Design, construction and testing of a wing with retractable damage on an Unmanned Aerial Vehicle

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Design, construction and testing of a wing with retractable damage on an Unmanned Aerial Vehicle

Influence of damage on UAV flight dynamics

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Traineeship report of research done at the University of Minnesota, Minneapolis, United States of America

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Design, construction and testing of a wing with retractable damage on an Unmanned Aerial Vehicle – influence of damage on UAV flight dynamics

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Abstract

More and more airplanes and Unmanned Aerial Vehicles (or UAV’s) are used in combat situations. The risk of a hit by small arms or missiles is therefore increasing. After a hit, it is desirable to maintain control over the aircraft to accomplish the mission. To see whether it is possible to reach this goal, research on the influence of damaged wings on the structural as well as the aerodynamical effects of damage on a UAV’s flight dynamics is performed. Furthermore, control of aircrafts suffering from battle damages is desirable. Eventually it might be possible to scale the results of this research to large aircrafts to make them more robust to damages as well.

Nomenclature

UAV       : Unmanned Aerial Vehicle
Re-number : Reynolds number
L.E.      : Leading Edge
c/4       : quarter chord
c/2       : half chord
T.E.      : Trailing edge
AOA       : Angle of Attack
CL        : Coefficient of Lift
CD        : Coefficient of Drag
MAC       : Mean Aerodynamic Center
L/D ratio : Lift to Drag ratio
DOF       : Degrees of Freedom
ABC       : Aircraft Body Coordinates
u         : horizontal velocity in ABC
\( \ddot{u} \) : horizontal acceleration in ABC
w         : vertical velocity in ABC
\( \dot{w} \) : vertical acceleration in ABC
\( \dot{\theta} \) : angular velocity between x-axis (ABC) and gravity
\( \theta \)  : angle between x-axis (ABC) and gravity
\( \dot{\theta} \) : angular acceleration between x-axis & gravity
l         : distance between CG and wing MAC
\( I_y \)  : moment of inertia around y-axis
\( g \)     : gravity acceleration
m         : mass of UAV
T.E.      : Trailing edge
w         : vertical velocity in ABC
\dot{\omega} \) : vertical acceleration in ABC
\( \dot{\omega} \) : vertical acceleration in ABC
\( \dot{\theta} \) : angular acceleration between x-axis & gravity
l         : distance between CG and wing MAC
\( I_y \)  : moment of inertia around y-axis
\( g \)     : gravity acceleration
m         : mass of UAV

1. Introduction

In this research, there is focused on the influence of damage to the structural integrity of the wing, as well as on the changes in the aerodynamical forces and moments. The undamaged as well as several damaged wings are investigated. To get an idea of how large the “effective size” of the applied damage has to be, flight tests have been performed to get a feeling of the aerodynamical degradation of the wing. Furthermore, bending and torsion tests have been done. In this way the structural degradation of the wing can be investigated with different damage sizes. After these experiments, the largest damage size is chosen to be about 15 cm wide and about 12 cm deep at the leading edge of the wing, which is approximately 6% of the wing area. A design is made with a retractable damage which can be altered from the undamaged wing to the 15 times 12 cm damaged wing. This wing has been tested in the wind tunnel in different formats and the forces and moments it generates are measured. These values are used in a longitudinal dynamical model for which a controller can be synthesized. Research in this field is important because more and more aircrafts are suffering from battle damage. However, there hasn’t been a lot of research done on damaged aircrafts. Past research has typically focused on aerodynamic effects of damage with higher Re-numbers [1] of about 500,000, although some research is done for Re-
numbers of about 25,000 [2]. In this research, the focus is on Re-numbers of about 180,000. Structural as well as aerodynamical effects of damage have been investigated as well [3]. Reconfiguration of flight controls has been applied on a NF15b [4]. Concerning the UAV group of the University of Minnesota, it is of great interest to simulate the effect of a damaged wing during the flight and synthesize a controller to cope with this damage because the control law can be applied on UAV’s.

2. Previous studies on damage

Earlier studies have focused on three main topics considering damage, being:
1) Effects of damage on structural integrity of wings
2) Effects of damage on aerodynamics of wings
3) Control of aircrafts with wing damage

Next, these three topics will be discussed in more detail.

Structural effects
From [4] it is concluded that aeroelastic instabilities are not easily triggered by ballistic damage. Structural degradation of the wing due to damage leads to a reduction in bending and/or torsion stiffness. Also a shift in elastic axis can occur. The reduction in stiffness can induce two kinds of instability: flutter instability which can lead to resonance of the wing, and/or divergence instability. However, a reduction of 90% of the torsion stiffness has to be applied to reduce the flutter margin by 25%. Furthermore, it is observed that a wing would not fail due to a lack of stiffness but due to a lack of strength.

Aerodynamical effects
The two effects as mentioned above are in fact aerodynamical damages, but they relate to the structural integrity of the wing as discussed in [4]. The first one is aeroelastic damage present as localized drag, which lowers the divergence speed of the wing and might even make a wing snap. This phenomenon is called “drag divergence”. Furthermore, periodic aerodynamic forces can force the wing into dynamic unstable oscillations known as “parametric resonance”. This only occurs when the forces are tuned to the structural mode frequencies. Also there are some pure aerodynamical effects of damage on wings, discussed below, from [1]. In this research, holes have been applied with a diameter of 10 and 20 % of the chord at different locations at the wing for chord sizes of 10 and 20 cm. These holes are located at the leading edge (L.E.), quarter chord (c/4), half chord (c/2) and trailing edge (T.E.). For the 10% chord diameter holes, it appeared that especially the c/4 and c/2 holes provided the largest decrease in lift and the largest increase in drag. L.E. as well as T.E. damage had very little effect on both. Furthermore, without damage, flow separation only occurred at about 80% of the chord measured from the L.E. With damage, the pressure differential in between the upper and lower surface causes a so called jet which produces additional drag due to earlier flow separation. The effects for the 20 % chord diameter holes are more pronounced than those of the 10 % chord diameter holes. From an angle of attack (AOA) of 4 degrees on, the c/4 holes gave the largest reduction in the lift force. This is probably due to the location of the pressure peak near the c/4 location. Furthermore, the stall angle increased when a c/4 hole was applied. The jet effect helped to attach the flow over a chord wise position, further downstream, thereby increasing the stall AOA. The L.E. hole showed a significant reduction in lift from an AOA of 8 degrees on, caused by localized L.E. stall. Concerning the drag effect due to the larger hole, the c/4 and c/2 chord locations showed the largest increases. It can be concluded that locating the damage close to the upper surface pressure peak results in the largest decrease in lift and increase in drag. This point shifts from about 40% chord measured from the L.E. to the c/4 position. For the pitching moment, the most sensitive positions are c/4 and c/2. For high AOA though, L.E. damage results in a localized L.E. stall which results in a sudden drop in pitching moment gradient. The drop in pitching moment is also observed in this research. In [5] the diameters of the holes are up to 40% of the chord and show the same trend as [1].

Control of damaged aircrafts
Some research has been performed to reduce the negative effects of damage on the flight performance of aircrafts. In [5] a method is presented to reduce a strong jet into a weak jet by applying a flap. Positive flap deflection led to more drag and less lift, whereas negative flap deflection resulted in less drag and increased lift compared to zero deflection of the flap. In [4], a so called “Self-Repairing Flight Control System” is used to detect damage or failures and change the control settings in such a way that the aircraft remains trimmed. This gives the pilot more change to land the aircraft safely.

3. Flight tests

One of the standard airfoils used in the UAV group of the University of Minnesota, is the SD 7037, picked because of the high lift to drag ratio for Re-numbers in the order of 100,000. This wing is put on a Slowstick small UAV with a weight of about 500 gr., a wing span of 1.10 m
and a chord of 27 cm, also extensively used in this group. First, a flight test was performed without any damage to get a feeling of the airplanes handling. After that, increasing damage up to 15 times 12 cm was applied to the right wing close to the root of the wing, as can be seen in figure 1.

Figure 1: damaged wing on Slowstick

It showed that with increasing damage size, the nose pulled right when taking off. This is caused by the damaged wing which has a slightly larger AOA and therefore a larger drag. Also, slightly more throttle was needed to fly, due to the increased drag. After these tests, the left wing was damaged also (while keeping the 15 times 12 cm damage on the right wing). The effects of the damages were more pronounced, leading to unstable stall behavior. Also, the airplane tended to go into a spin after stalling. Furthermore, the trim AOA and power increased. It was noticed that a roll maneuver led to unstable behavior as well, probably due to fact that the flow over the fuselage could not counteract against the wings because damage was applied there [6]. Although the airplane could still be flown, it be noticed that a human pilot flying was able to adapt to changing flight dynamics. A robust or adaptive controller might be used to gain the same effect and make it possible to fly.

4. Bending and torsion tests

After the flight tests, some idea about a reasonable damage size was present. However, it was desirable to simulate damage in a structural manner as well. To see the effect of damage, torsion and bending tests were performed. To get realistic values for the loads, two different flight situations were taken into account. First of all, it is reasonable to assume that the airplane has to be able to pull 1 g. Secondly, from earlier tests on a symmetric profile with the same overall dimensions as the wing used on the Slowstick, a value for the pitching moment is taken of -0.36 Nm.

Setup

To test the wing under these conditions, a setup has been made as can be seen in figure 2.

Figure 2: static wing loading setup

It consists of a foam part with the contours of the airfoil, to clamp the wing. On the other side of the wing, a plastic plate with the contour of the airfoil can slide over the wing. By using Tornado, a Matlab program, it is possible to determine the location of the neutral point where all the forces can be applied to. Because the SD 7037 airfoil does not exist in Tornado, it is modeled as a NACA 6310 airfoil. The neutral point lies on 6.1 cm from the L.E. Three holes are applied on the plastic plate; one at the neutral point and two, at 22 cm left and right of this hole. In this manner, bending as well as pure torsion can be applied due to weight and a pulley to reverse the direction of the force as can be seen in figure 2. It is assumed that the load of the wing is not distributed but can be seen as a point load and moment at the tip of the wing.

Results for the foam wing, stiffness and strength

To check the strength and stiffness of the wing under loading, the setup as shown in figure 2 is used. All measurements can be found in Appendix A. For bending tests, weights are hung at the c/4 point up to 1 kg. In figure 3, one can see the average deflection of the c/4 point (averaged over the deflection of all 3 mentioned points) against the applied force. Hysteresis due to strain hardening occurs, under loading and unloading. Furthermore, the wing does not fail when a 400 gr. weight is hung at it and a damage of 15 times 12 cm is applied. This leads to a safety factor of about 3. Note; the unloaded deflection is unequal to zero because of data fitting. In figure 4, the deflection of the left end point is plotted against the applied torque. Again hysteresis occurs, and a moment of 2.2 Nm is applied, which is a force of 10 N with an arm of about 22 cm. This is a safety factor of about 8. The left and right side of the wing can be twisted 90 degrees without breaking.
5. Wing design

From the flight, bending and torsion tests, it was clear that a damage size of 15 times 12 cm should result in significant degradation. This degradation was observed on the aerodynamics, bending and torsion stiffness. The goal was to design a wing which could fulfill these 3 tasks due to damage. After some designs, a moving leading edge bar is chosen, sliding along two guidances as can be seen in figure 5.

Figure 5: leading edge bar with cables

It is actuated by 2 push-pull cables, in this way it is easier to keep the leading edge perpendicular to the sliders. A force of approximately 4N is needed to actuate the system which is applied via a servo. The shape of the airfoil is guaranteed by using balsa wooden covers for the upper as well as for the lower surfaces as can be seen in figure 6. The balsa wooden cover of the airfoil is guided by a “bridge” type guidance, in this way suppressing flapping of the cover.

Figure 6: balsa wooden cover partly retracted

This concept has some advantages and disadvantages:

Advantages
1) The damage can be chosen from and undamaged wing up to 15 times 12 cm
2) The size of the damage is adjustable in flight
3) The weight of the construction is very low (about 60 gr.)
4) The shift in CG when moving the bar is negligible

Disadvantages
1) Although the weight addition is small, trim is needed
2) The damage occurs quasi instantaneous and not instantaneously which is not realistic

Results of the prototype wing

With the prototype wing done, tests are performed with the fully covered wing. All presented results are fitted data. In figure 7 (Appendix A), one can see the average deflection of the c/4 point against the applied force. Three different wings are plotted. All wings show hysteresis due to strain hardening. The undamaged foam wing has a deflection equal to the covered wings when the applied force is low. For larger forces, the covered wing shows smaller deflections compared to the foam wing. This is probably due to the “bridge type” guidance as can be seen in figure 6. It provides resistance against bending at the most effective location, being the furthest away from the bending axis. The undamaged wing with a full cover shows more resistance to bending as the damaged one. The difference in deflection (and therewith the bending stiffness) of the covered wings is about 10 %. The safety factor in bending is about 3. In figure 8 (Appendix A), one can see the averaged deflection of the left endpoint of the wing against the applied torque. Again all wings show hysteresis, except for the damaged wing with full cover which is tested with increasing weight only. The undamaged foam wing shows a larger resistance to torsion than the undamaged covered wing, probably because of the solid wing structure. The damaged foam wing has a stronger resistance to torsion than the undamaged wing which is unexpected and not realistic. To simulate a more realistic wing and damage, a wing such as applied to the Yardstik could be used, having 2 spars and some joists.

6. Wind tunnel tests

The wind tunnel tests have been performed in the closed return wind tunnel. The measurement section has dimensions (w x h) of 1.20 m times 90 cm, so no scaling is needed when only 1 part of the wing is tested with a span of 55 cm. Because the wing is too small to house the sting in, an intermediate body has been designed to fix the wing to the sting measurement device. Corrections have been made for the additional moments due to the offset in z- and x-axis. In
figure 9, one can see the wing mounted in the tunnel.

Figure 9: wing on sting intermediate body

All three forces and three moments are measured, but only the lift and drag force and pitching moment are used in this research. The tests are performed at 10 m/s, unless stated otherwise. The forces are presented in wind tunnel coordinates, that is lift positive upwards and drag positive with the direction of flow. The AOA is measured with intermediate steps of approximately 1 degree unless stated otherwise and had to be adjusted manually.

Calibration

Calibration of the sting measurement device has been performed using weights. The results from this calibration can be seen in table 1.

<table>
<thead>
<tr>
<th>Measured quantity [-]</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag force</td>
<td>11</td>
</tr>
<tr>
<td>Transverse force</td>
<td>4</td>
</tr>
<tr>
<td>Lift force</td>
<td>9</td>
</tr>
<tr>
<td>Roll moment</td>
<td>6</td>
</tr>
<tr>
<td>Pitching moment</td>
<td>20</td>
</tr>
<tr>
<td>Yaw moment</td>
<td>9</td>
</tr>
</tbody>
</table>

From table 1, one can see that especially the measured drag force and pitching moment show large deviations from the expected values. This has to be kept in mind when analyzing the results of the wind tunnel tests.

Measurements

Three different types of wings are tested:
1) A wing where holes are cut out of (as can be seen in figure 1)
2) A wing with moving leading edge and a top cover only (as can be seen in figure 9)
3) A wing with a moving leading edge and both upper and lower surfaces covered

The three configurations will be discussed in the following. All presented results are data fits.

6.1 Wing with cut-outs

In order to make a comparison between different covers, the foam wing with cut-outs is tested also. The AOA sweep is from 0 up to 20 degrees. In figure 10, one can see the coefficient of lift (CL, which is the lift force normalized with the dynamic pressure) plotted against the AOA. For clarity, only 4 damaged configurations are plotted. The errorbars represent the error in the lift as measured during calibration. For small damages, the lift increases slightly compared to the undamaged wing (in blue). This can be explained by the influence of the sharp edge which induces a vortex, thereby creating extra suction and therefore extra lift. The effect disappears for larger damage sizes. However, the errorbars of the undamaged and the 4.5 times 7.5 cm damage coincide, which makes it hard to draw an exact conclusion. Furthermore, it appears that the stall AOA of the undamaged wing is at about 13 degrees, whereas for larger damages it shifts to about 15 degrees. An explanation for this might be that the vortex through the hole helps to attach the flow to the wing, thereby increasing the stall AOA. This effect has been observed in [1] also. In figure 11, one can see the coefficient of lift against the CD (or the coefficient of drag, the drag force normalized with the dynamic pressure). From this measurement one can see that the increase in lift of the 4.5 times 7.5 cm damage is significant compared to the undamaged case. The larger the damage becomes, the more drag is generated for the same amount of lift. For very large damage sizes, the decrease of lift and increase of drag is not significant anymore. The airfoil has lost about 40 % of its lift at the highest lift point already, because the wing area is cut out beyond the c/4 point, thereby reducing its lifting capacity. The pitching moment against the AOA can be seen in figure 12. In blue, the undamaged wing is plotted. The pitching moment up to 10 degrees AOA is a straight line. After 10 degrees it drops radically, which probably has to do with L.E. stall, although it occurs earlier than the drop in lift. The drop in pitching moment has been observed in [1] also. With increasing damage size, the pitching moment becomes more negative as one would expect. This effect is due to the lack of surface in front of the Mean Aerodynamic Center (MAC). However, for damage sizes of 3 times 5 inches and upwards, the negative tendency of the pitching moment is lower. Furthermore, the drop in pitching moment for AOA larger than 12 degrees is less radical as in the undamaged case. It might be possible that the flow through the larger damages induces attached flow, thereby decreasing the negative pitching moment. Furthermore, the flow will partly blow straight through the hole, thereby not “feeling” the airfoil.
6.2 Wing with top cover only
The second set of tests is performed using a wing with a moving leading edge bar as can be seen in figure 5. The AOA sweep is from -5 up to 20 degrees, which makes it possible to see the zero-lift AOA. Now, the damage is always about 6 inches wide because of the slider mechanism, but the chordwise “depth” of the hole can be adjusted from 0 up to about 12 cm. In this test, this depth is adjusted in steps of about 3 cm. In figure 13, the lift force (or LF) is plotted against the AOA. It is apparent that for low AOA up to about 8 degrees, the lift does not change more than 10 percent when comparing the undamaged to the 9 times 15 cm case. There might be two reasons for this:

1) The shape of the airfoil with increasing damage changes. This leads to a changing performance of the airfoil
2) The shape of the pocket underneath the over-cambered wing might lead to extra suction and therefore to more lift

For AOA larger than 8 degrees, the first damage size of about 3 times 15 cm shows an increase in lift compared to the undamaged wing. Only the largest damage size of 12 times 15 cm shows a significant drop in lift compared to the other damage sizes. The zero-lift-AOA of the undamaged wing lies about - 2.7 degrees, whereas the zero-lift-AOA of the damaged wings lies in between -1.9 and -2.2 degrees, but close to each other. However, in figure 14, where the lift force is plotted against the drag force, one can see that the increase in lift comes with a drag penalty.

For the damage size of 3 times 15 cm, the increase in lift lies in between AOA of 8 up to 14 degrees. Above this value, the undamaged wing has the larger lift for the same drag. For AOA of 17 and higher, the lift of the undamaged wing is lower than that of the first damaged one. This is strange because it is expected that stall would occur here. There seems to be a flaw in the sting measurement device. In figure 15, one can see the pitching moment against the AOA. Now, the undamaged wing has a negative slope, where the pitching moment decreases with larger AOA. The pitching moment of the undamaged wing is a straight and level line and has a more negative value compared to the wing with the top cover only. One can say that the restoring moment of the over-cambered wing is smaller than that of the wing with cut-outs. The stall AOA seems to be shifted to a larger value compared to the wing with cut-outs, from 10 to 13 degrees. Again, with increasing damage size, the pitching moment becomes more negative, which is the result of lack of area in front of the MAC. The same applies to the less negative pitching moment with negative AOA. For AOA higher than 15 degrees, the value of the pitching moment lies in between that of the undamaged wing and the 3 times 15 cm damage.

6.3 Wing with both sides covered
The third set of tests is performed with a moving leading edge, now with the upper as well as the lower side of the wing covered. The AOA sweep is in between -5 and 25 degrees. In figure 16, one can see the LF against the AOA. In blue the undamaged wing is plotted with an obvious stall AOA, at about 15 degrees. This stall AOA is again higher than the angle for the other two airfoils. This effect is unexpected, but probably has to do with the slightly different shape of the airfoil due to the balsa wooden cover. With increasing damage, the lift does not drop significantly for AOA up to 7 degrees. This might have to do with the changing airfoil shape of the “damage”. For AOA larger than 7 degrees, the lift drops with approximately 20 percent compared to the undamaged wing. This relatively small effect can be explained by a jet effect from the flow through the damage. The flow remains attached to the wing for higher AOA, even when normally stall would occur, thereby increasing the lift. However, for the smaller damages up to 9 times 15 cm, the stall AOA vanishes which is strange. Only the largest damage of 12 times 15 cm shows a large and significant drop in lift compared to the undamaged wing. It might be possible that the jet effect vanishes because of the large damage and the flow becomes turbulent at lower AOA and L.E. stall occurs. The zero-lift-AOA of the configurations now is more equally spaced, ranging from -1.6 up to -2 degrees. However this value does not shift with equal amounts for increasing damage size. In figure 17, the LF is plotted against the DF. In blue, the undamaged wing is plotted. It shows the largest lift for the lowest drag force. Again, the larger the damage size, the lower the generated lift force. However, especially for the smaller damage sizes of 3 times 15 and 6 times 15 cm, the difference in performance up to about 15 degrees AOA is small. All the lift to drag curves have an optimum, which is a peak in the lift force for a low value of the drag. This peak is absent only for the largest damage. What is striking is that the performance of the wing with different damage size is asymptotical for the smallest lift and drag and the largest lift and drag. The increase in lift for very large AOA and drag forces can not be explained and is against common sense. This might again be a flaw in the measurement device. The general trend however, is a decrease in lift with an increase in drag for larger damage sizes, which is exactly as one would expect. In figure 18 one can see the pitching moment against the AOA. The pitching moment of the undamaged wing is indifferent...
with increasing AOA up to 11 degrees after which it drops. With increasing damage size, the pitching moment becomes more negative. For damage sizes extending beyond the MAC, for high AOA, the pitching moment becomes less negative. This is because of the lack of area in front of the MAC. However this does not fully apply to the 9 times 15 cm damage. For very low AOA, the pitching moment becomes less negative for the same reason as mentioned before. Furthermore, for very high AOA, the pitching moments reach an asymptotic value, except for the undamaged case which remains constant.

After the three different types of tests, the wing with the upper as well as the lower side covered was used for further testing. This wing was chosen because of the adjustable damage and because it shows a significant drop in lift coefficient and increase in drag with larger damage sizes. Furthermore, the pitching moment becomes more negative with increasing damage size and less negative when the damage comes beyond the MAC. This is what one would expect. It is expected that the forward velocity of the aircraft changes when damage occurs, because of the change in trim AOA and the difference in lift and drag force. Therefore, tests were performed at 6, 10 and 14 m/s, for which the lift and drag force as well as the pitching moment were measured. The AOA sweep is from -5 up to 25 degrees with intermediate steps of 5 degrees. In figure 19 one can see the lift force against the AOA. What is very apparent is that the undamaged wing has an obvious maximum in the generated lift at about 15 degrees AOA. For the damaged configuration, there does not seem to be a point where the wing stalls, which is very strange. A possible explanation for this is that the flow through the hole helps to keep the flow over the wing attached to it, thereby increasing the stall AOA. The lift force generated by the wing increases with increasing velocity. However, the lift is not proportional to the square of the velocity, but increases with a factor of 2 when the 10 and 6 m/s case is compared and with a factor of 1.7 for the 14 and 10 m/s case, both at an AOA of 15 degrees. The expected factors are 2.77 for the 10 and 6 m/s case and 1.96 for the 14 and 10 m/s case. For higher Re-numbers, the airfoil becomes less efficient. Furthermore, the damaged wing provides less lift for the same AOA as the undamaged wing as one would expect. Also, the zero-AOA shifts in between -0.2 and -2.6 degrees. In figure 20, the lift- is plotted against the drag force. The undamaged and damaged wings show the same trend for different airspeeds. The undamaged wing generates lift quite efficiently, having a low drag. The larger the airspeed becomes the more the 6 m/s LF-DF plot “blows up”, generating more lift with more drag as a penalty. The L/D ratio at maximum lift is 6.1, 4.3 and 6.2 for 6, 10 and 14 m/s respectively. The drop in L/D ratio for 14 m/s is unexplained. The damaged wing shows a different trend, following some kind of square root function, not having an obvious stall point. The generated lift by the damaged wing is lower than that of the undamaged wing as one would expect, also for very low or negative AOA. Asymptotically, the lines of the damaged and undamaged wing follow the same trend, but only for very high or very low AOA. In figure 21, the pitching moment is plotted against the AOA. The pitching moment of the undamaged wing at different airspeeds is almost a straight and level line right up to the stall AOA of about 12 degrees. Furthermore, the pitching moment becomes more negative with increasing airspeed as one would expect. The pitching moment for the damaged wing has a negative slope and flattens out a bit for high AOA due to the area in front of the MAC which makes the moment less negative. For the same reason, the pitching moment is less negative for negative or small positive AOA.

7. Simulink model
The results of the wind tunnel tests at different airspeeds of 6, 10 and 14 m/s with the full covered wing were used in a Simulink model. This Simulink model describes the longitudinal motion of the UAV. The model has three degrees of freedom (DOF), being the translation in x- and z direction and the rotation around the y-axis of the airplane. The states are x, z and q. The equations of motion in aircraft body coordinates (ABC) used in this research are the following:

\[ \dot{u} = -w \theta - g \sin \theta - \frac{D_u + D_{elev} - F_{thrust}}{m} \]  
\[ \dot{w} = u \dot{\theta} + g \cos \theta + \frac{L_u + L_{elev}}{m} \]  
\[ \dot{\theta} = \frac{1}{I_z} \left( L_u - l_c L_{elev} - c \theta \right) \]

The lift- and drag force and the pitching moment have been stored in a 3-D look up table. These values are a function of AOA, airspeed and damage (undamaged or full damage 6 times 4.5 inches). Damage is applied to the right wing only, but this effect is averaged over the wings because no lateral motion is taken into account. The elevator is taken as a control input to control the angular pitch rate to zero. Furthermore, the thrust and damping ratio were taken as free parameters. In figure 22, one can see the Simulink model. It consists of 6 blocks in which different values are
calculated. Unfortunately, there was not enough time to complete the model, so no simulations have been done. In the future will be possible to evaluate and expand the 3 DOF model to a 6 DOF model. For this expansion, measurements can be used of all the forces and moments which have been done, but are not used in this research.

Conclusions and recommendations

Conclusions

In this research, the effect of damage on wings has been investigated. There has been focused on structural as well as aerodynamical effects of damage. From previous studies, flight tests and bending and torsion tests, a maximum damage size has been chosen, which is implemented in a prototype wing. This wing exists of a leading edge bar which can be actuated by a servo. By covering the upper and lower side of the wing with balsa wooden sheets, a wing with retractable damage is made. The damage size can be adjusted in flight, from the undamaged wing to the full damage of 15 times 12 cm. Wind tunnel tests have been performed with three different wings; one with cut-outs, one with only the upper surface covered and one with the upper and lower surfaces covered. The tests as described below were performed at 10 m/s, unless stated otherwise. It showed that the wing with cut-outs has a better L/D ratio when small damages of 4.5 times 7.5 cm are applied (figure 11), compared to the undamaged wing. This is probably due to a vortex which is generated by the upper sharp edge of the damage. This vortex induces suction at the upper surface of the wing, thereby increasing the lift. For the wing with a top cover only, the stall AOA was not always obvious anymore, which can be caused by a jet-effect helping to attach the flow further downstream, thereby increasing the stall AOA (figure 13). The top covered wing showed an increase in lift without a drag penalty for AOA in between 8 and 14 degrees (figure 14). The changing airfoil shape as well as the pocket underneath the wing can induce this effect. Furthermore, from figure 15, it is apparent that the pitching moments shows a negative slope compared to the wing with cut-outs, thereby increasing its restoring moment with increasing AOA. From figure 16, one can see that with increasing damage, the lift of the airfoil drops and the drag increases, as one would expect. However, the difference in between the small damages not significant. Also its stall AOA is larger compared to the other 2 wings, which probably has to do with the different shape of the airfoil. The pitching moments of the full covered wing (figure 18), are less negative but show a level and straight line for the undamaged wing. For larger damages, this line becomes negative, so the restoring moment for larger AOA becomes larger also. Measurements have been performed to use in the Simulink model. Three different airspeeds of 6,10 and 14 m/s are used. In figure 19, one can see the lift force of the undamaged and 15 times 12 cm damaged wing with full cover. It is apparent that the stall AOA of the damaged wing is not clear anymore which probably has to do with a flaw in the measurement device which showed deviations up to 20 % in expected and measured values during calibration. The damaged wings show less lift-for a larger drag force as one would expect as one can see in figure 20. Furthermore, the pitching moment of the undamaged wings is always a straight line up to the stall AOA, whereas the damaged wings have a negative slope with larger AOA. These measurements have been used in a Simulink model as can be seen in figure 22, describing the longitudinal dynamics of the UAV with parameters x,z and q to describe the forward- and upward velocity as well as the rotation around the y-axis. A 3-D lookup table stores the lift- and drag force and the pitching moment, which are a function of AOA, airspeed and applied damage. Due to a lack of time, no simulations have been performed with this model.

Recommendations

For further research, some recommendations are given:

1) Use a wing as on the Yardstik. It exists of different spars and joists, having a realistic aircraft like wing layout. In this way it will be easier to see the structural effect of damage at the wing
2) Increase the radius of the push-pull cable; in this way it is possible to reduce the friction of the inner- and the outer cable. Than, the servo has to provide less power and the damage can be applied faster
3) Use the wing with cut-outs or with the top covered. Those wings can provide more lift without a drag penalty for curtain AOA.
4) Calibrate the sting measurement device
5) Build a 6 DOF model with all measurements of all forces and moments included to get a more realistic picture of the motion of the aircraft

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About the author
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References
Appendix A

Figure 3: bending test on undamaged foam wing

Figure 4: torsion test on undamaged foam wing

Figure 7: bending tests on foam and covered wings

Figure 8: torsion test on foam and covered wings

Figure 10: CL against AOA of wing with cut-outs, 10 m/s

Figure 11: CL against CD wing with cut-outs, 10 m/s

Figure 12: PM against AOA, wing with cut-outs, 10 m/s

Figure 13: LF against AOA, top covered wing, 10 m/s
Figure 22: Longitudinal model of the flight dynamics of the Slowstick