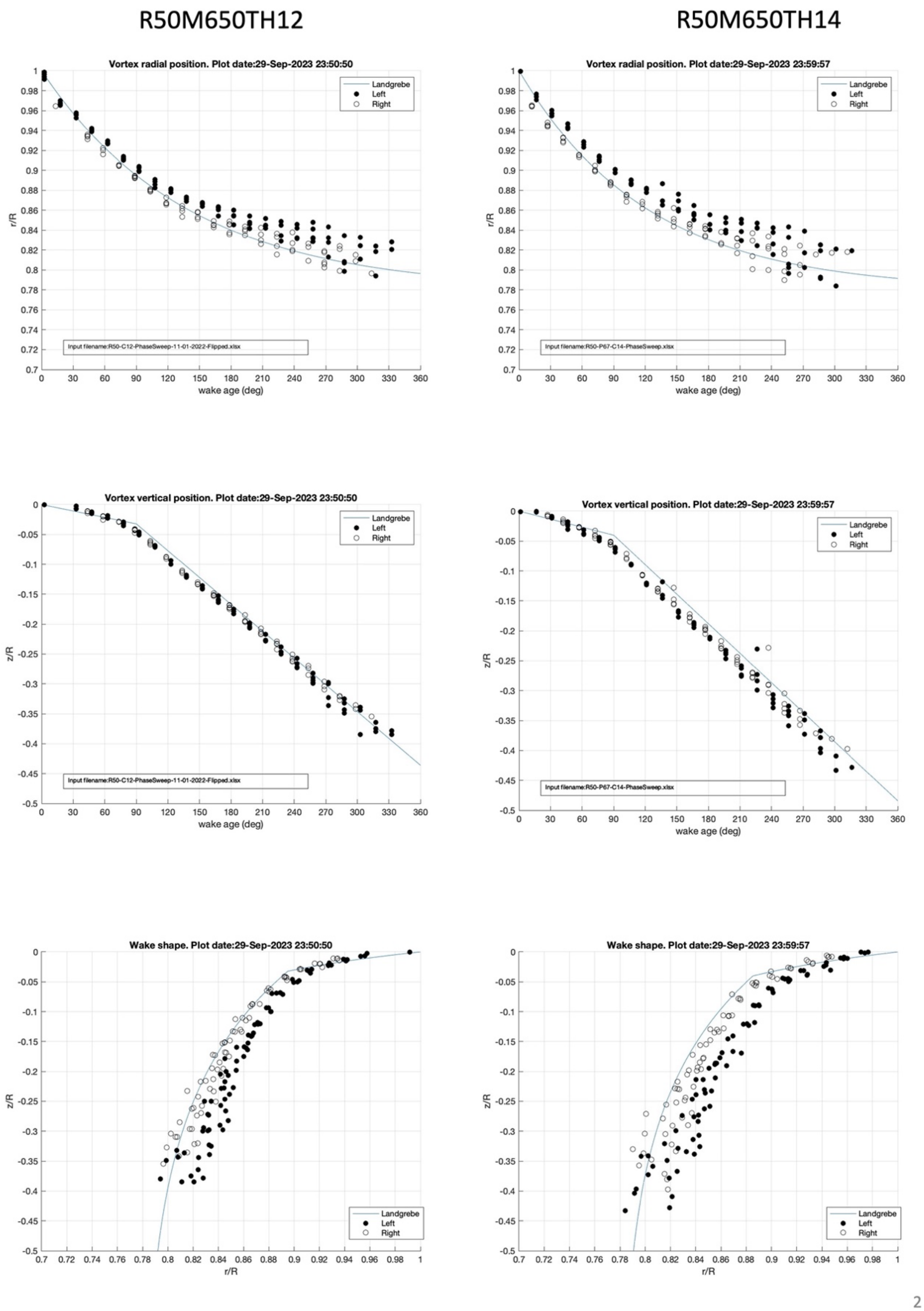

Figure 6. Non-dimensional radial and vertical positions of tip vortices: Mtip = 0.65, Collective pitch = 12, 14 degrees.

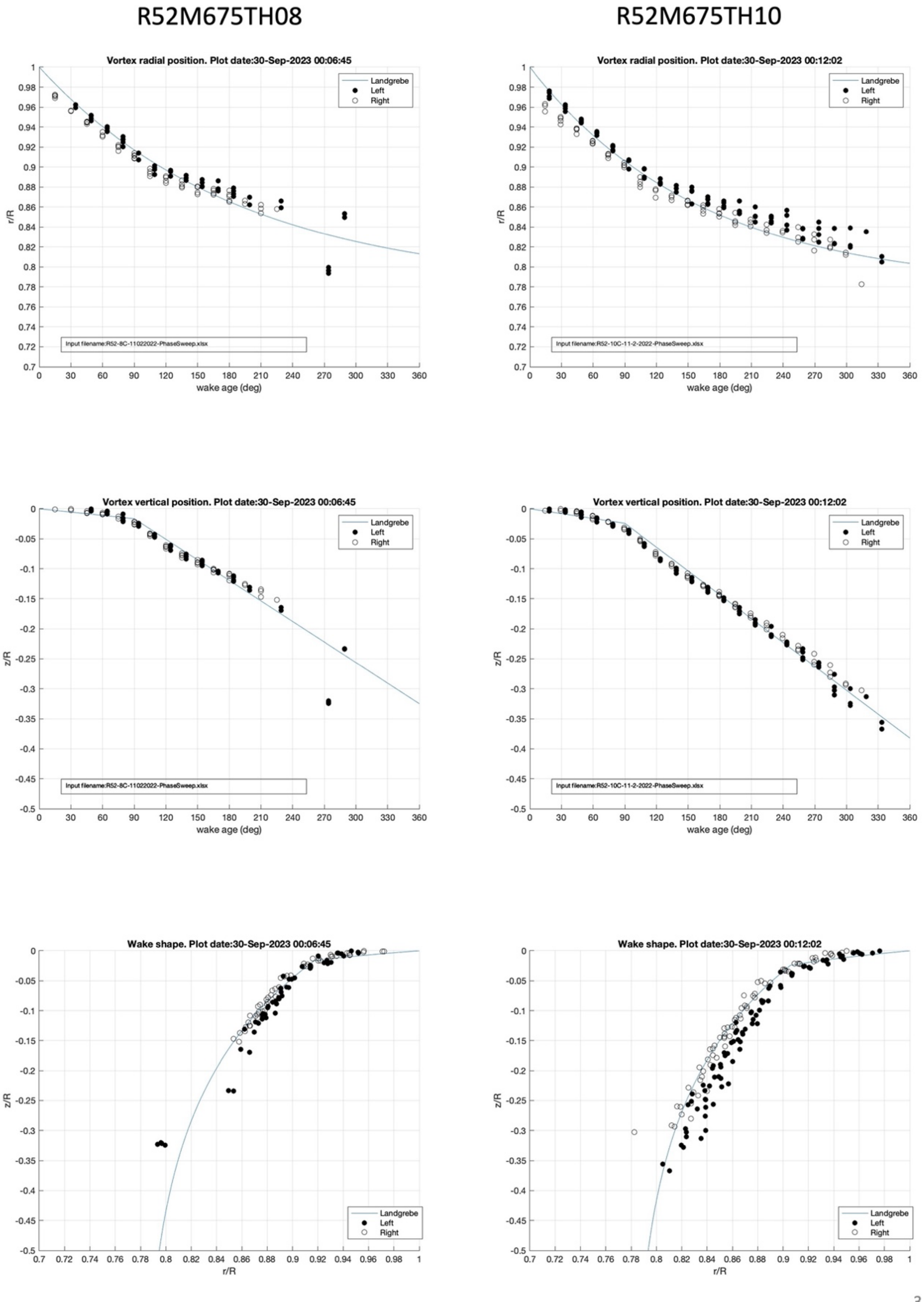

Figure 7. Non-dimensional radial and vertical positions of tip vortices: Mtip = 0.675, Collective pitch = 8, 10 degrees.

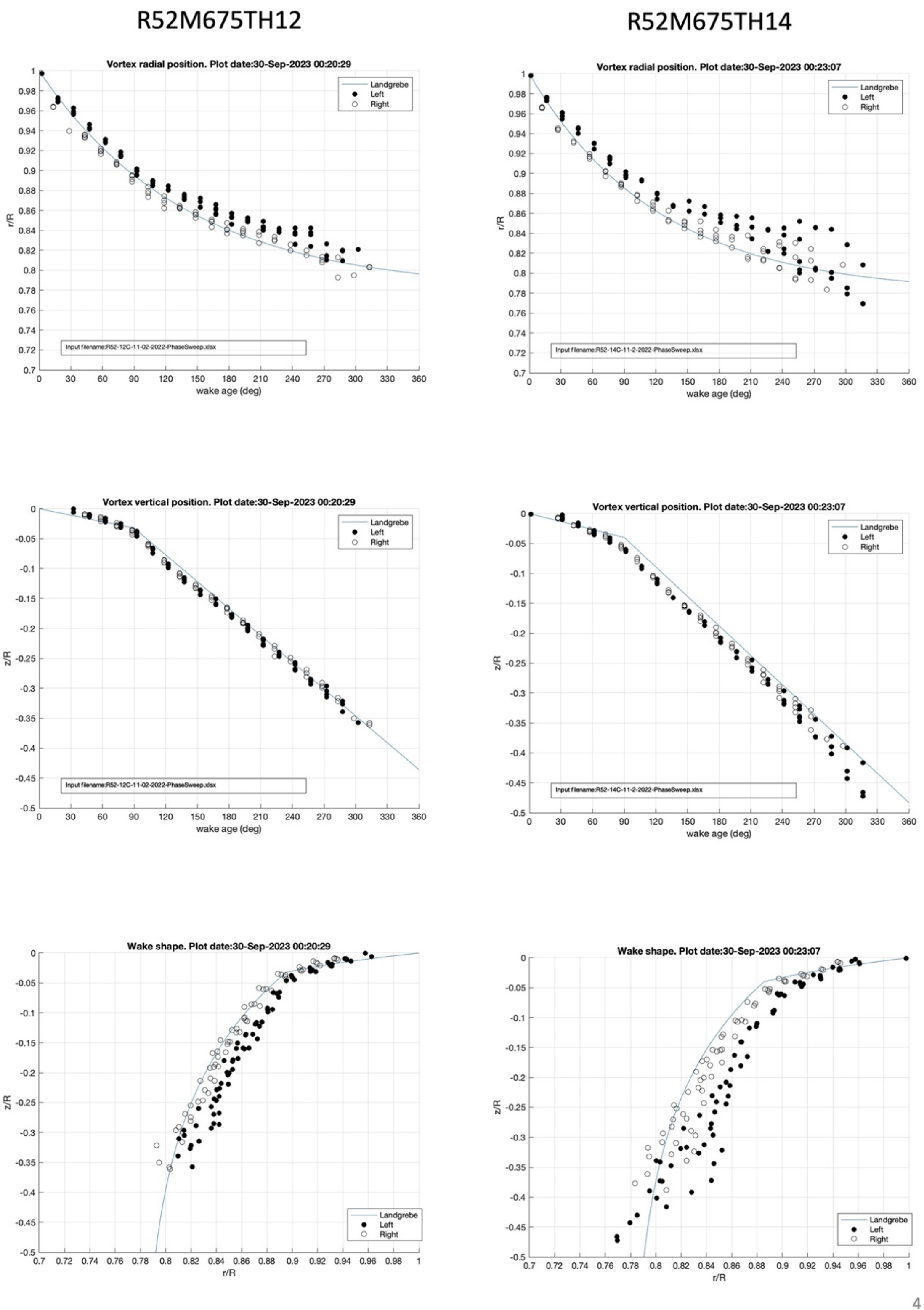

Figure 8. Non-dimensional radial and vertical positions of tip vortices: Mtip = 0.675, Collective pitch = 12, 14 degrees.

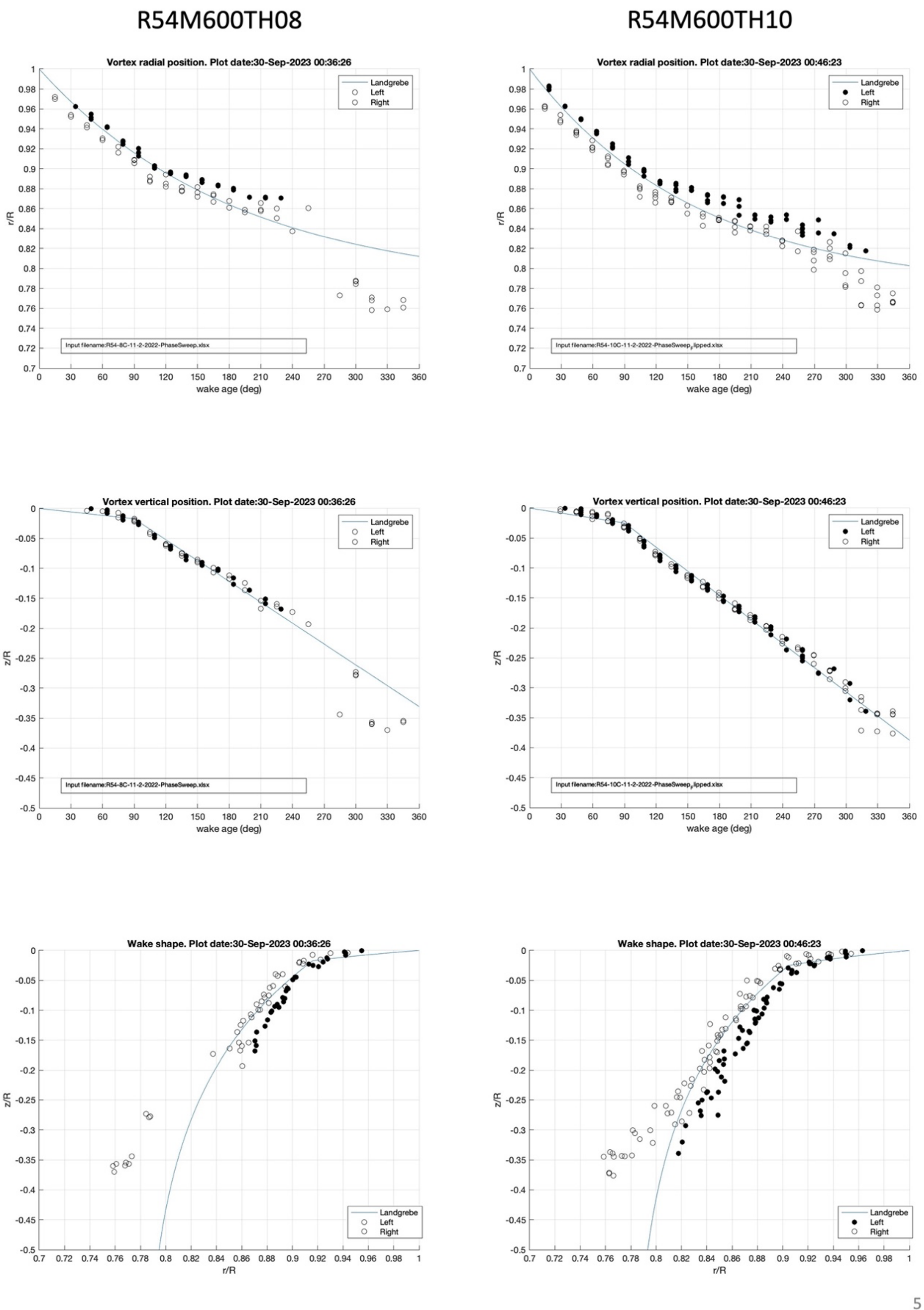

Figure 9. Non-dimensional radial and vertical positions of tip vortices: Mtip = 0.600, Collective pitch = 8, 10 degrees.

R54M600TH12 R54M600TH14

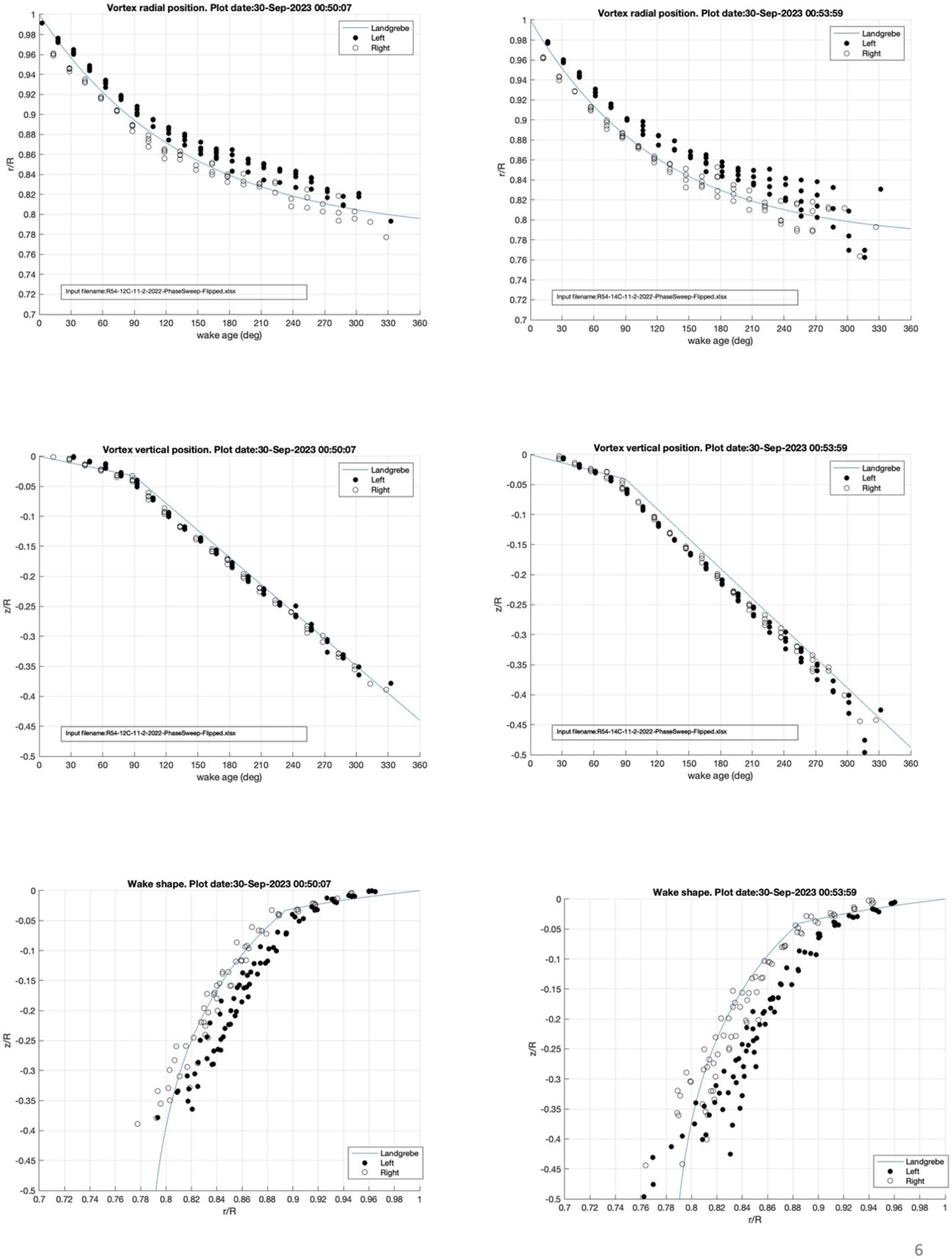

Figure 7. Non-dimensional radial and vertical position of tip vortices: Mtip = 0.600, Collective pitch = 12, 14 degrees.