On the Flight Test Campaign of a Coaxial Helicopter for the Development of an Unmanned Aerial System

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For the development of an unmanned version of an existing helicopter with a maximum takeoff weight of 600 kg and coaxial rotors, a manned flight test campaign is conducted in order to identify the flight physics characteristics of the basis helicopter. Furthermore, the intention of the campaign is to test the future avionics and flight control system which is serving as a measurement system in this campaign. This ensures to incorporate all inherent effects of the avionics system, including sensor dynamics and latencies, for the development of the flight controller of the future unmanned system. Additionally, the flight test campaign is used as a proof of functionality of the avionics system together with the data links under a real physical environment. This paper gives insights into the planning and considerations that went into the flight test campaign. As the identification of the model is performed in the time domain, the focus is set on square wave maneuvers. To identify a set of trim states for the dynamic maneuvers, a simulation study is conducted. At the identified maneuver points, the eigenfrequencies of a linearized flight physics model are calculated to identify the maneuver lengths for the excitation of an appropriate frequency spectrum at the specific flight attitude. To apply maneuvers with the exact length, a way to guide the pilot through the correct maneuver injection via audio input has been developed. This proved to have a significant effect on the maneuver accuracy. Furthermore, a pilot training campaign in a simulator prior to the flight test is carried out and the maneuvers flown by the pilot are analyzed. Finally, the conduction of the flight tests is described and the flown maneuvers and results are evaluated regarding the maneuver quality and the observability of the helicopter dynamics.

I. Nomenclature

ECU	engine control unit	-	T_{doub}	doublet maneuver length	s
GPS	global positioning system	-	T_{Man}	maneuver length	s
MTOW	maximum takeoff weight	-	$\boldsymbol{u}$	control input vector	-
UAS	unmanned aerial system	-	$\boldsymbol{x}$	state vector	-
$\boldsymbol{A}$	system matrix	-	α	aircraft angle of attack	deg
$\boldsymbol{B}$	control matrix	-	β	aircraft angle of sideslip	deg
f	frequency	Hz	Θ	aircraft pitch angle	deg
T	period duration	s	Φ	aircraft roll angle	deg
T_{3211}	3-2-1-1 maneuver length	s	Ψ	aircraft yaw angle	deg

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II. Introduction

An unmanned helicopter with an MTOW of 600 kg is being developed at the Technical University of Munich in cooperation with the rotorcraft manufacturer edm aerotec GmbH and ZF Luftfahrttechnik GmbH. As part of the research project the two institutes of Helicopter Technology and Flight System Dynamics are cooperating to develop the avionics system and the automatic flight control system. For this purpose, a real-time capable flight physics model of the CoAx 600 helicopter is needed, which is validated in terms of dynamic behavior. Therefore, a manned flight test campaign is conducted during the development phase of the unmanned system. As detailed in [1] the system identification is performed in the time domain which determines a huge part of the conducted flight maneuvers. Many flight test campaigns in this scale have been performed for identification in the frequency domain as described in [2] [3] and [4]. For this purpose, mostly frequency sweeps are applied and the time domain specific square wave maneuvers are mainly used for validation purposes. For the system identification in the time domain, these maneuvers are used for the excitation of eigenmodes and couplings in the helicopter dynamics in order to identify the corresponding model parameters. An example for this methodology is given in [5].

The following chapters give an insight into the planning, the training and finally the conduction of the flight test campaign. Also, the flight test data quality is assessed regarding maneuver quality.

III. Measurement system

The final measurement setup, intended for the unmanned flights is installed on the helicopter to ensure that the sensor data quality resembles that of the unmanned system. This is important, since the identified model and the measurements are used for designing control laws for the future system and the flight tests are also used to test the system under realistic conditions. From this system, the angular and translational velocities as well as the accelerations are obtained. The airspeed is measured with a pitot sensor placed outside the rotor downwash together with the sensors for the angles of attack α and sideslip β of the aircraft. Also, GPS and magnetic field orientation data is collected. The control inputs are measured underneath the swashplate in the nonrotating frame as well as at the pilot controls in the cockpit. The control forces are measured via strain gauges applied on the control rods right underneath the swashplate as well as on the cyclic and collective controls. All data of the basis helicopter (e.g. of the ECU) including engine data and rotor speed is recorded. A picture of the instrumented helicopter can be seen in Figure 1.

Figure 1: Front view of the test aircraft with air data boom, antennas and ground contact switches visible on the landing skid and the avionics system rack on the copilots' seat

For operational reasons this data is sent to a ground control station alongside with system surveillance data, as with the measurement system on board there is no space left for a flight test engineer. On the ground, the flight test team has the ability to observe the flown maneuvers and to guide the pilot through the flight test program while evaluating the maneuver quality in real-time, which allows to repeat maneuvers if they are inadequate.

For the model identification (see [1]) especially the velocities and accelerations of the helicopter as well as the pitch angles of the rotor blades are of importance. The velocities and accelerations are measured directly as mentioned above. In order to obtain the blade angles, a detailed mapping of the blade pitch angle at $R = 0{,}7$ to the swashplate position is performed for several control inputs and rotor positions. Between these positions the blade pitch angles of each swashplate position during flight test can be interpolated.

IV. Flight test purpose

The flight tests in this campaign have different purposes:

- Identification of the flight dynamics model
- Range tests for the data link and control receivers of the future unmanned system
- Testing of the operational practicality of the whole system including the ground control station
- System tests of the future unmanned system without actuators

The main purpose is to use the recorded data to identify the parameters of a model for the development of the control algorithms for the unmanned system. For this model, the input dynamics over the whole flight envelope are of interest with the main focus for this program lying on the slow flight regime near hover.

The range tests of the control receivers are conducted during the higher velocity flight regime tests of the identification flights combined with a series of hovering states in specified distances from the ground control antennas with varying aircraft orientations. A detailed monitoring of the received signal packages enables the evaluation of the individual receiver status, which is recorded on the ground control station as well as on the aircraft for later comparison.

The testing of the system is mainly based on validating the performance for a flight time of more than 20 hours without failures. Also, the operational practicality of the ground control station is proven during the identification flight tests and important flight state parameters are identified to be displayed in the UAS version. The practice and experience in operating the whole avionics system is used to further develop the operational conduct and the checklists needed for the operation of the UAS.

V. Flight test planning and maneuver definition

For the purpose of the dynamic parameter identification flight tests, a simulation study is conducted prior to the flight test campaign. A CAMRAD II [6] model of the CoAx 600 is used to evaluate the maneuver points necessary to obtain an accurate model of the helicopter by interpolation between these data points. For this purpose, in [7] the linearization output of the Flutter task is used to obtain several linear matrix models of the form

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu}\,. \tag{1}$$

With an interpolation algorithm in the three velocity axes it is evaluated how many data points are needed in the velocity directions as well as their angular spacing and distribution over the flight envelope in order to reach minimal interpolation error with a minimum amount of flight states. It is observed, that not only the variation of the flight speed in x-direction is of high relevance for the model but also the sideslip angle has great influence.

Therefore, flight tests are also planned at 30, 60 and 90 degrees of sideslip, with varying flight speeds. At each of the identified maneuver points at least a trim condition is planned to be logged, wherever possible the conduction of dynamic maneuvers is planned as well.

These maneuvers include doublets, steps and 3-2-1-1 maneuvers which are widely used for model identification (see [5] and [8]). The maneuver times are set using the estimated nonlinear model presented in [1], which is implemented with known physical helicopter data with a 6-DoF rigid body model of the CoAx 600 prototype with a dynamic rotor model and aerodynamic coefficients based on the blade profile and a lookup table. From this model, a set of linearized models for each maneuver point is calculated. With the eigenfrequencies of these linearized models it is possible to deduct the maneuver times needed such that the axis- and possible coupling-eigenmodes of the helicopter are excited adequately. According to [5], for the doublet maneuvers, the maneuver length is set equal to the period duration of the eigenfrequency which is

$$T_{doub} = \frac{1}{f} \tag{2}$$

and for the 3-2-1-1 maneuvers the maneuver length is calculated to be

$$T_{3211} = \frac{2.45}{f}. \tag{3}$$

With this method, a set of maneuver lengths was determined with a fast and a slow maneuver in each input axis varying over the flight speed. Each maneuver is divided into equally spaced steps, doublets into two steps and 3-2-1-1 maneuvers into seven steps. These steps are the basis for the audio input described in chapter VI.

The estimated nonlinear model is also used in a training campaign in the simulator environment of the Institute of Helicopter Technology with the pilot who is later flying the flight test campaign. With his comments on the flight dynamics, the estimated model parameters are adjusted in order to come closer to the real behavior and to get a good estimation of the maneuver lengths. In the same time the test pilot is trained on the maneuvers to be flown in the identification flight test campaign. A total of more than 5 flight hours has been flown during the campaign.

VI. Simulator campaign

The simulator campaign is used to assess the practicality of the designed flight maneuvers and trim points. Also, a practical method is tested to communicate with the pilot to guide him through the maneuvers and to give him as much assistance as possible. For this, a workaround is developed as in the flight tests the space of the copilot's seat is occupied by the avionic system, thus none of the typical guiding aides (e.g. control fixtures [8]) can be implemented. In Figure 2 the simulator setup can be seen, flying a 3-2-1-1 maneuver which can be observed by the test engineer on the screen behind the pilot. This enables a fast interpretation and evaluation of the flown maneuver and is therefore implemented in the same way at the ground station of the free flight test campaign.

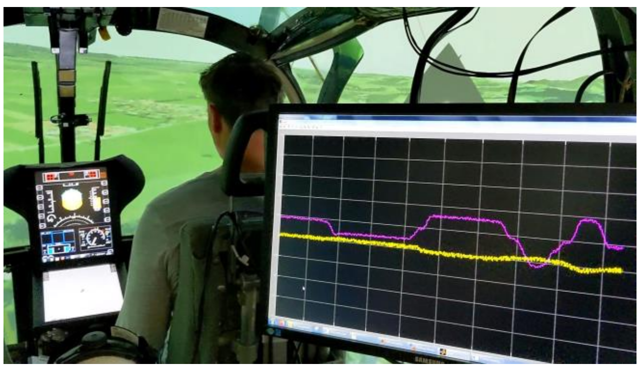


Figure 2: Simulator setup for the maneuver training

For the guidance of the pilot through the maneuver injection from the ground control station, audio input methods were tested. This sound input assisted the pilot to determine the right maneuver timing. The improvement of the maneuver timing by the assistance is shown in Figure 3. The maneuver accuracy is improved significantly by supporting the pilot with a metronome and can be even more improved by directly counting the maneuver timing. So, for the 3-2-1-1 maneuvers a counting on the maneuver steps of "1, 2, 3, 1, 2, 1, 1" is established with the pilot input changes taking place at each "1". For the doublets, the counting is "1, and, 2, and, 1, and 2 and" or "1, 2, 1, 2" depending on the maneuver length. The first 1 is emphasized to mark the maneuver starting point.

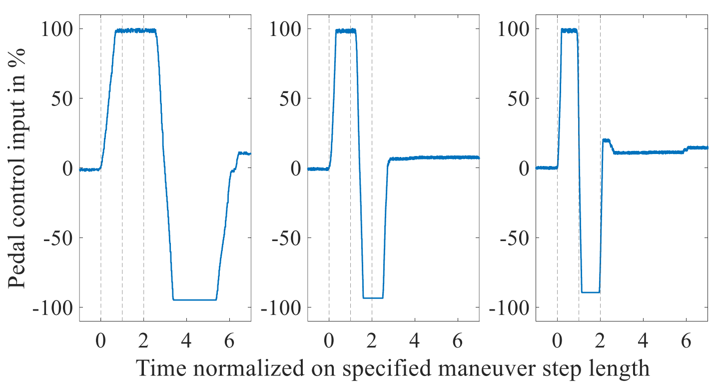


Figure 3: Maneuver improvement on the example of the first three doublet maneuver injections on the pedal controls. From left to right, maneuver only with pilot instruction, maneuver with metronome audio input, maneuver with explicitly counting in "1, and, 2, and, 1, and 2 and" schematic. The grey dashed lines mark the desired time points for the input switches.

The time spacing between the counting is constant. With this input, the pilot on the one hand has a constant clock like from a metronome, but also receives the exact switching position for nonsymmetric maneuvers like the 3-2-1-1. This counting is performed in a loop during the flight test, using a recorded audio file. This audio support can be applied via radio link from the ground and is therefore suitable for the flight test campaign.

Another outcome of the simulator campaign is the implementation of a pilot marker in the recorded dataset of the flight test campaign. It is implemented using a push button at the cyclic control which is recorded as a counter variable. By pushing the button, the pilot marker variable increases by one step. With this marker, the pilot has the ability to indicate specific events. During the flight test campaign, it is pushed every time a new set of maneuvers is started. The current marker value is displayed at the ground station and is noted in the flight test cards. This facilitates the later analysis of the data, because only a section with a specific marker value has to be examined.

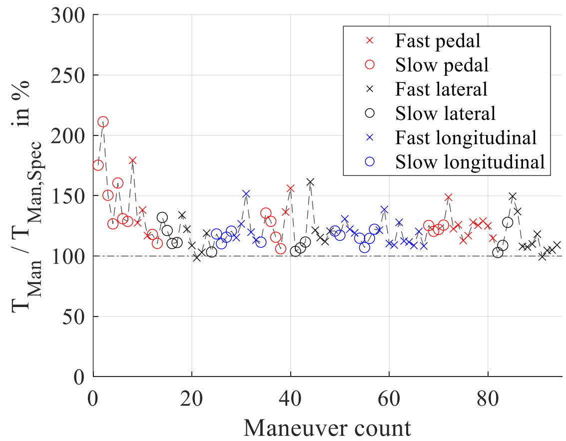


Figure 4: Simulator campaign 3-2-1-1 maneuver length percentage ratio to the specified maneuver length according to the test plan, plotted over the maneuver number in their order. With maneuvers in the pedal (red), lateral (black) and longitudinal axis (blue). Fast maneuvers are marked with x-markers, slow maneuvers with o-markers.

In order to visualize the training effect of the campaign and analyze the maneuver quality, the flights in the simulator are recorded and an analysis method is implemented, which is described in the following. This method gives a good basis to be used later on for the flight tests in order to evaluate the quality of the flown maneuvers and to repeat certain maneuvers which need to be improved. Also, on basis of the data a reevaluation can be performed in going through certain points with the pilot which need improvement and to discuss how this improvement can be achieved.

The maneuvers are analyzed for this purpose regarding the maneuver length, the timing of the input switches and the axis separation of the maneuver inputs. This is shown exemplarily in the following for the 3-2-1-1 maneuvers.

In Figure 4 the maneuver length ratio of the trained 3-2-1-1 maneuvers in relation to the desired length is plotted over the maneuver number. In the beginning there is a clear improvement visible which reaches saturation after 20 maneuvers. By switching to the fast maneuvers, the relative maneuver length is increased again and the learning curve is delayed. The training has also an effect on these maneuvers although the saturation lies slightly higher than for the slow maneuvers as the workload for the pilot is higher and the switching times are within the reaction time of the pilot. Still, the saturation point of each maneuver is in sufficient proximity to the desired maneuver length.

The timing of the input switches can be observed in Figure 5 where the 3-2-1-1 maneuvers of each axis are plotted in six individual graphs with differentiation between slow and fast maneuvers. On each graph the first maneuver is displayed together with the mean value of all maneuver inputs and the last maneuver. The first slow maneuver in the pedal axis is completely out of the timing as it is the first 3-2-1-1 maneuver and has also a great influence on the mean value. The last maneuver in this axis is timed on the desired points and has a clear square wave form visible. In the other axes, the mean input line shows good timing and a positive development between the first and the last maneuver can be observed. Especially in the longitudinal axis, the helicopter model shows strong reactions on the slow maneuver inputs which makes it difficult to regain control afterwards, therefore the pilot is applying recovering inputs earlier in this axis. For the fast maneuvers in lateral and longitudinal axes, the maneuvers are no clear square wave signals anymore, due to the small time between the switching points.

The last aspect to be analyzed is the axis separation of the maneuver input. For a clear observation of input couplings between several axes of the helicopter dynamics, it is important to perform the maneuver input as separated as possible with minimal off-axis inputs. In Figure 12 b) the maximum inputs in all axes are plotted for each maneuver. The inputs are performed mainly in the maneuver axis. Between the longitudinal and the lateral inputs there is a coupling visible as their separation is not that easy due to both inputs being made with the cyclic controls and without mechanical assistance with for example a control fixture [8]. Especially for lateral maneuvers with the fast timing there is a larger coupling into the longitudinal axis. For these maneuvers a clear trend of decreasing coupling is visible over the training time. This is achieved by implementing measures to make it easier for the pilot to only perform an input in one axis, as for example steering only out of the wrist for longitudinal inputs and lay down the elbow for lateral inputs.

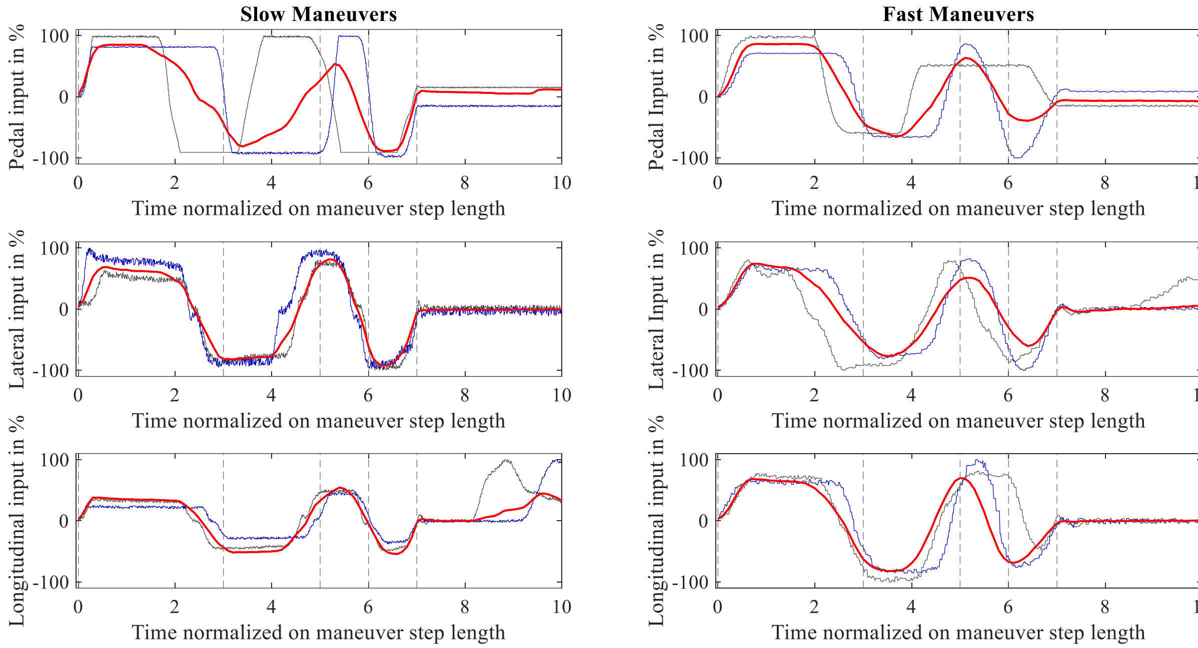


Figure 5: Simulator campaign 3-2-1-1 maneuver timing in the pedal, lateral and longitudinal input axis (up to down) for the slow and fast maneuver variant (left to right) with the first maneuver in black, the mean value in red and the last maneuver in blue. The values are normalized on the maximum amplitude and on the maneuver step length to make the timing of the switching points visible (desired points: grey dashed vertical lines).

VII. Flight test

The flight test plan is set on conducting mostly doublets and 3-2-1-1 maneuvers in the pedal, as well as the longitudinal and lateral cyclic input axis. In the collective axis, only step inputs are performed as the helicopter uses a teetering rotor system and is therefore not allowed to perform low-g maneuvers. At flight attitudes where no maneuvers could be flown, a trim point is recorded as with this data at least some dynamic parameters can be identified. This concerned mainly flight attitudes with sideslip angles and backward flight conditions. The maneuvers are performed, starting from trim conditions. These trim conditions are distributed over the flight envelope beginning with hover, moving on to several forward flight velocities and finally adding sideslip angles of 30 and 90 degrees.

The order of conduction is always starting from the maneuvers in the pedal, then in the lateral and finally the longitudinal input axis. Additionally, based on the experience of the simulator campaign, the slower maneuvers are performed before the faster maneuvers and the doublets prior to the 3-2-1-1 maneuvers. In this way, the level of difficulty is increased step by step, at least regarding the maneuver complexity. During the flight tests certain slow maneuvers prove to be more difficult to control than fast maneuvers, due to the strong reaction of the helicopter and the long input times. Therefore, it is decided to switch the tempi and start with the fast maneuvers and to go on with the slow ones afterwards.

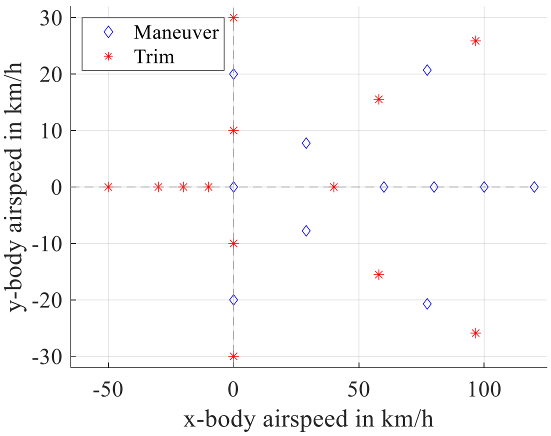


Figure 6: Overview over the maneuvers conducted during the flight test campaign plotted over the velocity u in x-axis direction and velocity v in the y-axis direction of the body fixed frame of the helicopter. Maneuvers (3-2-1-1, Doublets, Steps) flown in flight states marked with blue ◊-marker and Trim points flown in flight states marked with red ∗-marker.

The planned flight tests are completed with more than 20 flight hours during 30 flights. Out of those 20 flight hours, a total of 13h 13min pure maneuver time is flown at the flight conditions shown in Figure 6, which means that there is a factor of 0.64 between flight time and the pure maneuver time. 1050 maneuvers are flown with an average duration of 45 seconds per maneuver. In Table VII-1 the flight test time needed for the individual maneuvers is listed. Especially long time is needed for the slow pedal maneuvers, as depending on the flight state the maneuver length lies between 6 to 8 seconds for doublet maneuvers and 15 to 20 seconds for 3-2-1-1 maneuvers. The other maneuver lengths are all situated between 1 to 3 seconds for the doublet maneuvers and 2.5 to 6 seconds for the 3-2-1-1 maneuvers. Normally a set of 5 to 10 maneuvers is flown with inputs starting in each direction of each axis at every maneuver point. Doublets are applied at every maneuver point, whereas 3-2-1-1 maneuvers are conducted mostly in hover and forward flight conditions.

Table VII-1: Maneuver flight test time needed (total flight time 20h 44min)

Maneuver	Axis	Maneuver Length	Flight Time hh:mm:ss	Maneuver Count	Time per Maneuver hh:mm:ss
Total	-	-	13:13:00	1050	00:00:45
Doublet	-	-	08:41:00	738	00:00:42
	Pedal		02:52:00	238	00:00:43
		Slow	01:15:00	84	00:00:53
		Fast	01:37:00	154	00:00:38
	Lateral		02:51:00	242	00:00:42
		Slow	01:14:00	90	00:00:49
		Fast	01:37:00	152	00:00:38
	Longitudinal		02:58:00	258	00:00:41
		Slow	01:26:00	94	00:00:54
		Fast	01:32:00	164	00:00:33
3-2-1-1	-		02:25:00	245	00:00:36
	Pedal		00:56:00	76	00:00:44
		Slow	00:23:00	18	00:01:17
		Fast	00:33:00	58	00:00:34
	Lateral		00:45:00	91	00:00:30
		Slow	00:12:00	29	00:00:24
		Fast	00:33:00	62	00:00:32
	Longitudinal		00:44:00	78	00:00:34
		Slow	00:08:00	14	00:00:34
		Fast	00:36:00	64	00:00:34
Step	-		00:26:00	15	00:01:44
	Collective		00:26:00	15	00:01:44
Trim Point	-		01:41:00	52	00:01:57

The approach for documentation of the flight tests is described in the following. In Figure 7 the setup of the ground control station is shown. On the displays the system status as well as the helicopter attitudes and velocities are portrayed together with the pilot inputs. It is beneficial to be able to see the pilot inputs, trim conditions and maneuver reaction of the helicopter in real-time on the ground in order to decide if another repetition of the maneuver is necessary.

For documentation of each flight, test cards are developed consisting of an overview table with the planned flight program and a set of tables for specific information concerning the flight test process (see Figure 7). The overview table incorporates the planned maneuvers with their acronym, a short description, the trim state and the tempo of the maneuver. Additionally, it contains empty columns to note the flight numbers in which the specific maneuver is conducted. The flight test cards consist of a table as well, containing empty columns to write down the maneuver acronym, the corresponding pilot marker value, the start time of the group of maneuvers and a comment section to take notes (e.g. maneuver counter, short information about the weather condition, etc.). Also, it incorporates a cover sheet containing basic system information like battery status, fuel level, weights and weather data.

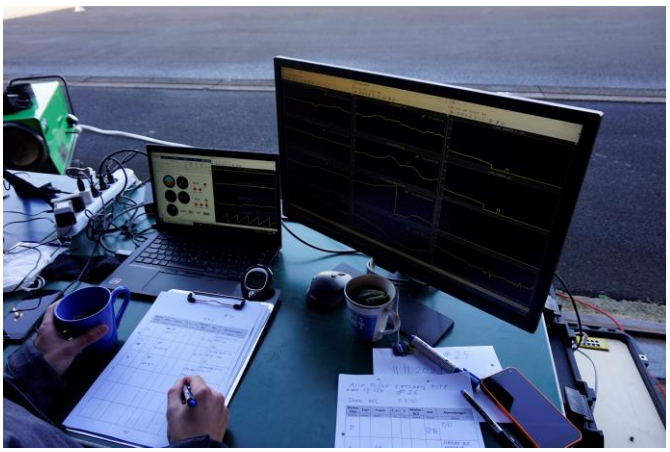


Figure 7: Ground control display and flight test cards

VIII. Flight test quality analysis

In order to evaluate the quality of the flight test maneuvers, the same methodology as for the simulator campaign is used. The analysis shown in this paper is focused on the 3-2-1-1 maneuvers in hover, as a high number of those is conducted in order to guarantee the best possible coverage of this flight state.

In Figure 8 the first doublets in the flight test campaign are plotted over the time. The timing of the switching points is accurate and the square wave form is clearly visible. Still, some improvement over the first maneuvers can be seen.

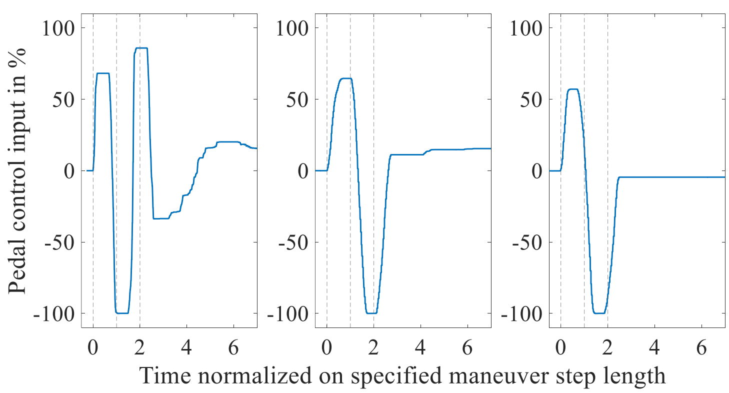


Figure 8: First doublets in flight test (hover condition, pedal input), from left to right in their order of occurrence. The grey dashed lines mark the desired time points for the input switches.

To evaluate the yet unvalidated model used in the simulator campaign and for the determination of the maneuver length, the helicopter movement of maneuvers performed in the simulator and in the flight tests is compared. This is plotted exemplarily for a longitudinal 3-2-1-1 maneuver in Figure 9. The simulator model shows helicopter movements in the same order of magnitude as the helicopter in the flight tests. Also, the excited frequencies are in a similar range although the superimposed oscillation with the higher frequency is only slightly excited by the maneuver in the simulator model and is therefore less observable than in the real flight tests.

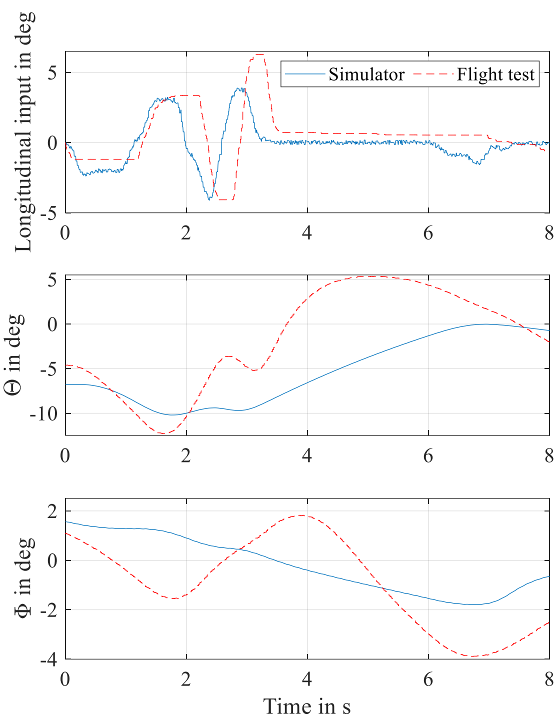


Figure 9: Comparison of the helicopter reaction to a longitudinal 3-2-1-1 maneuver in the simulator campaign with the unvalidated, estimated model (blue) and during the flight test campaign (red). Both maneuvers were conducted out of a trim state of 60km/h forward flight with the maneuver input starting in forward direction.

Analyzing the maneuver length ratio in comparison to the desired length (see Figure 10) it is shown that the maneuvers are varying around the 100 % line. This variation can be observed mostly during axis or maneuver length changes, as the pilot needs some time to get used to the new tempo (as each axis has its own tempo depending on the eigenfrequencies estimated by the a priori model [1]). But the variation is also beneficial as a higher frequency range is covered and therefore an erroneous estimation of the eigenfrequency can be covered to a certain degree. Only for the maneuvers 19 to 31 a significant increase of the time ratio can be observed, which is due to the switch to the fast roll axis maneuvers which have a high tempo, compared to the other maneuvers, of 170 beats per minute with seven beats per 3-2-1-1 maneuver. For the following maneuvers, the tempo is switched to the slow roll axis maneuvers which results in a significant dip in the time ratio below 100 % until it reaches normal levels after 5 maneuvers. This dip can also be observed for other maneuvers after switching from the fast to the slow tempo. But in the roll axis it is the most significant. The fast roll axis maneuvers are rerun at maneuver numbers 65 to 75 and are then in a similar range as the other maneuvers.

Plotting the maneuvers of the individual axes (see Figure 11) shows that the timing of the switching points of the 3-2-1-1 maneuvers is very good in line with the desired switching points and also the square wave signal is clearly visible in almost every axis even for the fast maneuvers with some individual exceptions. For this reason, it is recommendable to conduct several repetitions of the same maneuver, because as the plotted mean value shows, with enough samples the maneuvers are timed well and some exceptions become less relevant for the overall result.

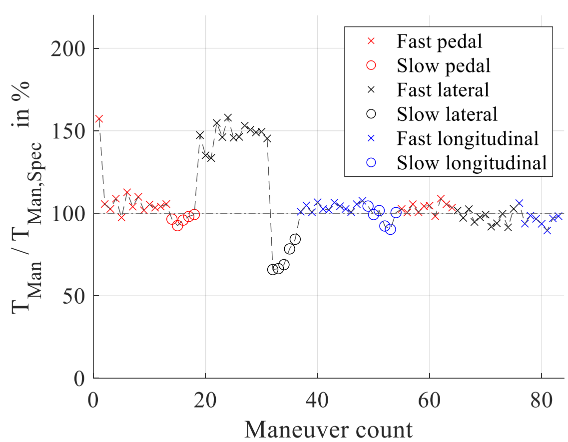


Figure 10: Percentage ratio of the flown 3-2-1-1 maneuver lengths to the specified length according to the test plan over the number of their succession. Fast maneuvers are marked with x-markers, slow ones with o-markers

The slow pedal maneuvers though, prove to be quite difficult because of the slow tempo and the resulting long maneuver time. Especially in the hover condition it is difficult for the pilot to apply a maneuver input over several seconds and keep the other axes untouched. Also, the longitudinal maneuvers are difficult to conduct, due to the very strong reaction of the helicopter dynamics, which has already been predicted during the simulator campaign (see Figure 9). Therefore, these maneuver inputs are not that smooth in comparison to the others.

For the axis separation shown in Figure 12 a slightly greater pilot input coupling into the other axes than in the simulator can be observed. These couplings are stronger for the slow maneuvers which may be explained with the longer duration and therefore longer exposure to other instabilities of the helicopter in hover. Especially a coupling of the slow lateral maneuver inputs with pedal inputs is visible.

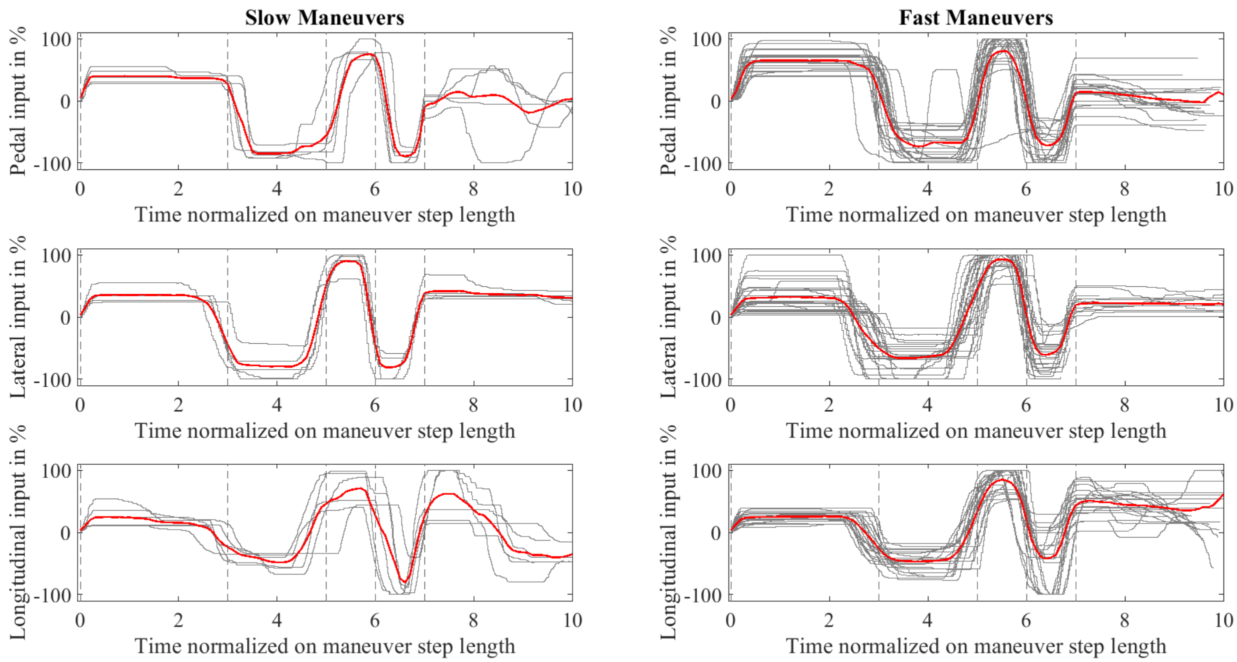
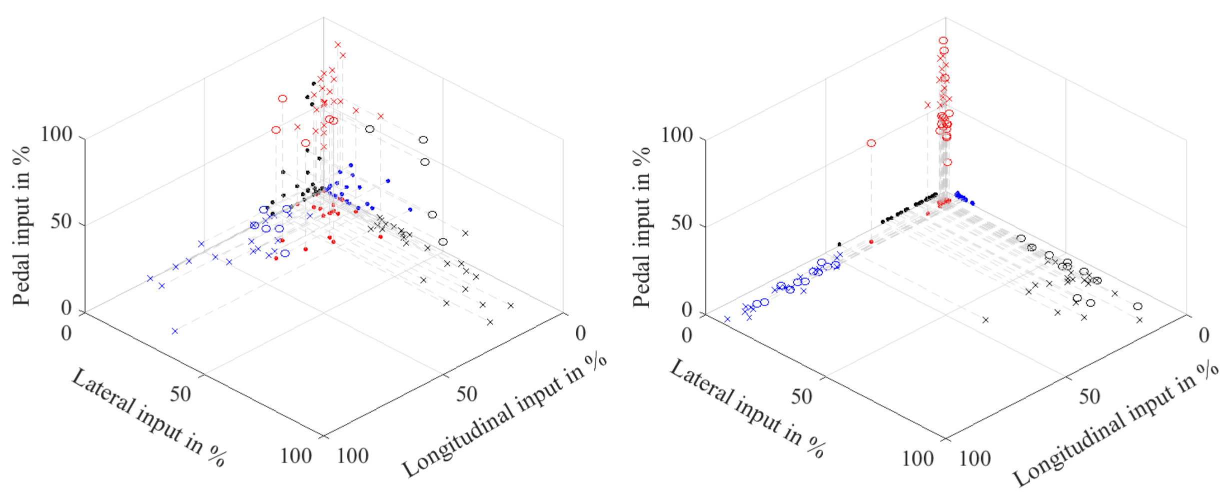


Figure 11: Flight test 3-2-1-1 maneuver timing in the pedal, lateral and longitudinal input axis (up to down) for the slow and fast maneuver variant (left to right). The individual maneuvers are plotted in grey with the mean value of all maneuvers in red. The values are normalized on the maximum amplitude and on the maneuver step length to make the timing of the switching points visible (desired points: grey dashed vertical lines).



a) Flight test **b) Simulator**

Figure 12: Axis separation of 3-2-1-1 maneuvers in all input axes during the flight test campaign a) and the simulator campaign b). Every point resembles the maximum input amplitudes during one maneuver for each input axis. With pedal maneuvers in red, lateral maneuvers in black and longitudinal maneuvers in blue. Additional differentiation is made between slow maneuvers with o-markers and fast maneuvers with x-markers and also the projection into the non-maneuver plane is plotted, marked with a dot.

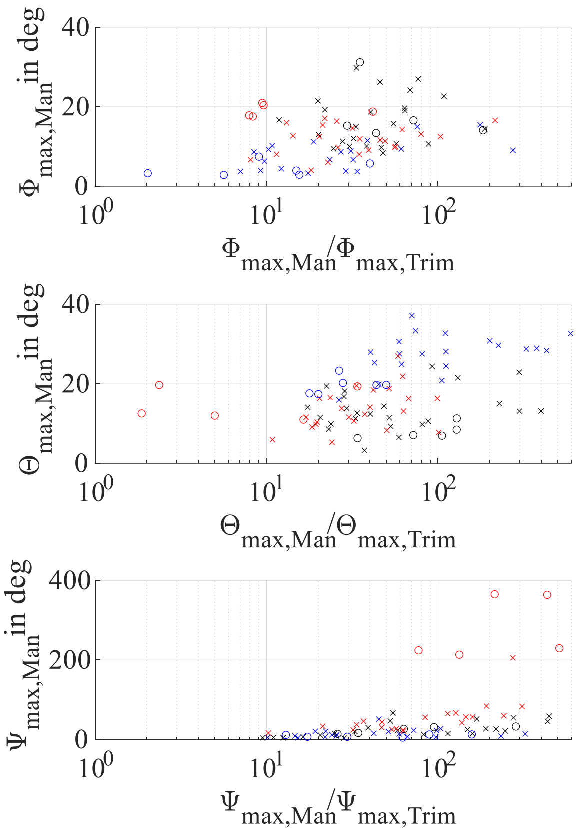


Figure 13: Maximum attitude angle amplitude of the body fixed helicopter frame, plotted for each 3-2-1-1 maneuver over the ratio of the maximum angle amplitude during the maneuver divided by the maximum angle amplitude during the trim state beforehand of the respective maneuver. Different maneuvers can be distinguished by the input axis (pedal – red, lateral cyclic – black, longitudinal cyclic – blue) and by the maneuver length (fast – x-markers, slow – o-markers).

This may be explained with the unstable dutch roll mode which was identified in [1] and therefore a strong yaw movement resulting due to the lateral input. Overall the maneuvers are still very well decoupled, the inputs are largely in the desired axis and the sample size is big enough, thus we got a set of maneuvers which are completely separated. As the simulator for the training campaign is a stationary type, most parts of these pilot input couplings in the maneuvers could not be observed there, as the pilot was not forced into movements by the helicopter dynamics (for comparison see Figure 12 b)).

Another pilot control coupling can be seen for the lateral and longitudinal maneuvers. These inputs are slightly coupled into the other respective axis, which could already be observed in the simulator campaign and is probably related to the difficulty of making a completely decoupled input at the cyclic controls. Still, the coupling is less strong than it was in the beginning of the simulator campaign.

Finally, the resulting amplitudes in the helicopter dynamics are evaluated. In Figure 13 this is done exemplarily for the maximum amplitudes of the change in the helicopter attitude which are plotted over their ratio to the maximum amplitude during the trim state beforehand of the respective maneuver. Most maneuvers are situated in a ratio range between 10 and 100 on each axis, which shows a good observability of the maneuver reaction in these variables. The highest amplitude values during the maneuver can be observed in the axis directly related to the input axis of the maneuver. In the roll and yaw axis, the amplitudes of the pedal (in the roll axis) and the lateral cyclic maneuvers (in the yaw axis) are higher than those of the longitudinal maneuvers and close to the amplitudes of the maneuver of this respective axis. This may point to a helicopter inherent coupled movement in these two axes, which also was observed by [1] during the model identification.

IX. Conclusions and outlook

In this study, the planning and conduction of a flight test campaign is presented. Beginning with the selection of maneuver types and points of the flight envelope where these maneuvers are performed, followed by the determination of the frequency range to be excited by the maneuvers, which then determines the maneuver length. Subsequently a simulator campaign over more than 5 flight hours is carried out in order to train the pilot on the maneuvers and to validate the operational procedures. For the maneuver injection an audio-based method is developed to guide the pilot through the maneuver execution, which shows to have significant impact on the maneuver accuracy. Also, an evaluation method for the maneuver quality is implemented and applied to the simulator campaign.

A flight test campaign of more than 20 flight hours containing about 13 hours of maneuver time is conducted. An evaluation method is used to assess the quality of the flight test data and eventually reperform certain maneuvers. The analysis of the flown 3-2-1-1 maneuvers is shown in this paper.

As presented in [1], the flight data has been used to successfully identify the helicopter model parameters in the hover flight condition. The obtained data in this flight regime proves to be sufficient regarding maneuver quality and observability of the helicopter reaction. In the future, this will be extended to the complete flight envelope using the whole set of recorded data. The model will then be used to finalize the UAS control algorithms, which are currently under development.

After completion of the development of the UAS, several flight test campaigns will be performed with the unmanned system.

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