PREVENTION OF RETREATING BLADE STALL BY ASYMMETRICALLY GENERATED LIFT: FREE-FLIGHT INVESTIGATIONS WITH A FULLY AUTONOMOUS HELICOPTER TESTBED

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1. Abstract

Helicopters in forward flight experience highly asymmetrical flow conditions. While transonic effects on the advancing side of the rotor are responsible for a high generation of drag and noise, the retreating side operates in low-speed flow at high angles of attack, close to dynamic stall. This inherent aerodynamic dissymmetry of the main rotor could be counteracted with the intentional generation of asymmetrical lift on the fuselage. To gather more information about the effects of asymmetrical lift and their consequences for the rotor, a UAV helicopter testbed was developed and equipped with a four-axis autopilot system, which enables it to perform fully autonomous flights using GPS waypoints. As a result, the measurements can be conducted in precisely defined flight conditions which can be maintained over long periods of time. Consequently, the averaged data reach a very high level of accuracy that could not be achieved with conventional, manually controlled systems. Successful tuning of the PID loops and other controller parameters for low and high-speed flight (up to 125 km/h fully autonomous cruise flight) was conducted. A remotely adjustable horizontal stabilizer was used to investigate different situations of asymmetric lift. Due to gyroscopic effects of the rotor, a phase shift has to be taken into account, which means that the lift should not be produced directly on the retreating side. The results prove that asymmetrically generated lift can indeed counteract and even overcompensate for the natural rotor asymmetry of a helicopter in forward flight. The retreating blade operates at significantly lower angles of attack, leaving a greater margin to dynamic stall, which allows for lower rotor speeds and therefore resolves the transonic problems of manned helicopters on the advancing side. As a result, either higher flight speeds or lower fuel consumption and noise emissions (eliminated HSI noise) can be achieved.

2. Introduction

Retreating blade stall (RBS) is one of the most limiting factors in helicopter aerodynamics[1,2,3,4,5,6]. In forward flight the main rotor experiences very uneven flow conditions[3]. On the advancing side, the flight speed increases the relative airspeed of the blades, while it has a decreasing effect on the retreating side. This leads to a rotor asymmetry, which is an inherent characteristic of every helicopter rotor. The tips of the advancing side operate in high-speed up to transonic flow conditions[1], whereas the retreating side barely generates enough lift to keep the helicopter balanced[5]. If the flight speed is further increased, the situation worsens: The constant change between high-speed aerodynamics and subsonic flow generates high and possibly destructive torsional loads on the blades and mechanical shocks transferred to the control rods. Meanwhile, the retreating side experiences severe dynamic stall effects[7,8,9], leading to an uncontrollable pitch up movement of the helicopter and roll reaction towards the retreating side[3,5] in combination with high vibratory loads and mechanical stresses[2].

These effects constitute a major limitation of the flight envelope[10] of most helicopters and are responsible for the predominant noise source in fast forward flight, the high-speed impulsive (HSI) noise[11]. Additionally, the speed of the advancing blades is unnecessarily high compared to the required lift on that side, which generates a high amount of drag and leads to a very uneven distribution of angle of attack (AoA) over the rotor, which further decreases the overall rotor efficiency.

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A possible solution for these problems is the compound helicopter[12]: A wing added to the fuselage unloads the main rotor in high-speed flight[13], which results in a reduction of the high angles of attack and therefore a shift of the dynamic stall effects towards higher flight speeds. This means that the rotor can be slowed down[14], which also remedies the transonic issues on the advancing side. These advantages come at the cost of a higher aircraft weight, reduced hover efficiency due to the wings being installed in the downwash of the main rotor and a reduced maneuverability because of the higher moments of inertia.

In forward flight, the wings of a compound helicopter lead to a homogeneous unloading of the main rotor. However, except for a small region on the retreating side, where the effective AoA exceeds the stall limit, the rotor does not need to be unloaded. In fact, rotor efficiency is reduced by unloading the advancing side. Due to the high dynamic pressure, the blades operate at very low angles of attack to generate the necessary amount of lift for that side. Since most blades are twisted, the tip regions of a conventional helicopter can even reach negative angles of attack in a stationary horizontal flight, as Figure 1 shows. Depending on the blade profile, parts of the rotor produce very low amounts of lift or even downforce.

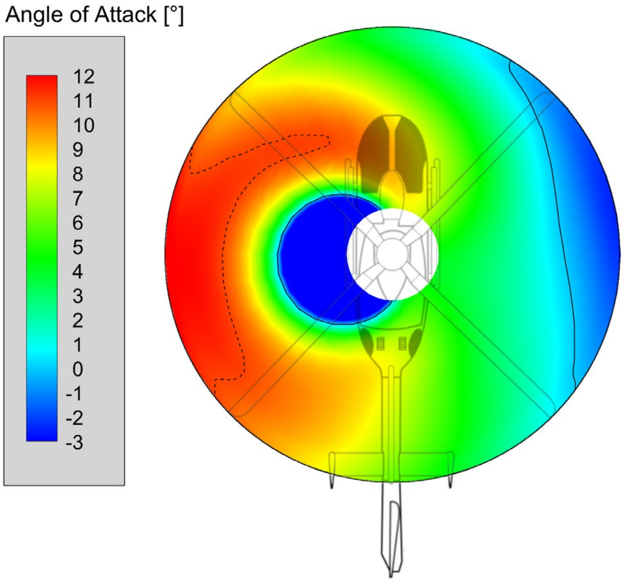


Figure 1: CAMRAD II analysis of the AoA distribution of a light utility helicopter at v_{NE}. The solid line is placed at 0 degrees, the dashed line at 11. The tip region of the advancing side operates at negative angles of attack, yet still produces the highest amounts of drag and noise due to transonic effects. The dark blue area on the left is caused by airflow reversal.

If the rotor is unloaded homogeneously by additional wings, blade pitch is further reduced, and the negative lift parts of the rotor grow. Nevertheless, drag is still present in these regions and the downforce has to be counteracted with additional lift in other parts of the rotor.

To avoid these problems, the rotor could be unloaded exclusively in the critical regions of the retreating side. Thus, the modifications compared to a conventional helicopter would be much more minor with less additional weight, cost and download penalty in hover and slow flight conditions. Instead of adding two symmetrical wings, the lift would need to be generated asymmetrically on the fuselage to be able to counteract the natural rotor asymmetry of the helicopter. Due to gyroscopic effects of the rotor, a single wing on one side of the helicopter does not lead to an unloading of the blades in the desired position. Depending on the phase shift of the particular rotor system, the asymmetrical lift needs to be generated in a position between the retreating side and the tail of the helicopter. Accordingly, the AoA distribution over the rotor can be equalized ideally, which eliminates dynamic stall issues, allows for an RPM reduction of the rotor and finally results in an extended flight envelope, reduced noise (HSI share) and increased efficiency.

3. UAV Helicopter Testbed

To investigate the effects of asymmetrically generated lift and their impacts on the rotor condition, control inputs, stability and the complete helicopter system under real flight conditions, a UAV testbed was built. With an unmanned system it is possible to identify potential problems in a very early stage of development and gather flight data of new configurations without having the costs, risk or approval issues that come with manned aircraft flight experiments. The major drawback is that it is very difficult to generate reproducible flight conditions with a remotely piloted aircraft, which is crucial for conclusive comparisons of any kind.

To solve this issue, a four-axis autopilot system was integrated into the UAV, which enables it to follow predefined flight paths using GPS coordinates and given speed profiles. For multirotor aircraft such capabilities are already quite common, but for single main rotor, collective/cyclic pitch controlled helicopters tasks like vibration damping and especially PID tuning are very sensitive and quite challenging, which is why the helicopter is one of the first measuring systems of this kind. Conventional stabilization systems like mechanical flybars or the more modern electronic flybarless systems were intentionally not used to avoid control inputs that are not part of the data logging system. All stabilization tasks run in the autopilot and are logged at high resolution for flight analysis. The basic structure of the UAV testbed is shown in Appendix A. The helicopter is based on an Align T-Rex 800 with a Pixhawk 2.1 Cube Black flight controller running a modified version of ArduPilot. As it is a precisely adjusted and calibrated system, safety is still a concern. For this reason, important electrical components are double or even triple redundant. One example is the power supply for the flight controller, which is fed out of three different batteries and can tolerate an internal short circuit in any of these power sources. In this case, the defective battery is switched out of the system to isolate the failure and to prevent a voltage breakdown in the flight controller.

4. PID Tuning

To achieve a good controllability of the aircraft for both the pilot and the autopilot, the PID controllers of the flight controller need to be tuned carefully. The basic internal structure of the flight controller can be seen in Appendix B. The abbreviations printed in red are the parameters that need to be adjusted to achieve the desired flight characteristics. Figure 2 shows the dynamic flight behavior of the UAV in a fully autonomous flight profile after successful PID tuning.

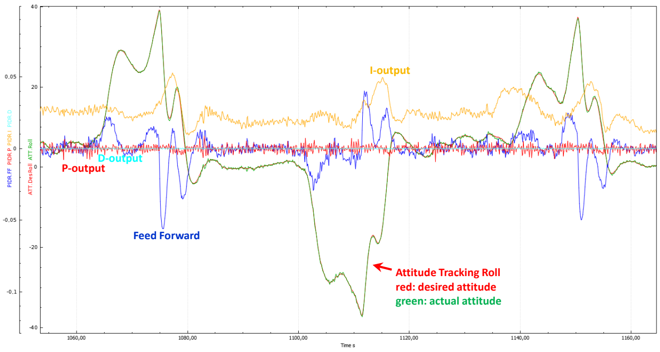


Figure 2: Attitude tracking around the roll axis in an autonomous flight mission after successful PID tuning. The actual attitude (green) is almost identical with the desired attitude (red), both plotted in degrees. The control inputs generated by the autopilot are also shown, split up into P, I and D components.

The actual and desired roll attitude are almost identical. The plot also shows the composition of the control inputs generated by the autopilot. It can be noticed that the commanded attitude changes are executed almost exclusively via feed forward commands. The precise adjustment of the feed forward loop is an important step to achieve a good attitude tracking since it does not tend to induce oscillations like increasing the P or I value would do. Therefore, all intentional attitude changes can be executed precisely with FF commands, which reduces the amplitudes in the PID loop and leaves it with the task of compensating for external disturbances. Consequently, the PID loop itself can be tuned more aggressively without experiencing oscillation issues. As a result, the aircraft can achieve a more agile and crisp control response.

5. Modification

The UAV was modified to generate asymmetrical lift that is located in the tail section. Since the rotor is influenced by gyroscopic effects, phase shift has to be taken into account. For teetering rotors – even if they have a very rigid connection to the rotor head and fuselage like in most model helicopters – the phase shift is exactly 90 degrees, which means that lift needs to be generated in the tail region to unload the retreating blade. For this reason, a custom tail unit was added to the UAV. The horizontal stabilizer is equipped with a NACA 2415 profile in positive-lift configuration. The whole surface can be adjusted in tilt angle between -5 and +33 degrees during flight to be able to investigate very different lift situations. The modified tail can be seen in Figure 3.

Figure 3: UAV testbed with modified tail section. Due to the phase shift of the rotor, a side mounted wing does not lead to the desired unloading of the retreating blade.

6. Phase Shift

Because of the gyroscopic effects of every helicopter rotor, a force acting on a rotor blade does not immediately rotate the fuselage in the corresponding direction. Instead, there is an angle difference between the control input and the reaction of the fuselage. The azimuthal angle between the position where the blade reaches its highest setting angle due to the cyclic input and the direction in which the rotor starts to tilt (with or without the fuselage) is called the phase shift. For the measuring helicopter the phase shift is 90 degrees. That means that, for example, an increase of the blade angle in the 90-degree position and a decrease in the 270-degree position leads to a pitch up movement of the helicopter. This effect is well known and already integrated into the controls. For the same reason, the modification is installed in the tail section of the helicopter: The desired control input to avoid dynamic stall issues is a reduction of the blade angle on the retreating side (270°). However, the resulting pitch-up movement has to be prevented to maintain a constant forward flight. The initial thought was that the pitch-up can be inhibited with additional lift in the tail section. Unfortunately, this turned out to be not correct because of more complex effects regarding the phase shift that were not understood by then:

Before the high-speed flights with the modified tail were conducted, a simplified test was performed – revealing very surprising results. The helicopter was held in a stationary hover with a weight added to the tail. The weight can be considered the same as negative lift in that case. The expected result was that the pilot would have to push the stick forward to compensate for the weight, which would have increased the blade angle in the 270-degree position. However, the stick needed to be pushed forward and to the right at about same amounts, increasing the blade angle around the 315-degree position. The averaged blade setting angles of this flight can be seen in Figure 4. Obviously, the phase shift was reduced to around 45 degrees for this situation. The test was repeated with another helicopter which had no data logging system, yet clearly showed the same effect regarding pilot inputs.

The reason for this unexpected behavior is that a hover flight with a weight on the tail is a static situation. The cyclic input does not lead to a rotational movement of the fuselage as usual and the rotor cannot be considered a free gyroscope anymore. The blade experiences an upward force in the 315-degree region, but as the fuselage does not follow the movement, it starts to push against the flapping feather/damper or even bend the blade. This creates a repelling force, which increases the natural flapping frequency of the blade (which is 1/rev. for a free resonant rotor). In other words, the blade reaches its highest point earlier, which is the point of maximum moment transfer to the hub. Consequently, the phase shift is reduced. The moment introduced into the hub exactly compensates for the moment produced by the weight on the tail. From this it can be deduced that the blade in the experiment reached its highest point exactly in the 360-degree position, where the weight was installed, although there was no visible tilt of the rotor due to the very stiff rotor head of this specific helicopter.

Despite the reduced phase shift in this test, normal control inputs (that lead to a rotational movement of the fuselage) still underlie the usual phase shift of 90 degrees at the same time. If the stick is pushed further forward, the blade angle in the 270-degree position is increased and the fuselage starts to tilt forward.

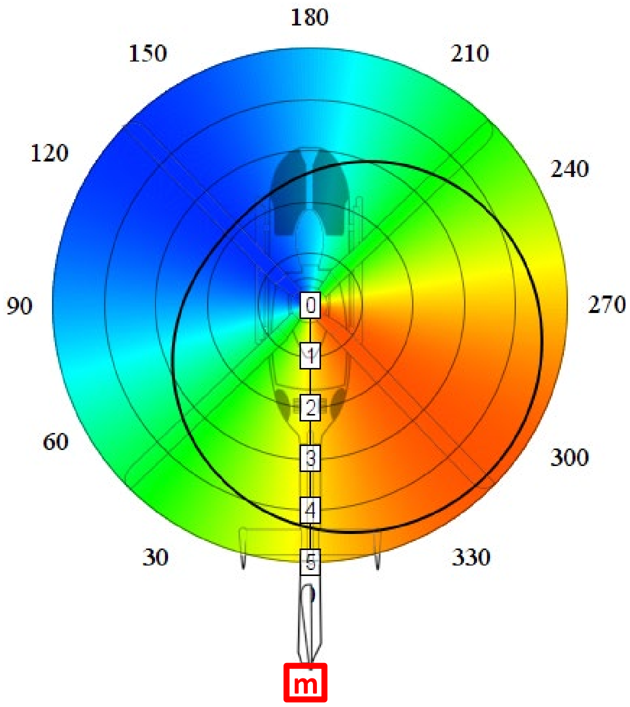


Figure 4: Blade setting angle (mechanical blade pitch regarding the rotor plane) of the UAV helicopter in a stationary hover with a weight added to the tail. 342 g were used with a distance of 1 m to the center of gravity, which is a very large weight imbalance for a helicopter of this size. The values are averaged over a time span of 37 seconds. The black polar chart line represents the setting angle in degrees for every azimuthal blade position and can be read off using the numbers of the corresponding circles. The color coding also reflects the blade setting angle.

Summarized, it can be said that the normal phase shift of the rotor for dynamic flight situations is different from the phase shift in situations where the control input is used to counteract static forces like weight imbalance, asymmetrically generated lift or mounting forces/moments in wind tunnel experiments. In these static cases (no evasive movement of the fuselage), the phase shift is reduced, depending on the rigidity of the rotor suspension and blade stiffness regarding the flapping motion. The reduction in phase shift for static situations could be observed in numerous flight tests as well as numerical rotor simulations. The latter were explicitly performed to gain a better understanding of the complex movement of the blades and the emergence of phase shift. As commercial simulation software has to be considered a black box, a custom simulation tool was written for this task, which was intentionally limited to the use of very fundamental equations. Despite of the simplicity of the tool, the measured effects could be clearly verified.

Although the placement of the lifting surface for the flight tests was not perfect, because the dynamic phase shift was used instead of the reduced phase shift for static situations, it turned out to be a sufficient starting point, resulting in an effective counteraction of the natural rotor asymmetry, as the flight tests show.

7. Calculation of Rotor Head Lever Movements

The flight controller is able to log all servo movements at high temporal and spatial resolution. Unfortunately, this does not directly match true blade setting angles because of the rotor head mechanics. A simple calibration that maps the given servo inputs to blade angles would be possible but does not provide high precision results. One reason is that the blade angles are highly dependent on the type of control input. Collective and cyclic inputs undergo different lever ratios and mixing. That can be seen in Figure 5: For a collective input, which shifts the swashplate up and down, the distance marked with “5” has no impact on the movement of the blade. A cyclic input, however, tilts the swashplate (plane “4”) around the center point at a constant vertical position. In that case, the distance of the ball link to the pivot point is important and reduces the servo input to around half of the value for collective inputs.

Another reason, not to use a simple calibration method, which would consider the whole rotor head assembly a black box, is that cyclic inputs depend on the collective position and vice versa. For example, the linkage point of the blade grip (“7”) is moving on a curved path, which means that the same vertical shift of the swashplate leads to various rotation angles of the blade grip at different swashplate heights.

Therefore, a tool was built to calculate the movements of all mechanical parts of the rotor head, swashplate and linkage rods as a result of the given control inputs in flight. The program also includes secondary effects like the changing tilt of the pitch links (“6”) due to the curved movement of the linkage point (“7”) of the blade grip arms, resulting in different effective (vertical) lengths of the lever.

Thus, the true blade setting angles can be determined with high precision without using sensors in the rotating system. There is no measurable freeplay or deformation in the mechanical parts of the rotor head due to tight ball links and high-grade aluminum parts. Only the servos themselves (“1”) have some freeplay due to their gear reduction, which adds up to around ± 0.1° at the blades.

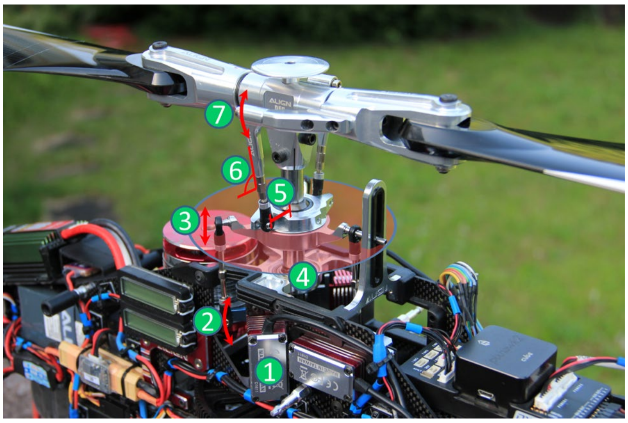


Figure 5: Rotor head mechanics of the UAV. The blade setting angle can be determined by the known positions of the three swashplate servos. Collective and cyclic inputs undergo different lever ratios and mixing.

8. Flight Test Results

The performed flight tests could demonstrate that asymmetrically generated lift can indeed effectively counteract the natural rotor asymmetry and reduce high blade angles on the retreating side. Figure 6 shows the blade setting angle for different amounts of tail lift, increasing from left to right. The plot on the right is the most homogeneous because it was flown with the highest stabilizer setting angle (14.9°), which still corresponds to a moderate effective angle (7.4°) due to the forward tilt of the helicopter. Stabilizer sweeps over the whole range showed that it is even possible to generate a state of strong overcompensation, meaning that the highest blade setting angles can be found on the advancing side of the rotor. Obviously, all blade angles are quite low, compared to manned helicopters, which is a result of the lower disc loading, yet the effects of asymmetric lift generation remain unchanged.

Furthermore, a slight efficiency improvement can be noticed in Figure 6 from left to right, despite the rotor speed stayed exactly the same. This is caused by the equalized AoA distribution, which results in a more efficient usage of the rotor on the advancing side. This cannot be directly seen in the plot, as it only shows the blade setting angle and not the effective inflow angle. However, the latter is of great interest, as it is the crucial factor for all aerodynamic effects like dynamic stall. The difference between these values is caused by the surrounding air meeting the blade at a certain angle e.g., due to the induced velocity, which is not in parallel with the blade path. The air flowing through the rotor from above reduces the effective angle of attack of the blade. The same effect can be noticed as a result of the flight speed in combination with the forward tilt of the helicopter, which generates a flow component perpendicular to the rotor plane. As the speed of the blade is highly dependent on the radial position, these effects have the greatest impact in the inner regions of the rotor, where the vertical component is not neglectable compared to the rotational speed.

For obvious reasons, the AoA distribution cannot be directly measured in the helicopter or in the rotor blades. However, with the known blade setting angles, speed of rotation for a given radial position, induced velocity, flight speed, forward tilt of the helicopter and a few less important parameters, it can be calculated. As the rotor head of the UAV is exceedingly stiff, blade flapping was neglected. Nevertheless, even if a soft blade suspension is assumed, this would not affect the measurements: The flapping motion leads to a tilt of the thrust vector of the rotor (also referred to as blowback), which

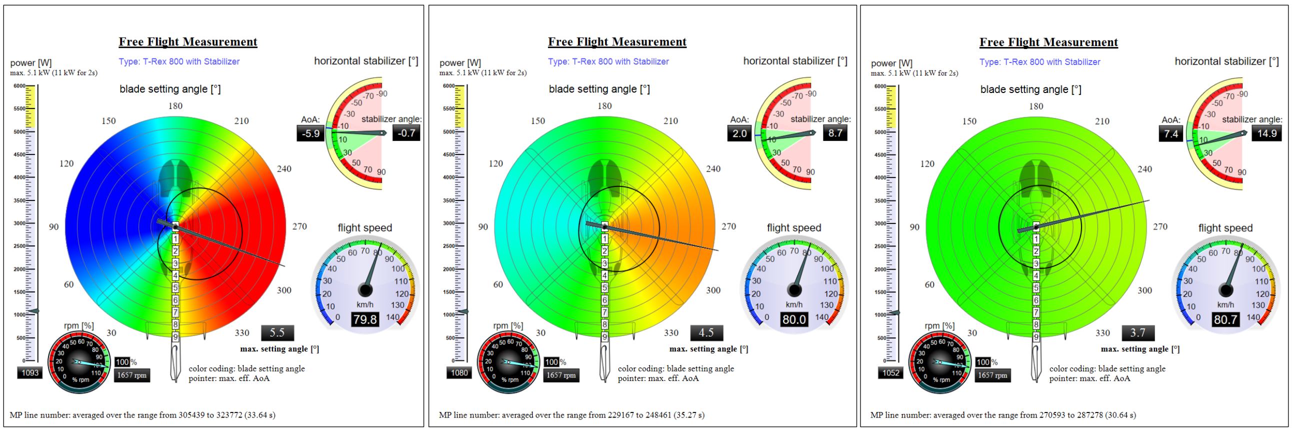


Figure 6: Blade setting angle (line and colors) for different amounts of tail lift, increasing from left to right. The true setting angle of the blades in degrees can be read off the black line of the polar chart for any azimuthal rotor position. All results are averaged for more than 30 seconds straight, horizontal flight at constant speed, governed by the autopilot.

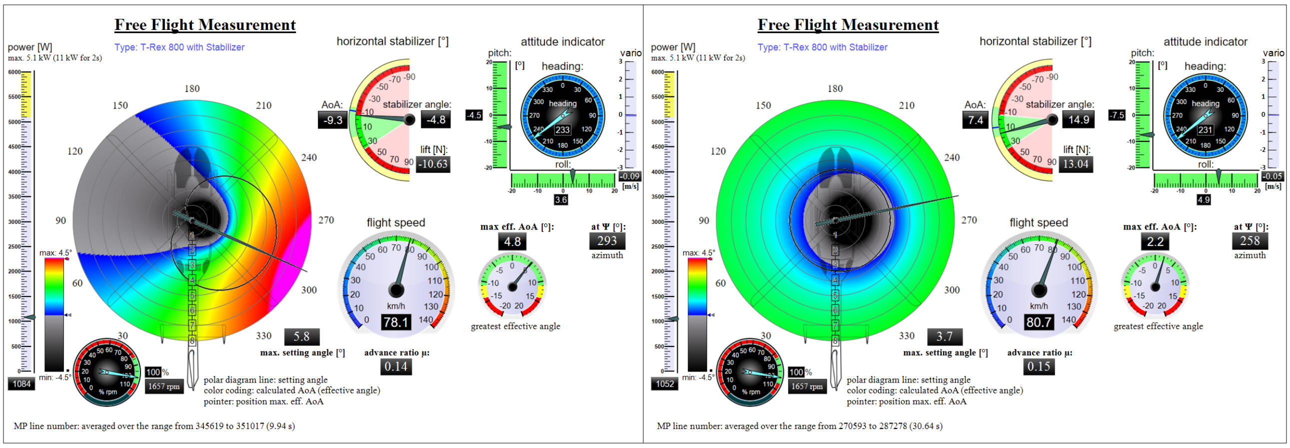
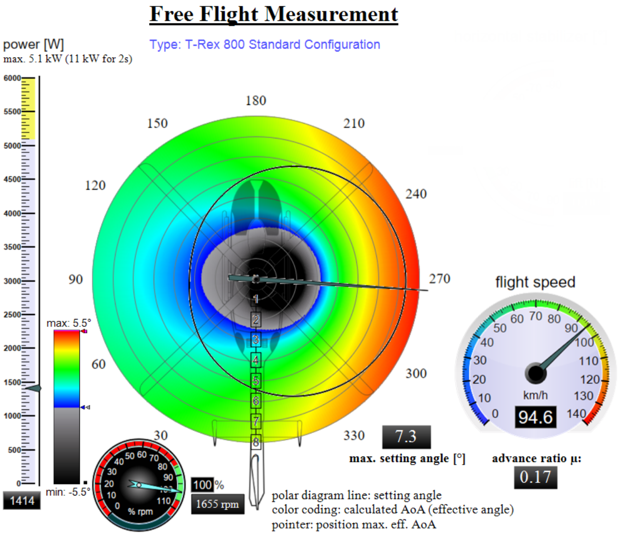


Figure 7: Effective AoA distribution of the UAV. The polar chart line shows the blade setting angle, while the colors reflect the effective AoA in this case. The double color scale is used to identify negative lift areas (gray/black) of the symmetric blade profile. The results were obtained in an autonomous, constant, horizontal flight.

slows the helicopter down. Because the autopilot is programmed to maintain a desired speed, it starts to increase the cyclic input until the thrust vector is tilted in the original direction, which means that all blade flapping has vanished. Thus, the measured setting angles maintain their validity in a stationary horizontal flight even with a very soft or completely free teetering rotor head.

The calculated effective blade angles can be seen in Figure 7. As a symmetric blade profile is used, all negative AoA regions (gray/black) produce negative lift. The deep black regions reflect very low angles of attack, caused by airflow reversal and the induced velocity meeting low rotor speeds. It can be observed that different stabilizer settings have a huge impact on the AoA distribution and can increase or decrease the rotor dissymmetry. A higher amount of tail-lift shifts the polar-chart line (setting angle) to the upper left corner, which also means a reduction of the high effective blade angles on the retreating side (pink areas). Simultaneously, the gray negative lift areas on the advancing side are reduced and moved to the lower right. As blade speed is low in the inner rotor regions and lift/downforce is proportional to the speed squared, negative effective blade angles have very little effect there which increases the rotor efficiency. The shift of the high blade angles on a line from the lower right to the upper left is caused by the reduced phase shift for static flight situations, described above. A perfectly placed lifting surface (at 315°) would shift the high blade angles on the retreating side (right) directly towards the advancing side (left). As the installation of a wing in this position might cause mechanical difficulties, it can be split up in two parts, a horizontal stabilizer and a side-mounted wing.

Figure 8 shows another flight of the UAV at higher speed without horizontal or vertical stabilizer. The color scale had to be slightly adjusted to show the whole range. The results are in good agreement with the Camrad II analysis of the manned helicopter in Figure 1. Please note the changed direction of rotation. The main differences are caused by the blades of the UAV not being twisted. Therefore, the low AoA regions of the manned helicopter are shifted towards the tip.



polar diagram line: setting angle
color coding: calculated AoA (effective angle)
pointer: position max. eff. AoA

MP line number: averaged over the range from 143366 to 152150 (17.62 s)

Figure 8: Effective blade angle without stabilizer.

It could be shown that purposefully deployed asymmetric lift leads to lower effective blade angles on the retreating side. As a result, the rotor speed can be reduced without provoking retreating blade stall. Figure 9 shows the efficiency improvement due to reduced rotor speed in cruise flight. Each measuring point reflects the averaged value of a straight horizontal flight at constant speed. The markers were split up into the two opposing flight directions to point out any directional effects like wind influence or compass inaccuracies. The result of a reduced power demand due to lower rotor speeds could be verified for full size helicopters with Camrad II simulations in different configurations with asymmetrical lift.

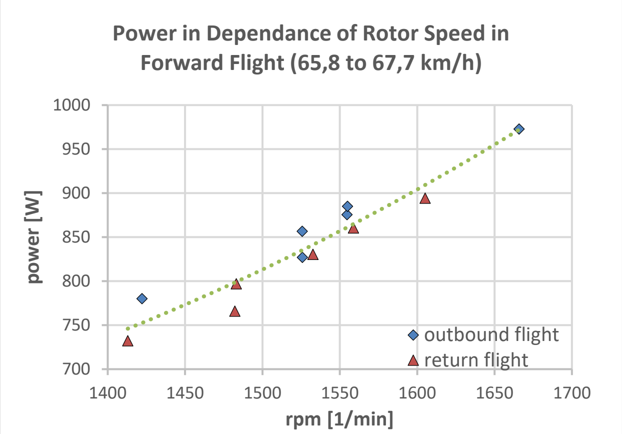


Figure 9: Power demand of the UAV in cruise flight at different rotor speeds.

9. Conclusions

To investigate the effects of asymmetrically generated lift for the main rotor, especially regarding retreating blade stall, a UAV helicopter testbed was developed and equipped with an autopilot system. The use of a flight controller for autonomous waypoint missions turned out to be a great improvement compared to conventional free flight experiments, because the measurements could be performed in precisely defined flight conditions and over long distances that could not be flown manually by a pilot on the ground. Compared to wind tunnel experiments an important advantage is that the phase shift of the rotor remains unchanged, which is not the case as soon as the helicopter is connected to a fixed mount anywhere in the wind tunnel. The UAV has proven to be a precise yet very cost-effective tool to gather flight data of new configurations in an early stage of development.

Intensive PID tuning was performed in low and high-speed flight to achieve an agile and precise control response. The blade setting angles could be obtained by calculating the movements of the mechanical parts of the rotor head in response to the given control inputs. With the aerodynamic parameters and flight trajectory, the effective AoA distribution of the rotor could be derived.

For the investigation of asymmetrical lift, an adjustable horizontal stabilizer was built. Later findings showed that the rotor phase shift for counteraction of static forces is different from the usual phase shift in dynamic situations. Although the positioning of the lifting surface was not perfect due to that reason, the results could clearly demonstrate that asymmetrically generated lift can counteract the natural rotor asymmetry of a helicopter in forward flight. It was even possible to achieve a stationary horizontal flight with the highest angle of attack on the advancing side of the rotor. That is very untypical for a helicopter and means, that all asymmetric effects resulting from the forward speed could be completely cancelled out by the tail lift. As a result of the reduced effective blade angles on the retreating side, the rotor speed can be lowered without provoking retreating blade stall. This leads to a reduced power demand for the UAV and full-size helicopters. The latter also benefit on the advancing side, as transonic problems like the generation of HSI noise are resolved. Alternatively, the flight speed can be increased.

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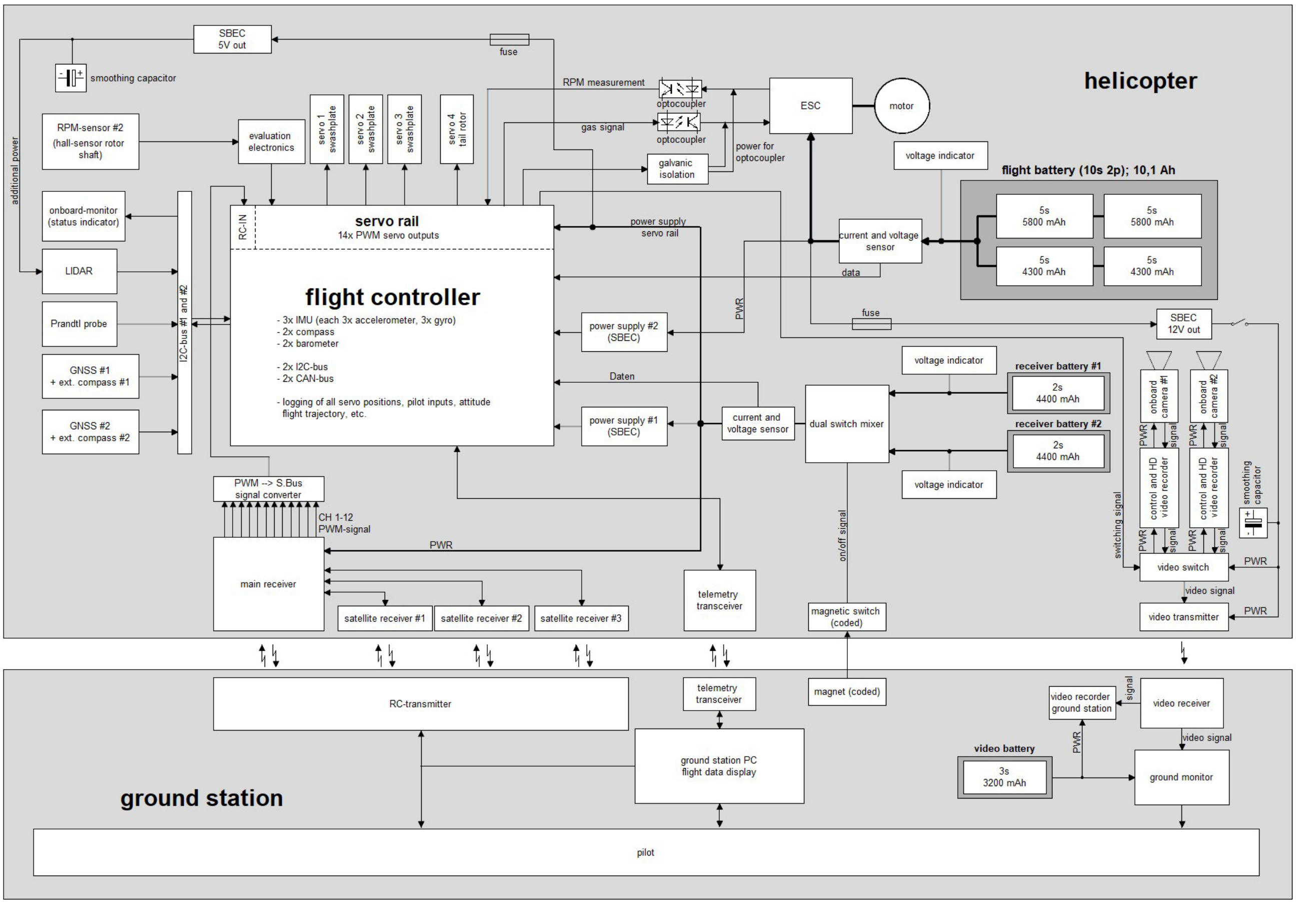
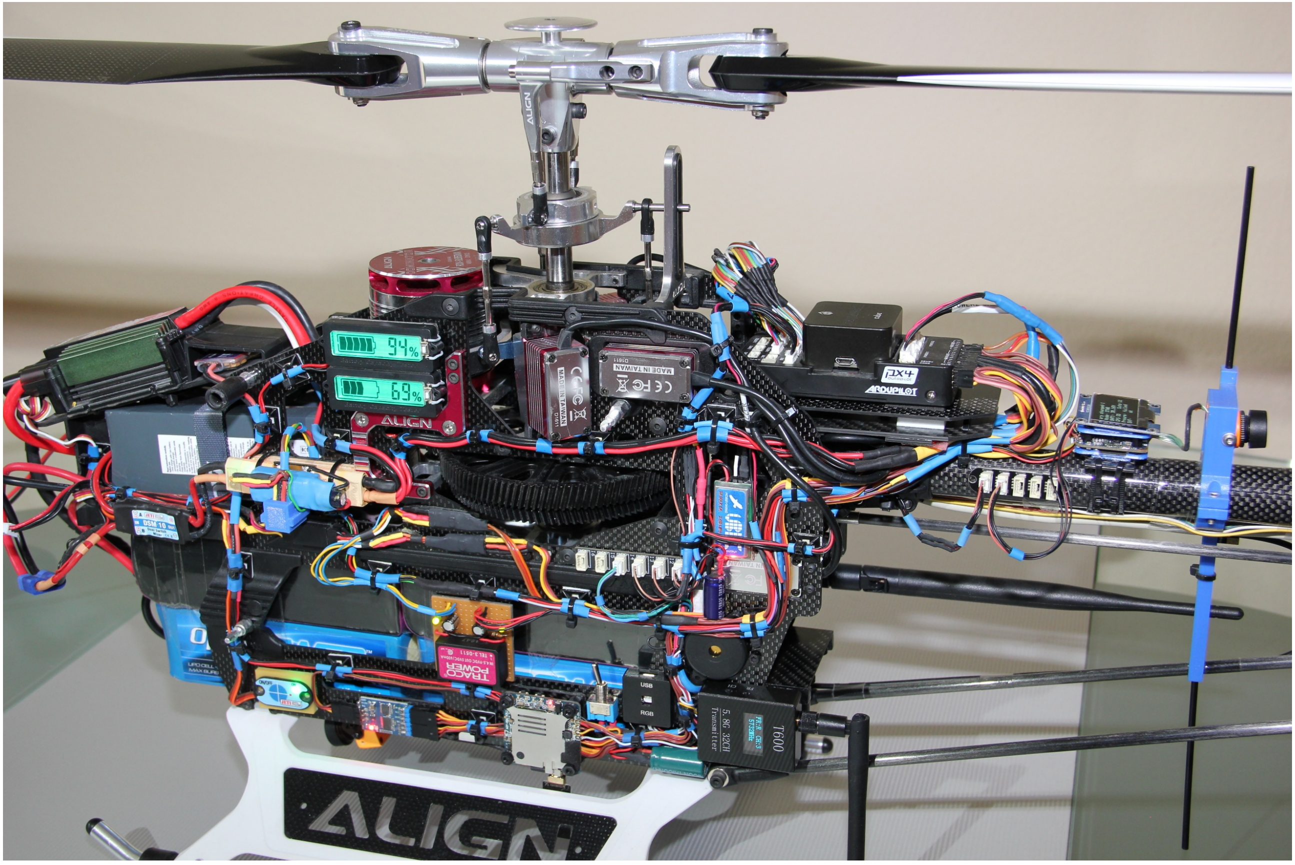
Appendix A. System Architecture of the UAV Helicopter Testbed





Appendix B. Working Principle and Control Parameters of the ArduPilot Flight Controller