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HYSTERESIS IN TIP VORTEX BEHAVIOR ON A ONE BLADED BEARING LESS MODEL ROTOR IN A WIND TUNNEL

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Abstract: A hysteresis phenomenon in tip vortex behavior is presented. The one bladed bearingless model rotor used is described as well as the circumstances under which this sort of event occurs in a wind tunnel.

1 Introduction

Almost a quarter of a century ago a special wind turbine model was designed and fabricated to investigate flutter in an open jet wind tunnel (reference 1 and 2). Elements of the surprisingly long survival record of the model are reported in reference 3. The present paper describes a finding after a substantial upgrade of the complete installation in 2000. Coincidentally the phenomenon pictured in the figures 1 and 2 where, as a result of a small change in wind speed, a reduction of torsion excursions was noted.

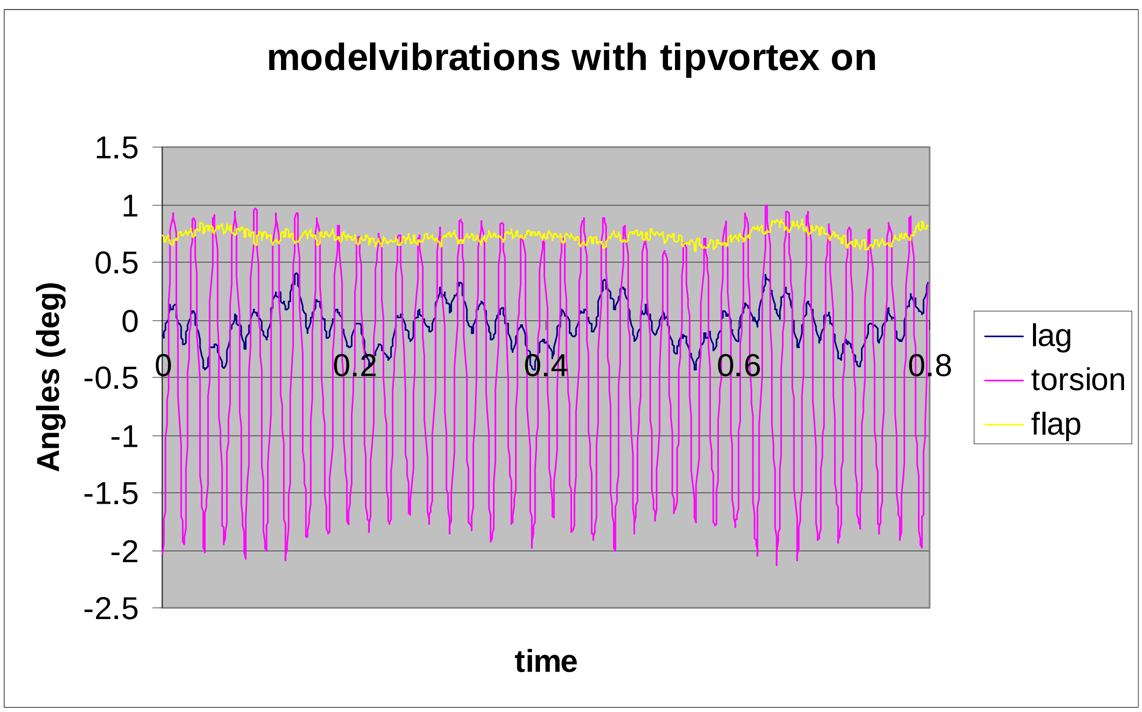

Figure 1. Time series with vortex still attached to blade

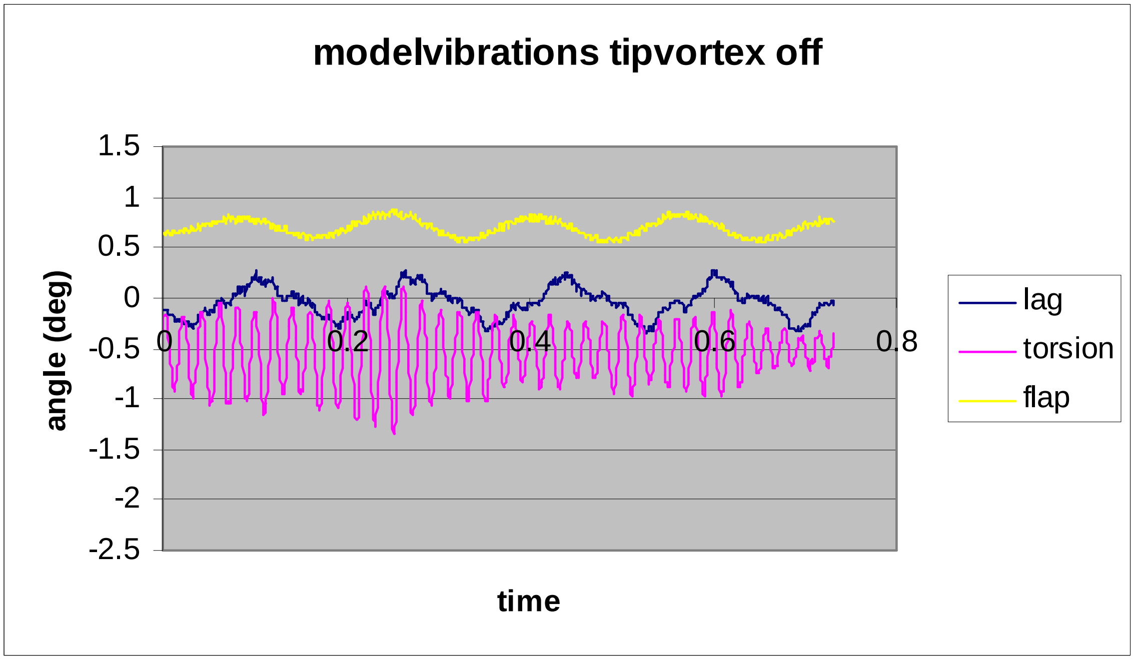

Figure 2. Time series when the tip vortex has left the blade

From video observations of the tip section of the blade, on which tufts were mounted (figure 3), it became clear that the event was created by the presence or absence of the tip vortex. A number of runs, by which the wind speed was in- and de-creased around this point, were made. Within the mean angle of lag, flap and torsion (the later shown in figure 4) a hysteresis behavior revealed. More recently it became clear why this hysteresis was involved.

As far as the authors are aware such a hysteresis phenomenon has not been reported before. But there was another particularity: at 5.5 Hz behavior was identical, however, at 11 and 13 Hz catastrophe events happen (reference 5); the 13 Hz case shown in figure 1 but not further treated in this paper. In this situation all the blade movements change from relatively small and in depended deflections to large and coupled movements. The torsion angle varies between +29 and -19 degrees and the amplitude of the second flap became ± 8 mm. (both with an frequency of 52 Hz).

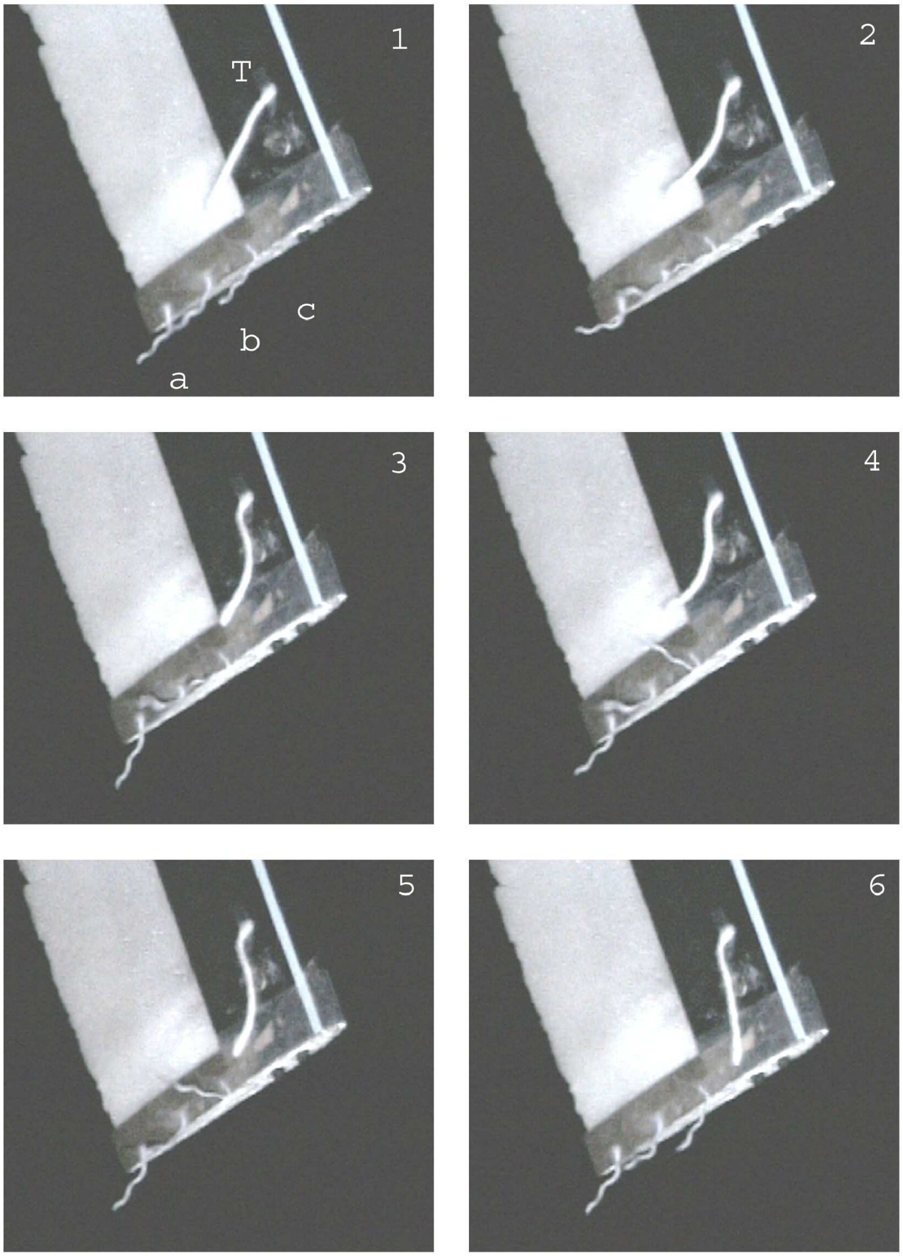

Figure 3. . Tip tufts movements (light colored line is tripwire) the picture shows the tufts reaction during an increasing wind speed. On the first picture the tufts are pointing in the flow direction. In the pictures 2 to 5 a little more wind creates a transition situation in with all tufts move independent from each other. In the last picture all tufts pointing in a more outward direction. (The tip vortex has left the blade).

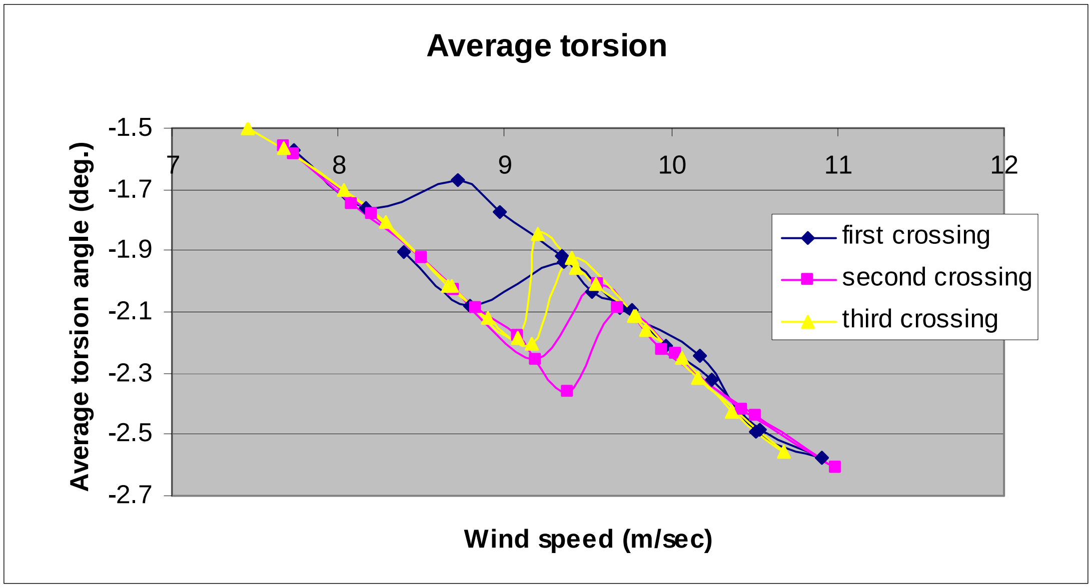

Figure 4. Hysteresis loop in mean torsion angle (similar behavior in mean flap and lag angles)

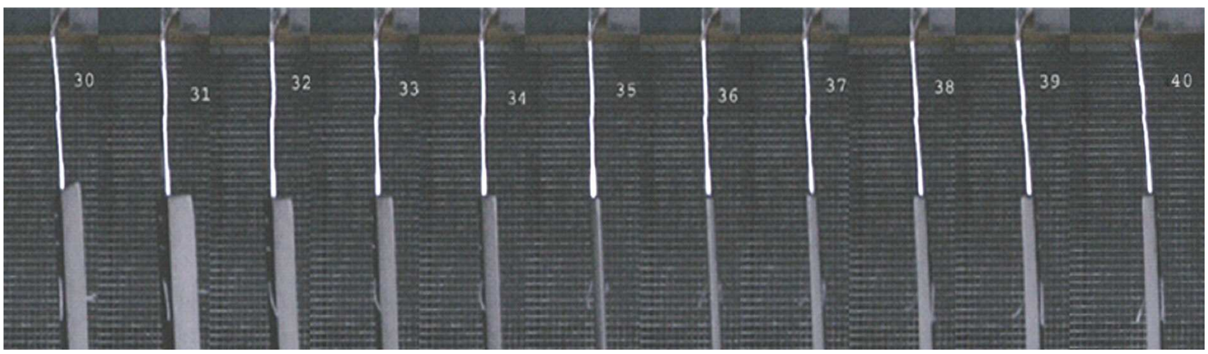

Figure 5 Torsion and flap movements during 13 Hz event

2 Installation

Delft University of Technology has a long tradition of rotating wing model flutter experiments, for example reference 1 (which contains reference to more literature).
The there in described one bladed bearingless model was stripped and used for the present test. The rotor consists of a hollow four-ply lime wood blade spar with alternate fiber layers at 45˚ with the blade axis at the leading edge and a Styrofoam trailing edge. At the tip a uranium weight was mounted. The reasons for this tip weight were its tip vane background, the lack of flap stops and to move the center of gravity from 28 to 26 % of the chord. (Lock no. without tip weight > 16). The root of the blade was mounted on a thin flexible Dural 2024 ST-T_3 element which gives the blade a certain amount of flap, lag and torsion freedom. The rotor had no controls, no pre-cone, no droop, no δ_3, no sweep and no flexbeam pitch.
On this flexible element strain gauges were mounted to measure flap, lead-lag, and torsion. Between the flexible element and the main shaft a sensitive tube was mounted

to measure the axis torsion. The wiring of the strain gauges past underneath the main bearing to amplifiers that were fixed on the main shaft. From here the signals were transmitted to the non-rotating world by means of high quality slip rings and collected by a pc-based data acquisition system.
Since the stiffness of the blade was an order of magnitude larger than that of the flexible element, the deflections were considered taking place in the latter and those in the blade were neglected.
To control the rotational speed of the rotor a DC motor with an eddy current coupling was used. To measure the rotational speed a disc with 10 slots was fixed on the shaft and rotated through an optical sensor.
A second sensor was mounted by which it was possible to determine the exact azimuth position. For this purpose a sensor was used that was capable of measuring with an accuracy of 1 degree and interpolated every 0.1 degree.
In a fixed pitch configuration the angle of attack could be changed by varying the wind speed at constant rotational speed.
Since it was a one bladed rotor a round brass counter weight was mounted opposite the blade. Further properties of the model are provided in the appendix.

3 Brief description of experiment

The model was placed in an open jet wind tunnel (reference 2) then, at 6 Hz, increasing speed makes the model first behave as a windmill, with the flow attached over the whole blade. This was indicated by the tufts (figure 3). As soon as however, the root was stalled the flexibly mounted blade starts stall fluttering, vibrating in torsion, flap and edge-wise direction. Further on, stall spreads over the blade with ever increasing torsion excursions up to -2˚and +1˚. Finally the very “nervous” tip vortex leaves the tip, resulting in shifts in mean lead-leg, flap, and torsion while torsion excursions diminish. (Figure 1, 2 and 4).
When the wind speed was reduced the vortex did not immediately reappear. The reduction has to proceed somewhat before the shifts vanish, the vortex reoccurs and torsion excursions are resumed.

4 Discussion of results

During the measurements the wind speed was increased and decreased consecutively. The blade movements became more violently up to the point where the tip vortex leaves the blade. Here the movements become much more at ease and the torsion deflection turns more in stall direction. Since this deflection intensifies the stall, this can only happen at a specific point, and since the movements, before reaching that point are so violent this would not be a fixed point. On the way back the blade will remain in its stalled situation longer because of the extra torsion deflection. This effect causes the hysteresis loop. At this transition point where the tip vortex jumps from attached to unattached (or visa versa) the wind speed and number of revolutions remain constant, so an attempt has been made to calculate the energy balance. The decrease in energy in the wake due to the change in induction factor before and after the transition should equal the energy increase in drag and energy required for the decrease in torsion. A lot of unknown factors were involved e.g. change in induction factor, change in aerodynamic center. Therefore these calculations will not be presented.

5 Conclusions

A rare hysteresis tip vortex phenomenon has been presented in this paper. The origin is explained. This concerns the rotor at low rotational speeds. It seems that this behavior was the beginning of catastrophe events at higher rotational speeds.
These last events at rotational frequencies of 11 and 13 Hz are to be studied further.

Acknowledgements

During the update of the installation and as a technical backup we had great support in electronics as well as in software and data acquisition by Mr. .ing C van Beek of the technical support division of the faculty of Civil Engineering and Geosciences.
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Appendix: model properties

The model geometric properties are shown in table 1. Rotor mass properties are given in Table 2. The non rotating natural frequencies with the blade downward are given in table 3. The natural frequencies with the blade in horizontal position, with and without artificial coning by 0.1 radian tilt of the stand, do not differ significantly from the tabulated values. Measurements were made by loudspeaker excitation in the appropriate directions. From these tests the position of the second flap node was obtained as well.

Table 1   Rotor geometric properties.

Aerfoil section	NACA 0012
Radius, m	0.6060
Blade root radius, m	0.1800
Blade chord, m	0.1000
Blade twist between R=0.6 and Rr, Radians	0.1000
Solidity	0.0526
Flex beam length, m	0.1700
Flexbeam width, m	0.0160
Flexbeam thickness, m	0.0015
Second flap node, % radius	83
Elastic axis, % of chord from LE	26
Reynolds number during test (tip)(at 6 Hz)	71700
$V_{tip\ max}$ (m/sec)	100

Table 2 Rotor mass properties.

Blade mass, kg	0.1039
Tip weight mass, kg	0.0668
Center of Gravity span wise, % radius	76.1
Center of Gravity chord wise, % from LE	26.1
k_θ static, Nm/rad	3.2
Lock number blade only	17.0
Lock number tipweight included	3.1
Reduced frequency (at 6 Hz)	0.219

Table 3 Blade non rotating natural frequencies.

Blade mode	Natural frequency (Hz)
First flap	1.5
Second flap	26
First lead-lag	12.5
First torsion	44.7

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