In this paper, a novel configuration of an energy harvester for local sensing using limit cycle oscillations has been designed, modeled and tested. A wing section has been designed with two free-floating flaps (FFF). The FFF are aerodynamically balanced flaps that are free to rotate around their rotation axis and are only controlled by trailing edge tabs. In the rotational axis of each flap a dynamo is mounted that converts the vibrational energy into electricity. It has been demonstrated numerically how a simple electronic system can be used to keep such a system at stable limit cycle oscillation by varying the resistance of the electric circuit. The system has been manufactured and tested in the Open Jet Wind Tunnel Facility of Technical University Delft. The numerical results could be reproduced and voltage generation could be demonstrated at cost of a moderate decrease in lift of 2%.

I. Introduction

Sensors are used in multiple aerospace and wind energy applications to measure the structural integrity and dynamics. The obtained measurement results can be used as input signals for controllers to reduce vibrations, thereby increasing passenger comfort or structural durability. For a full blade or a wing, a set of distributed sensors such as strain gauges and accelerometers is needed. Each sensor needs to be powered. Certainly, when considering the size of aircraft or wind turbines, the cables that connect each sensor to a central power system is a very complex and failure prone system. In the case of wind turbines, additional complexity is added to the power system as all energy need to be transferred from the non-rotating into the rotating blade reference frame. This operation is done by a system of slip rings and electric brushes which are subject to wear. A convenient solution to this problem is to generate electricity locally.

Energy harvesting of vibrations has been investigated for a long time, but exploiting aeroelastic instabilities has so far received little attention. Bryant and Garcia have made a start in this field [1], which has been followed up by Bryant, Fang and Garcia [2]. In their research a simple cantilever piezoelectric bender with a flap at the trailing edge is used to generate vibrations that can be harvested. Bryant, Wolff and Garcia [3] have further expanded this conceptual work by studying the sensitivity of the system parameters on the stability. It was found that by changing component masses and stiffnesses, the system...
behavior could significantly be changed. All research has been limited to a simplified structural system with 2 degrees of freedom and has been coupled to a sectional, unsteady, linear aerodynamic model. Park et al. [4,5] have performed a similar study, however the piezoelectric approach was replaced by an electromagnetic device. Instead of exploiting a coupled flutter mechanism, a T-shaped cantilever beam is used. A magnet is attached at the end of the cantilever beam such that it sheds vortices that lead to flutter. Coils are mounted in the non-moving reference frame.

In an effort to move towards a more practical implementation of such an aeroelastic energy harvester, the concept of a free-floating flap (FFF) is reviewed. Initial work on this subject has been done by Bernhammer et al. [6]. The free-floating control effectuator is used to suppress self induced flutter through trailing edge tab control. Pustelnik and Karpel [7,8] have performed numerical simulations of the same model to predict the limit cycle oscillations of such a system.

Free-floating flaps have so far been used to aerodynamically alleviate vibration loads, while Bernhammer et al. [9] used them as energy harvester. The flaps are aerodynamically balanced such that only marginal stability is present. The flaps are therefore very responsive to any external disturbance. An even low turbulence level can be used to excite the flap, which interacts with the dynamic response of the full structure. Aeroelastic instabilities can be used to amplify the vibration level. The energy extraction is done using electromagnetic devices. A coil, which is mounted inside the flap, oscillates through a magnetic field that is generated by permanent magnets. This relative motion generates electricity that can directly be used or stored in a battery. Details of the aeroelastic design of the wing have been presented by Bernhammer et al. [6]. The dimensions of the model were not altered and are given in Table 1. Compared to the original model, two angular potentiometers were replaced by commercially available dynamos.

Bernhammer et al. [9] perform a purely numerical analysis of the phenomenon. It has been shown on how the resistance in the electric circuit and the charging level of the battery have an effect on the aeroelastic instabilities. Variation of parameters can be used to keep the system marginally stable, such that limit cycle oscillations occur. The current paper forms the experimental counterpart to the research of Bernhammer et al. [9]. The system has been built and tested in the Open Jet Facility (OJF) of Delft University of Technology.

II. Wind Tunnel Set-Up

The system presented in Table 1 has been manufactured. Figure 1 shows a sketch of the concept. The two electromagnetic devices at the end of the flaps are connected such that the stator is magnetic and fixed to the wing structure. The rotor is a coil that is collocated with the rotational axis of the flap. The wing-flap combination was tested in the Open Jet Facility (OJF) of Delft University of Technology. The OJF has a test section of 2.8 by 2.8 meters and can reach wind speeds up to 35 m/s. Figure 2 shows the model in the tunnel. The root of the model has been connected to a 6 component balance that can measure up to 250 N with a resolution of 0.1 N or a lift coefficient resolution of 0.004 at 10 m/s wind speed. The structure is passed through an aerodynamic fitting, shielding the balance from influences of the flow as shown in Figure 2. Two numerical results were reproduced, namely the response of the structure and the associated harvested energy as a result of an initial deflection and a continuous excitation signal. The monitoring system needed to be outside of the wind tunnel. The dynamos were thus connected by
cable to the data acquisition system. Unfortunately, the resistance in the cables was too high to demonstrate a significant mechanical power extraction as has been shown numerically \[9\]. Therefore, it was not possible to demonstrate stability variation by changing the resistance in the electric system as done numerically.

Table 1: Tail plane model details

<table>
<thead>
<tr>
<th>Chord</th>
<th>Thickness</th>
<th>Span</th>
<th>Rudder chord</th>
<th>Rudder span</th>
<th>Dynamo</th>
</tr>
</thead>
<tbody>
<tr>
<td>400mm</td>
<td>11mm</td>
<td>1000mm</td>
<td>160mm</td>
<td>250mm</td>
<td>Basta Trio 3320</td>
</tr>
</tbody>
</table>

![CAD drawing of wing](image1)  
![Close-up on flaps](image2)

(a) CAD drawing of wing  
(b) Close-up on flaps

Figure 1: Energy harvester concept

The performance of the flap system was assessed before the wind tunnel tests were conducted. For this purpose, the flaps were connected to a shaker, that could cause flap rotations up to 4 degree with a maximum frequency of 10 Hz. Figure 3 shows the quadratic mean of the voltage output versus rotation angle and frequency. Equation 1 shows the relation between generated voltage and changing field strength.

\[ U = nl \frac{d\phi}{dt} \]  

In Equation 1, \( n \) is the number of coil turns, \( l \) the length of a coil loop and \( \phi \) the magnetic field strength. This linear relation can be observed for both flap deflection amplitude and flap deflection frequency as shown in Figure 3. Only for high deflection frequencies above 6 Hz, the linear relation does not hold true anymore and a reduction in voltage output can be observed.

III. Low amplitude limit cycles

The first step during the wind tunnel tests was to assess the aeroelastic stability of the system. A close-loop identification \[10\] has been carried out. The controller developed for the flutter suppression experiments by Bernhammer et al. \[6\] was used to stabilize the system above the flutter speed. Figure 4 shows the comparison of the identified frequency and damping to the numerical values. For both subfigures, the trends agree. A slight
numerical underprediction of the eigenfrequency can be observed, however the difference for the first bending dominated eigenfrequency is less than 5%. Even the small dip that is obtained numerically at 11 m/s is reproduced. While the numerical values show a more gradual decrease to this point, the experiment shows a sharper dip, a fact that might be caused by the numerical fitting of the state-space system parameters to the measurement values. The damping plot, performs excellently for the first 2 measurement points, which are practically identical with the numerical prediction. Around the flutter
point, experiment and numerical prediction diverge such that at 11 m/s a difference in the damping coefficient of 0.01 can be seen. This difference increases with increasing wind speed to a value of 0.025 at 13 m/s. While the main part of the damping below rated wind speed is caused aerodynamically, it is believed that friction in the system adds damping, which, once the system becomes unstable, contributes to visibly to the overall system damping. The flutter speed obtained in both cases is around 10.5 m/s.

![Damping and frequency plot](image)

**Figure 4: Damping and frequency plot**

A. Periodic excitation

To further assess the responsiveness of the system to disturbance input, a sinusoidal signal was sent on the trailing edge tabs on both flaps. Figure 5 shows the measurements of the voltage response for different frequencies. The background noise in the measurements caused by turbulence in the flow results in a base voltage of 0.005 V. An excitation signal at low frequencies of 1 or 2 Hz does not change the average voltage that is obtained irregardless of the wind speed. The same holds true for high frequencies of 4 Hz and above. Only for 3 and 3.5 Hz a structural response is visible. While damping the aerodynamic damping is still strong at wind speeds of 8 m/s, an increase to 9 m/s shows already an increase in achievable voltage output of a factor 3. When increasing the wind speed even further the maximum response is a factor 8 above the baseline value. Higher wind speeds in the experiment were not possible as for 11 m/s the system would be unstable and even a very small excitation would result in flutter. Consequently, the gear ratio between the baseline voltage level and the possible voltage generation at 11 m/s wind speed is infinite.

B. Small initial displacement

In a third step, the system given a small initial disturbance. For wind speeds below 10 m/s the initial disturbance is damped away relatively quickly and practically no energy can be harvested as displayed in Figure 6. At wind speeds of 10 m/s, the system is close to be neutrally stable. Any disturbance, be it initial or through turbulence, provokes a slowly fading oscillation. Consequently, the achievable power output is higher than for lower wind speeds. For 11 m/s, the system is unstable and the vibrations increase in amplitude. In the current simulation, the controller designed by Bernhammer et al. [9], was used to keep the system neutrally stable. For this purpose, the gain in the controller...
was altered manually such that the tip accelerations would not exceed 2g. One should notice that this is significantly below the physical delimiters of the system, which allow flap deflections up to 10 degree. As expected, the voltage output increases yet another 40% compared to the 10 m/s case.

For the wind speeds below flutter speed, the energy production of both flaps is equally low. For aerobically triggered energy harvesting, the outer flap interacts more with the first bending dominated structural mode. The voltage generation is consequently twice the one of the inner flap. Figure 7 shows the time history of the limit cycle for wind speeds of 11 m/s. The amplitude varies slightly over the cycles, which is a phenomenon that can be explained by turbulence in the inflow. The measurement data shows significant noise, which cannot be attributed to the aerelastic response, but rather to the sensors and the acquisition system. It is interesting to see, that despite being a limit cycle, the oscillations of both rudders are in phase. The opposite signs in Figure 7 are caused by the installation of the electromagnetic devices as shown in Figure 1. As the devices installed on both flaps are identical, but mirrored in orientation, a synchronous rudder deflection causes opposite voltage outputs. This is contrary to the numerical
findings of Bernhammer et al. [9], who have observed a phase shift between the rudders when being in limit cycle oscillation. One should however bear in mind that in the numerical case electromagnetic coupling and structural delimiters were used to create a limit cycle, while in the experimental case the oscillation amplitude was limited by trailing edge tab control.

![Figure 7: Limit cycle oscillations at 11 m/s](image)

The same difference to the numerical simulations can be observed in Figure 8. While agreement is reached concerning the damping and decay of the oscillations for 8 to 10 meters per second and the growing oscillation to limit cycle oscillations for 11 m/s, the synchronous nature of the vibrations of both flaps causes sinusoidal like variations in the power that can be achieved. Notice that in Figure 8 the absolute values of the power generation are displayed. The phase shift between the two rudders in the numerical results by Bernhammer et al. [9] cause the power output never to be zero, as always one flap is moving through the magnetic field.

C. Lift losses

Figure 9 shows the root lift forces the wing sees. While the lift in case of the fixed wing is practically constant and the variations are caused by low amplitude turbulence and the measurement signals, the force time history of the limit cycle oscillation coincides shows oscillations around the value of the fixed flap case. The oscillation frequency coincides with the eigenfrequency of the first bending mode. The oscillations are a originate from variations of the aerodynamic forces over time and the structural dynamics associated with the flap motion. The difference in average value between the forces during the flap fixed case and the LCO case for wind speeds of 11 m/s is 2%, while the oscillation amplitude stays below 5% of the mean value. Unfortunately, a similar measurement for the drag could not be performed, as the differences found between the fixed flap and the LCO case falls into the measurement accuracy of the balance.
Figure 8: Time history of voltage generation due to impulse, 8 m/s (top) to 11 m/s (bottom)

Figure 9: Time history of lift forces

IV. High amplitude limit cycle

In a final step, the controller was switched off and experiments have been performed at 11.5 m/s wind speed. The limit cycle amplitude was now not tuned manually as before, but only by the structural delimiters that allow the flaps to rotate between 10 and -10 degree. Figure 10 shows the tip accelerations of the wing as the system becomes instable. Just after 17 seconds in the measurement the wing starts to oscillate. While these oscillations are first small, they grow to 6g at 22 seconds in the measurement. The flaps reach the delimiters for the first time. At this point in time sharp peaks occur in the tip accelerations history, a result of the forces that are transferred between flaps and wing structure. The peaks reach almost immediately reach amplitudes above 20g, where
they system stabilizes.

Figure 10: Tip accelerations during limit cycle oscillation

Figure 11 further elaborates on the structurally limited oscillations as it shows the time history of the voltage generation. Up to 22 seconds the phase of the voltages of the inner and outer flap are perfectly aligned. The noise level is relatively low and the extrema of the voltages are round. Between 22 and 23.5 seconds, the peaks are becoming sharper and increase rapidly. This corresponds very well with what has been presented in Figure 10. At 24 the system seems to have stabilized in the limit cycle configuration. The phase coupling between the 2 flaps is lost and especially the outer flap seems to suffer more from the delimiters, a fact that can be attributed to the higher interaction of the outer flap with the instable bending mode compared to the inner flap. The deflection amplitudes are thus larger and the delimiter is reached earlier. While the frequency of the oscillation of the inner rudder does not change, the frequency of the outer rudder triples. One dominant oscillation peak in the outer flap voltage is observed that after a transition period of 3 seconds aligns with the oscillation of the inner rudder. Two additional lower amplitude cycles occur probably as a response to the impact the outer flaps has with the delimiter. The experimental results only partially confirm the numerical simulations by Bernhammer et al. While the loss of phase coupling during the transition period is present both in simulation and experiment, the permanent phase shift does not manifest itself in the experiment. The difference might be connected to the hard impact the flap sees every cycle, while the delimiter amplitude was significantly smaller during the numerical simulations and thus the maximum force is also smaller as the oscillation frequencies are identical. The additional peaks that occur in the experiment can consequently not be expected to be as large in the numerical simulations and might not be visible in the voltage history.

V. Conclusion

The potential of energy harvesting through electromagnetic devices using aeroelastic instabilities has been demonstrated experimentally. The strong coupling between the
wind speeds and the potential energy generation has been underlined, as crossing the flutter speed yields a tenfold increase in voltage generation as predicted numerically. The complex nature of the limit cycle oscillations could only partially be confirmed. While for a controller regulated low amplitude limit cycle oscillation, not phase shift between the flaps occurs, for a structurally limited oscillation, strong peak forces and voltages occur. However the oscillation pattern converges to one dominant oscillation for the outer flap in phase with the oscillation of the inner flap and two smaller oscillations that are out of phase. For the low amplitude oscillations, which are structurally preferred, the loss of lift of the structure is less than 2%.

References


