EVALUATION OF CONTROL EQUIVALENT TURBULENCE INPUT (CETI) MODELS FOR HOVER AND FORWARD FLIGHT

Susanne Seher-Weiß, Michael Jones,
German Aerospace Center (DLR), Institute of Flight Systems, Braunschweig, Germany
susanne.seher-weiss@dlr.de, michael.jones@dlr.de

Abstract

This paper details developments in Control Equivalent Turbulence (CETI) Input models. Using these models, control inputs are calculated that generate aircraft angular and vertical rates in calm conditions equivalent to those when flying in atmospheric turbulence. In this paper, previous efforts to generate CETI models for the EC135 in hover are extended to include dependency with respect to forward flight speed and flight altitude. The paper describes the flight tests conducted in turbulent conditions, the extraction of the equivalent control input traces and their power spectral densities, and the determination of the desired turbulence models. The paper also presents validation of the derived turbulence models. This is performed through piloted simulation trials conducted in the Air Vehicle Simulator (AVES) at DLR. Results showed the appropriateness of developed CETI models to simulate atmospheric turbulence over the flight envelope.

NOMENCLATURE

ACT/FHS	Active Control Technology / Flying Helicopter Simulator
AVES	Air Vehicle Simulator
CETI	Control Equivalent Turbulence Input
DLR	German Aerospace Center
HQ	Handling Qualities
PSD	Power Spectral Density
RQ	Ride Quality
TS	Turbulent Air Scale
UAV	Unmanned Aerial Vehicle

$A_{lon}, A_{lat}, A_{col}, A_{ped}$	turbulence filter amplitudes (longitudinal, lateral, collective, and pedal)
f_{p1}	scaling factor in vertical turbulence model
$f_{lon,lat}, f_{ped}, f_{col}$	factors for scaling turbulence model to a different helicopter
$G_{lon}, G_{lat}, G_{col}, G_{ped}$	turbulence filters (longitudinal, lateral, collective, and pedal)
j	imaginary unit
L_w, L_v	main rotor and tail rotor scaling parameters, m
p, q, r	angular rates (roll, pitch, yaw), rad/s
R_{MR}, R_{TR}	main rotor and tail rotor radius, m
s	Laplace variable
U_0	mean wind speed, m/s
W_{noise}	white noise input
w	vertical velocity, m/s
$\delta_{lon}, \delta_{lat}, \delta_{col}, \delta_{ped}$	pilot control inputs (longitudinal, lateral, collective, and pedal), %
Ω_{MR}, Ω_{TR}	main rotor and tail rotor speed, rad/s

1. INTRODUCTION

Both in flight testing and piloted simulation, it is important to perform evaluation in turbulent weather conditions. This is of particular importance in experimental flight testing, whereby it is often necessary to test in inclement weather conditions (i.e. controller robustness, occupant comfort) but it is not possible or easy to achieve these organically (e.g. good weather conditions, limited test time). In this way, turbulence models have already been used to define acceptable boundaries for disturbance rejection bandwidth in Ref. [1], determine the influence of turbulence on UAVs (unmanned aerial vehicles) in Ref. [2], and to investigate the influence of turbulence in degraded visual conditions in Ref. [3].

The traditional approach to model turbulence for fixed wing aircraft is the use of a frozen gust pattern, usually generated from a Dryden spectral model, Ref. [4]. For frozen gust patterns, the reaction of the aircraft to the turbulence is a function of the relative velocity with respect to the air mass through which it is flying and is thus not applicable in hover. Even though frozen gust patterns generated from Dryden models have received favorable comments at high speed forward flight, helicopter pilots have criticized them as not being representative for low speed flight, Ref. [5]. Other approaches such as complex rotating frame turbulence models from Ref. [6] are computationally expensive and currently not suitable for real-time simulation.

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

For rotorcraft, empirical hover and low-speed turbulence models have been developed using the so-called Control Equivalent Turbulence Input (CETI) method. This method determines the control inputs required to generate aircraft angular and vertical rates in calm conditions that are consistent with rates observed when flying in atmospheric turbulence.

Flight tests conducted in turbulent conditions are required to generate CETI models. CETI time histories are then extracted from aircraft angular and vertical rates using a mathematical model of the aircraft dynamics. Analyzing and modeling the power spectral densities (PSD) of the extracted control disturbances allows the generation of low order equivalent turbulence models that can be used for control system optimization, handling qualities (HQ) investigations, and pilot training.

The CETI method was first proposed by the National Research Council (NRC) Canada in Ref. [7] and subsequently extensively developed at the U.S. Army Aeroflightdynamics Directorate (AFDD) at Moffett Field California in Ref. [8], whereby a CETI model of the UH 60 Black Hawk helicopter was successfully developed from flight tests and validated, Ref. [9]. The method was later applied at DLR using the ACT/FHS (see Figure 1), a highly modified version of the EC135 helicopter, thereby demonstrating the applicability of the approach to a different aircraft, Refs. [10], [11].

Figure 1 Active Control Technology/Flying Helicopter Simulator (ACT/FHS)

In the past, the use of CETI models has been limited to hover/low-speed applications (examples including Refs. [1], [2], [3], [8], [9], [10], [11]). Only recently, previously identified CETI turbulence models of the ACT/FHS aircraft have been extended to forward flight in Ref. [12]. In this paper, the models are further extended to include flights at different altitudes. This effort is funded in part through the national research project CORINNE (Comfort Of Ride Improved eNgiNEering, see acknowledgement).

The paper starts with a description of the CETI methodology. Next, the flight tests conducted are outlined and the generated CETI models are presented. The evaluation of these models in DLR's AVES (Air Vehicle Simulator) simulation facility is presented in detail. Finally, some conclusions are drawn.

2. METHODOLOGY

The CETI method has been developed as an alternative means of accounting for turbulence during hovering and low-speed tasks, where classical Dryden models cannot be used. There are two main benefits of the CETI approach. Firstly, it provides a method to use turbulence in flight testing during calm conditions. This is a benefit during many research areas, such as validation of controller robustness (Ref. [1]), comfort testing, and HQ investigations (Ref. [13]). Secondly, it can be used as a simple turbulence model within real-time simulation, where it may not be possible to generate a complex turbulence model (e.g. rotating frame turbulence models, Ref. [6]) for computational reasons. Another benefit is the application of the method to simplified linear models, which are not suitable for using physics-based turbulence models due to the lack of physical modeling of the helicopter parts.

The CETI method does not represent direct turbulence simulation in full aerodynamic details, but rather generates equivalent control inputs. These are intended to produce the same effect on the vehicle as the turbulence itself. The extracted CETI models are generally specific to the helicopter that was used to collect flight data. This has the advantage that the models are automatically validated for the specific helicopter type and are therefore well suited for control system design when addressing disturbance rejection. However, in Ref. [14], a scaling method is presented that allows to scale CETI models from one helicopter to another.

The general method for ascertaining CETI models is depicted in Figure 2, separated into three stages; extraction, modeling, and simulation. For the **extraction** phase, data is collected from flight in turbulent conditions. The level of turbulence determines the intensity of the generated CETI model. The measured aircraft responses are then fed into an inverse aircraft model to obtain control inputs related to pilot and gusts. The quality of the final CETI model is dependent upon the quality of the inverse model used for the extraction process. Subtracting the measured pilot inputs yields equivalent control input traces that correspond to the response of the aircraft to the turbulence (see Ref. [8]). As shown in Ref. [11], time histories of the CETIs can either be extracted using a stable inverse model of the helicopter or by an observer approach. For the current investigation, the inverse model approach is

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

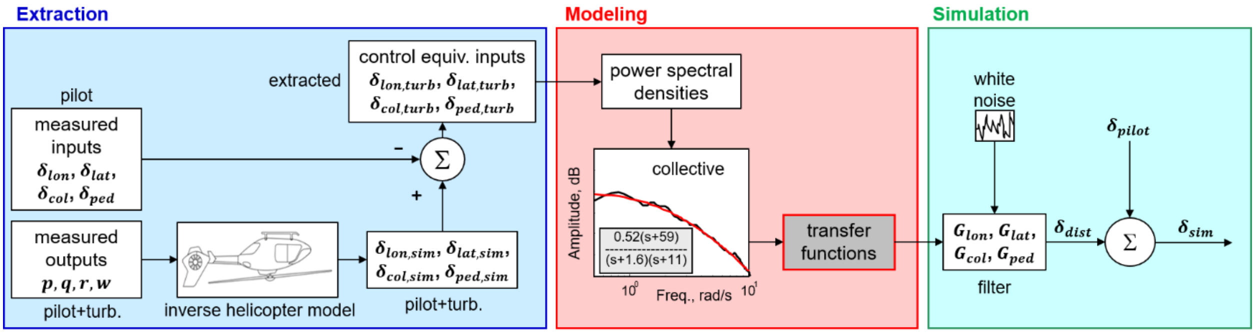

Figure 2 CETI method

used, based on high-fidelity identified models as described in Ref. [15].

In the **modeling** step, white noise driven transfer functions of a form similar to Dryden models are developed by analyzing the spectra of the extracted control disturbances. Therefore, the PSDs of the control equivalent inputs for each control are first generated. These PSDs are then each approximated by a transfer function to capture the turbulence characteristics of the corresponding axis. For a standard helicopter, this modeling process yields four transfer function filters, one for each control input.

When using the CETI model for **simulation**, white noise is passed through these transfer function filters to generate control equivalent turbulence inputs. These are added to the pilot input, sending a combined disturbance to the vehicle swashplate.

3. FLIGHT TESTS

To identify the new CETI models for forward flight, tests at four flight speeds; hover, 30 kts, 60 kts, 90 kts; were conducted in the summer of 2019. The baseline height for these flight tests was selected as 500 ft AGL (Above Ground Level). To investigate the influence of altitude, additional tests at 1000 ft and 5000 ft MSL (Mean Sea Level) were conducted in 2020. Both sets of flight tests were conducted using the same procedure described in the following paragraphs. Furthermore, the same evaluation pilots were used.

To increase the potential to encounter a broad range and intensity of turbulence, the majority of flights were conducted within the Harz mountains. The pilots selected trajectories (e.g. flights through valleys) in an attempt to encounter turbulence. It was not possible to directly measure the mean wind speed encountered during tests.

All flight tests were performed using the ACT/FHS, a highly modified version of the EC135 helicopter. The response characteristics of the aircraft do not reflect those of the serial aircraft type. All tests were performed using the bare airframe to allow subsequent CETI extraction to be conducted using the corresponding models obtained using system identification.

To collect flight data for extraction of turbulence models, the perfect condition would be to remain at the desired flight speed without additional pilot inputs. In this condition, perturbations from trim condition of the helicopter are due only to the external influence of turbulence. Due to the inherent instabilities in rotorcraft, this is often not possible, as the vehicle diverges from the given trim condition. As a result, it is necessary for the pilot to apply corrective inputs. This was the case during the flight tests conducted for this research effort.

As previously mentioned, the pilots were instructed to provide control input corrections only when necessary. As it was not desirable for pilots to follow tight performance tolerances, these were not rigidly defined prior to the tests. As a guideline, pilots were asked to maintain flight speed between ±10 kts, and height with ±150 ft. Pilots were also instructed to maintain a constant heading and track within ±5 deg. Pilots confirmed that these were suitable tolerances to conduct the flights. Each run was initiated once the pilot had established trimmed conditions at the desired altitude and flight speed. Following the tests, pilots commented that the flight performance tolerances were suitable and representative for flights in turbulent conditions.

To collect sufficient data for extraction of turbulence models for a frequency range starting at 0.5 rad/s, it is recommended that data recordings between 60-90 seconds are used (see Ch. 5.1 of Ref. [16]), within similar turbulence conditions. This is to allow for sufficient data to perform the extraction process. This practice was previously used when collecting data during hovering/low speed flight. During forward flight tests however, it was challenging to find consistent conditions throughout the length of each run. For most test points, it was not possible to find a suitable test area where turbulence intensity remained similar for a long time period. This was reflected through additional comments given by the

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

pilots. For a number of runs, the assessing pilots stated that the ratings awarded where based upon the most severe turbulence experienced during the run, and not based upon the average experience.

In the early investigations from Ref. [11], only generalized feedback regarding the level of turbulence was collected from pilots. This unstructured approach to obtaining feedback regarding the severity and intensity of the turbulence was of limited use when performing data processing. Therefore, in the 2019 flight test campaigns, pilot opinion ratings were obtained using the Turbulent Air Scale (TS) from Ref. [17] and shown in Table 1.

The TS is a 10-point scale, whereby the pilot is asked to assess the "Air Condition". A rating of TS = 1 is calm air; TS = 2-3 are classified as "Light" turbulence; TS = 4-6 are classified as "Moderate" turbulence; TS = 7-8 are "Severe" turbulence; and TS = 9-10 are classified as "Extreme". Differences between the turbulence levels are defined both in terms of severity and frequency of turbulence. The method has been developed for use in flight testing.

Table 1 Turbulent Air Scale (TS)

Scale	Definition	Air Condition
1	-	Flat calm
2	Light	Fairly smooth, occasional gentle displacement
3		Small movements requiring correction if in manual control
4	Moderate	Continuous small bumps
5		Continuous medium bumps
6		Medium bumps with occasional heavy ones
7	Severe	Continuous heavy bumps
8		Occasional negative "g"
9	Extreme	Rotorcraft difficult to control
10		Rotorcraft lifted bodily several hundreds of feet

As the TS rating method had not been used before, the plausibility of the given ratings was first checked by comparing them to measured data that should also correlate with the intensity of the turbulence. Figure 3 shows the standard deviation of the measured airspeed versus the TS ratings given by the pilots. It can be seen that there is clear correlation between the two. Similarly, it is shown in Ref. [12] that the intensity of the turbulence is also reflected in the strain gauge measurements for the bending of the tail.

On a number of occasions, the pilots found it difficult to understand the terminology of the scale. Often the pilots would ask for clarification regarding the interpretation of terms. To the authors' knowledge, there is only limited documentation outlining definitions and the proposed use of the TS scale.

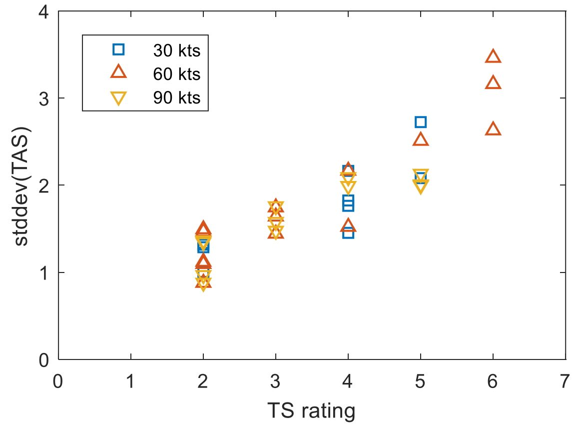

Figure 3 Standard deviation of airspeed vs. TS rating

One aspect that was raised was with regards to whether the scale should be used to assess "turbulence" or "ride qualities" (RQs). Here, the pilot was unsure whether he should assess directly the perceived level of disturbance of the aircraft (including flight control systems) or if he should relate the disturbances felt to the expected level of atmospheric turbulence. The former is related to 'ride qualities', rather than a direct assessment of turbulence. The latter was considered to abstract and difficult to assess without an in-depth knowledge of the influence of the flight control system. For this reason, the pilot was asked to assess the turbulence in terms of disturbance that was perceived during each test.

As previously stated, during flights at forward speed, the level of turbulence was constantly changing. Over the period of 60-90 seconds, a range of conditions were experienced. This made awarding ratings using the TS challenging. Here, pilots compromised by awarding ratings based on the worst condition experienced during the respective test run. This was therefore not necessarily representative of the average turbulence experienced, making the analysis using the process shown in Figure 2 challenging.

To account for this, during the 2020 campaigns, an alternative assessment scale was proposed and flight tested. This scale is shown in Table 2 and is referred to as the "Ride Qualities" (RQ) scale. It was developed through discussions with the pilots.

The RQ scale is intended to be a simple method of determining the level of disturbance felt and the frequency of occurrence. These two parameters were of most interest when determining the 'level of turbulence' for identification of CETI models. The disturbance is characterized by a number and the frequency of occurrence by a letter.

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

Table 2 Ride Qualities (RQ) Scale

Ride Qualities		Frequency of Occurrence			
		Once	Sporadic	Frequent	Persistent
Aircraft Disturbance	None	0			
	Light	1-A	1-B	1-C	1-D
	Moderate	2-A	2-B	2-C	2-D
	Severe	3-A	3-B	3-C	3-D
	Extreme	4-A	4-B	4-C	4-D

The scale may be used to award a single rating during a run or, if applicable, a number of ratings depending on the RQs experienced. For example, the pilot may award a rating 1-D and 4-A. This would indicate that a persistent light turbulence was experienced with one extreme disturbance.

The proposed RQ scale was used in parallel to the TS for the last two flight tests in 2020. Table 3 shows a comparison of the given TS and RQ ratings from these flights. As stated above, the turbulence level was constantly changing during the forward flight runs. This made it challenging for the pilot to award a single rating for a 60-90 second run. To solve this, the pilot awarded a TS rating corresponding to the most severe turbulence experienced during the run. For example, when awarding TS = 7, the pilot commented that during a period of the run, he experienced "continuous heavy bumps". Using the RQ scale, this problem was mitigated, as the pilots could give an indication of both the severity and frequency of these "heavy bumps". In this case, the pilot awarded 3-B, indicating severe aircraft disturbance but only sporadically. This matches the feedback given by the pilot.

Table 3 Comparison of TS and RQ ratings

TS	1	2	2-3	4	5-6	6	6-7
RQ	0	1-A	1-B	2-B	2-D	3-C	3-B

4. MODEL EXTRACTION

4.1. Power Spectral Densities

CETI traces were extracted using the process shown in Figure 2. The PSD for each input were determined using the chirp-z-transform based routine that had been applied in the determination of the turbulence models for hover from Ref. [11]. In these earlier evaluations, the data was band-pass filtered before the calculation of the PSDs. As pilots had stated that the resulting turbulence models lacked the low frequency disturbances, unfiltered data was used for the PSD calculation.

Figure 4 shows the PSD of the extracted CETIs for all runs at 60 kts. Not all turbulence levels are clearly separated, but a distinctive difference is visible between TS 2, TS 3-4, and TS 5-6 cases. Therefore, these three groups of TS ratings were chosen as low, medium, and high turbulence. All runs were grouped accordingly and the corresponding PSDs averaged for the subsequent modeling.

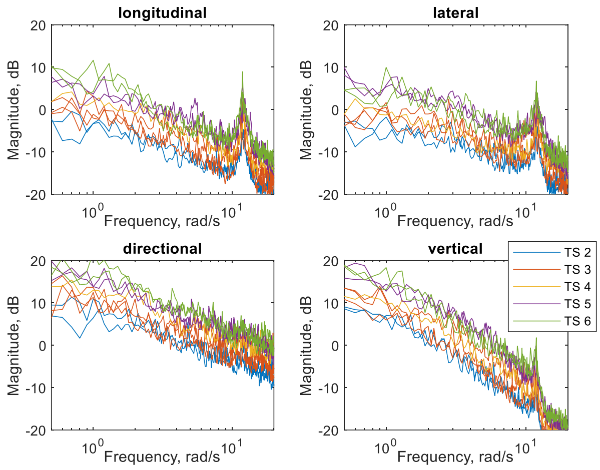

Figure 4 PSDs of the extracted CETIs (60 kts)

4.2. Basic Modeling

The same model structure as used in Ref. [11] for the hover case was applied for the turbulence models in forward flight, namely:

(1) $$G_{lon} = \frac{\delta_{lon,CETI}}{w_{noise}} = A_{lon} \frac{1}{(s+\frac{U_0}{L_w})}$$

(2) $$G_{lat} = \frac{\delta_{lat,CETI}}{w_{noise}} = A_{lat} \frac{1}{(s+\frac{U_0}{L_w})}$$

(3) $$G_{ped} = \frac{\delta_{ped,CETI}}{w_{noise}} = A_{ped} \frac{1}{(s+\frac{U_0}{L_v})}$$

(4) $$G_{col} = \frac{\delta_{col,CETI}}{w_{noise}} = A_{col} \frac{(s+20\frac{U_0}{L_w})}{(s+f_{p1}\frac{U_0}{L_w})(s+5\frac{U_0}{L_w})}$$

The model consists of 1st order transfer functions for longitudinal, lateral, and pedal inputs and a 2nd order transfer function for the vertical axis (collective inputs). The transfer functions for longitudinal and lateral control have the same denominator and only different amplitudes. The transfer function for collective is coupled to those for longitudinal and lateral inputs by U_0 / L_w.

In the turbulence models for hover determined in Ref. [11], the factor f_{p1} in the transfer function for collective from eq. (4) was set as a constant parameter, equal to 0.63. However, this value is valid

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

only for hover. It was found during the modeling process that, in order to match the corresponding PSDs, it was required to vary this parameter for forward flight.

Figure 5 shows the averaged PSD data and the identified models for the 60 kts case. It can be seen that the data from Figure 4 is grouped into three clearly distinguishable turbulence intensity levels and that the models fit the measured data well.

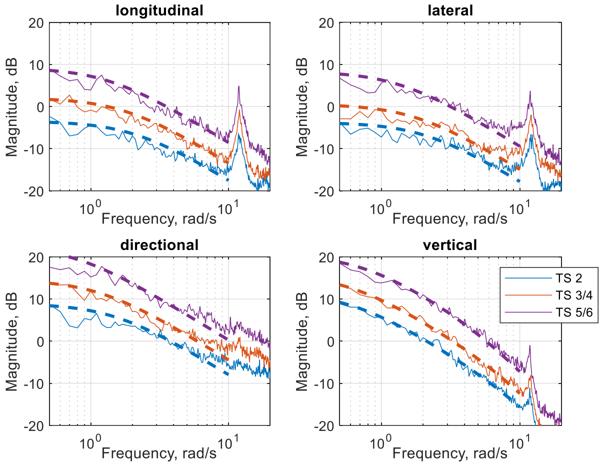

Figure 5 Grouped and averaged PSDs and extracted turbulence model (60 kts)

4.3. Model for Hover and Forward Flight

A goal of the CORINNE project is the development of one turbulence model for all speeds from hover to forward flight. Therefore, turbulence models using the above listed model structure were determined for 30, 60, and 90 kts forward flight. For hover, the data used in Ref. [11] was reprocessed using improved models of the ACT/FHS for the extraction of the CETI traces. Furthermore, unfiltered instead of band-pass filtered data was used for the determination of the power spectral densities.

The identified model parameters were then plotted as functions of turbulence intensity and speed. A second optimization step was performed to arrive at a model that can be smoothly interpolated between the speeds. In this step, the parameters from the separate identifications were modified slightly to arrive at smooth trends for all model parameters while not degrading the match of the individual PSDs significantly.

The corresponding results are listed in Table 4 and shown in Figure 6. It can be seen, that smooth surfaces were obtained for all parameters. The factor f_{p1} is equal to 0.63 at hover and reduced with forward speed. All amplitude parameters except for A_{lat} increase with speed and the amplitudes at the highest turbulence intensity level are bigger than those for the lowest level by a factor of 2-3.

Table 4 Identified parameters of the overall model

Param.	Turb.	Hover	30 kts	60 kts	90 kts
A_{lon}	Low	1.80	1.50	1.30	2.70
	Med.	2.40	2.35	2.15	3.30
	High	3.00	3.60	3.80	4.00
A_{lat}	Low	2.00	1.20	1.10	1.60
	Med.	2.70	2.00	1.80	2.40
	High	3.90	3.60	3.40	3.00
A_{ped}	Low	3.50	4.00	4.00	6.00
	Med.	5.00	6.00	6.00	7.50
	High	7.00	9.00	9.00	9.00
A_{col}	Low	0.35	0.50	0.56	1.10
	Med.	0.48	0.78	0.88	1.40
	High	0.75	1.70	1.80	1.80
$\frac{U_0}{L_w}$	Low	0.60	1.00	1.50	1.60
	Med.	0.70	1.10	1.60	1.70
	High	0.90	1.20	1.70	1.80
$\frac{U_0}{L_v}$	Low	1.60	1.10	1.05	1.05
	Med.	1.80	1.25	1.10	1.10
	High	2.00	1.40	1.15	1.15
f_{p1}	Low	0.63	0.50	0.45	0.40
	Med.	0.63	0.50	0.45	0.40
	High	0.63	0.50	0.45	0.40

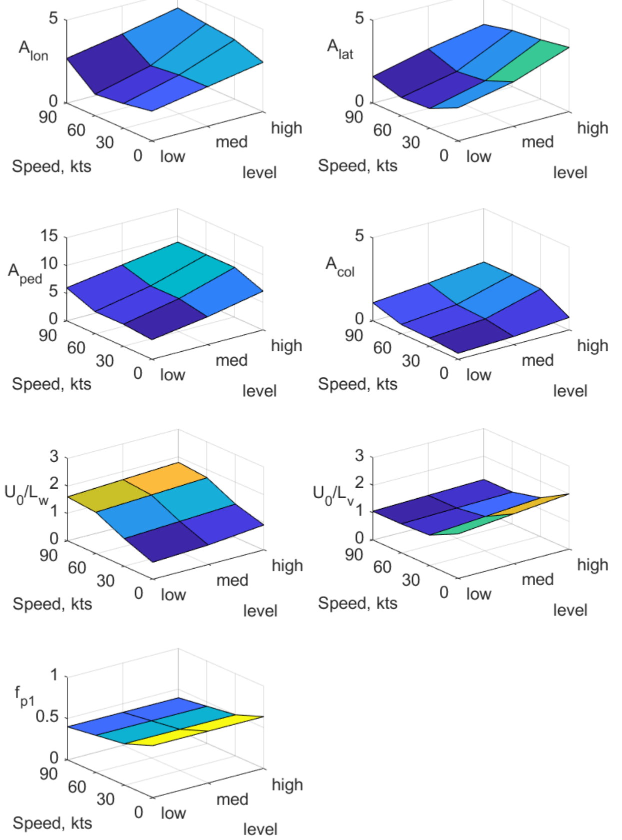

Figure 6 Model parameters vs. speed and turbulence level

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

4.4. Comparison with Dryden Turbulence Model

To investigate how the CETI models for forward flight compare with a Dryden turbulence model, simulator runs were conducted using a Dryden model (Ref. [18]) with different turbulence intensities at two altitudes (100 ft and 500 ft). CETI traces were then extracted from these runs and the PSDs of the CETIs compared to those from the runs where turbulence was simulated with the CETI model. Figure 7 shows that the PSDs of the CETI model compare well to those of the Dryden model at the lower altitude of 100 ft. The turbulence intensities of the Dryden model for an altitude of 500 ft, which is the altitude where the flight tests for the CETI model were conducted, are significantly lower.

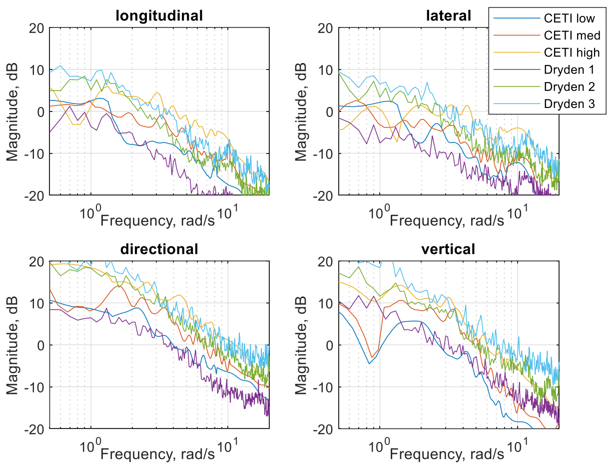

Figure 7 Comparison between CETI and Dryden turbulence @ 100 ft (60 kts)

4.5. Altitude Dependency

To investigate the reduction of the turbulence with increasing altitude, flights at the same location but at different altitudes were performed. For the evaluation it was assumed that the basic turbulence was constant and that the different levels of turbulence were only caused by the altitude variation. Flights were conducted at three altitudes; 500 ft, 1000 ft, and 5000 ft. Tests were performed at three flight speeds; 30 kts, 60 kts, 90 kts.

Figure 8 shows some results for 90 kts forward flight. The turbulence at 500 ft was rated as medium (TS 2.5 - 4) and the PSDs of the extracted CETIs match well with the corresponding turbulence model. It can be seen that the PSDs of the CETIs at 5000 ft have a similar shape as for the lower altitude but with a much smaller amplitude. The dash-dotted line in this figure is derived by scaling the low altitude (500 ft) models by a common factor of 0.35 for all controls. This simple scaled model fits the high altitude results quite well. The same effect was seen for all forward speeds and all turbulence levels that were tested.

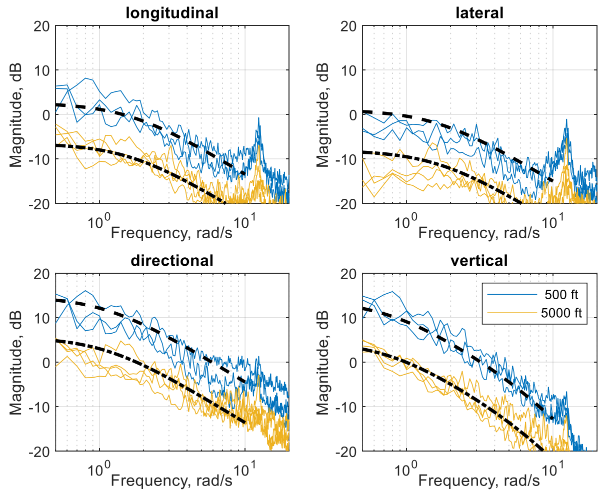

Figure 8 Extracted CETIs at different altitudes, baseline model (dashed) and scaled model (dash-dot) (medium turbulence, 90 kts forward flight)

As flights at 1000 ft were only available for two test points, no scaling for intermediate altitudes could be deducted. Therefore, linear scaling of the amplitudes $A_{lon}, A_{lat}, A_{col}, A_{ped}$ with altitude was used as a first modeling approach. The factor of 0.35 to derive a high altitude model from the low altitude baseline model worked for all cases where the turbulence level at low altitude was low or medium. When the low altitude turbulence was high, a stronger reduction by a factor of 0.1-0.2 was necessary. First results indicate that a simple linear scaling may be possible however, due to limited flight testing, further results are required to verify this.

4.6. Scaling to a Different Helicopter

In Ref. [14] equations are given that allow to scale CETI turbulence models to another helicopter. This scaling will be tested by generating CETI models for a large helicopter with the approximate size of a CH-53 from the ACT/FHS turbulence models. The relevant parameters for this scaling are radius R and rotational speed Ω of main rotor (MR) and tail rotor (TR). The corresponding numerical values for the two helicopters are listed in Table 5.

Table 5 Rotor parameters of ACT/FHS and CH-53

	EC135	CH-53
R_{MR}	5.1 m	11.01 m
Ω_{MR}	41.36 rad/s	19.37 rad/s
R_{TR}	0.5 m	2.44 m
Ω_{TR}	376 rad/s	82.9 rad/s

The transfer functions that the turbulence models from eqs. (1) - (4) have to be multiplied with are

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

(5) $$f_{lon,lat} = \frac{\Omega_{MR,EC135}}{\Omega_{MR,CH-53}} \frac{\left(s+{\pi U_0}/{8R_{MR,EC135}}\right)}{\left(s+{\pi U_0}/{8R_{MR,CH-53}}\right)}$$

(6) $$f_{col} = \frac{R_{MR,EC135}\,\Omega_{MR,EC135}}{R_{MR,CH-53}\,\Omega_{MR,CH-53}} \frac{\left(s+{\pi U_0}/{8R_{MR,EC135}}\right)}{\left(s+{\pi U_0}/{8R_{MR,CH-53}}\right)}$$

(7) $$f_{ped} = \frac{R_{TR,EC135}\,\Omega_{TR,EC135}}{R_{TR,CH-53}\,\Omega_{TR,CH-53}}$$

For the cyclic controls and for collective, scaling is performed with a transfer function that consists of a factor and a dipole. For the cyclic controls, the factor is the ratio of the rotor speeds, for collective it is the product of rotor speed and radius. The dipole is a function of the reference speed U_0, which is equal to wind speed for hover and is equal to flight speed in forward flight. The turbulence model for pedal is scaled with the product of tail rotor speed and radius. This scaling is independent of flight speed and turbulence level.

Figure 9 shows a comparison of the resulting turbulence models for hover. For the cyclic controls, the amplitude is increased due to $\Omega_{MR,EC135}/\Omega_{MR,CH-53} \sim 2$ and the dipole moves the curves towards lower frequencies. For collective, the factor is ~ 1 so that only the effect of the dipole can be seen. The scaling factor for pedal is $\sim .9$ which leads to a reduction in amplitude.

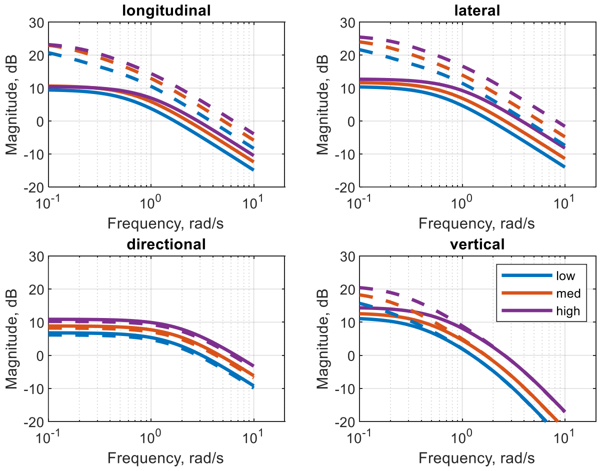

Figure 9 Turbulence models for ACT/FHS (solid) and CH-53 (dashed) in hover

As the scaling equations from eqs. (5) - (7) are valid for the swashplate angles, the gearing between pilot controls and swashplate angles for both helicopters has to be considered. This scaling has not been included in Figure 9 in order to better illustrate the scaling effect.

According to Ref. [14], scaling of CETI models with eqs. (5) - (7) is only possible for helicopters with the same configuration. As the CH-53 has a conventional tail rotor whereas the ACT/FHS is equipped with a Fenestron, it is to be expected that the scaled turbulence model will exhibit deficits in the yaw axis.

However, in Ref. [19] a method is given that allows to determine the radius and speed of an equivalent open rotor from the values for a shrouded rotor. Applying this method leads to a radius of 0.8 m and a rotor speed of 265 rad/s for an open tail rotor that is equivalent to the EC135 Fenestron.

5. EVALUATION

The identified models were implemented and tested in DLR's Air Vehicle Simulator (AVES, see Figure 10). AVES features a full-sized 6 degree-of-freedom electric hexapod motion platform, and a full replica of the ACT/FHS helicopter cockpit, the experimental helicopter maintained and operated by DLR. The simulation uses both hardware and software used in the ACT/FHS, including the flight control system software and active control inceptor sidesticks.

Figure 10 Air Vehicle Simulator (AVES) at DLR Braunschweig

AVES features a simulation model of the ACT/FHS. The simulation model has been developed using the HeliWorX simulation software suite, explained in detail in Ref. [20]. Differences between the model response characteristics and those of the aircraft may have influenced the perceived TS ratings. This consideration is discussed later in the paper.

5.1. Implementation

The models were implemented using a look-up table structure, based upon flight speed and desired turbulence level. Linear interpolation was used between the reference flight speeds (0, 30, 60, 90 kts). At the time of the investigations, the interpolation with respect to altitude was not implemented in AVES and was therefore not tested.

To modify the turbulence intensity, a selection switch was configured. This allowed the flight test engineer to modify the turbulence level during real-time simulation.

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

To check the implementation, CETI traces were extracted from the simulator runs with simulated turbulence following the extraction part of Figure 2 but using a model of the simulator instead of the helicopter model. PSDs were then calculated from the CETIs and compared with the underlying model (see Figure 6 and Table 4). Figure 11 shows the PSDs in comparison to the underlying turbulence model for the 60 kts case. It can be seen that there is a very good agreement between the simulated and the extracted turbulence even though the model was generated using flight test data and the PSDs were extracted using simulated data. The magnitude variations of the PSDs are larger than for the flight test cases (see Figure 5) because fewer runs were available for averaging.

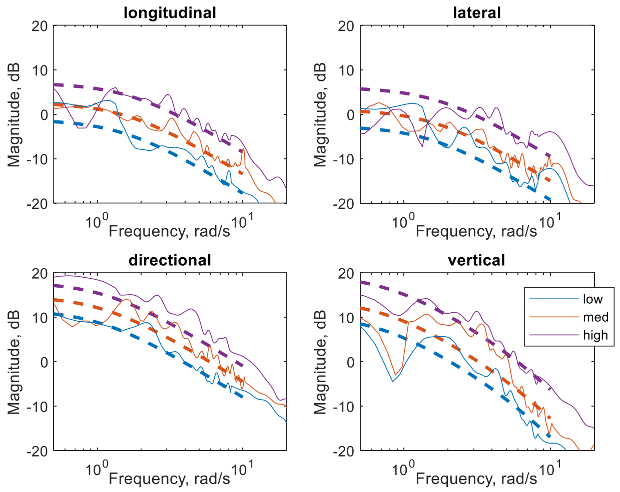

Figure 11 Comparison between simulated (dashed) and extracted (solid) turbulence

5.2. Full Evaluation of Model

Evaluation tests were conducted using the same test pilot who awarded ratings during the flight test campaigns. The same flight test procedures and assessment methods were used in the simulation evaluations. The pilot was asked to perform assessment using both the turbulent air scale (TS) and the Ride Qualities scale (RQ). This practice allowed direct comparison between perceived turbulence in the simulation and in-flight. Ratings were awarded directly after completion of each flight condition (speed and turbulence level). Turbulence was evaluated at the four flight speeds from the flight tests. The levels of turbulence for each flight speed were assessed in a random order.

The tests were performed using motion. In previous investigations Ref. [12], it was only possible to perform tests without motion. Pilots gave the feedback that this was a significant drawback and frequently commented that it was challenging to assess the influence of the turbulence.

With the motion active, the pilot stated that the turbulence felt much more realistic than in previous tests. The pilot commented that there was still a difference between the motion felt in the simulator and those that would be felt in the real helicopter. An example given was the response in the heave axis. On some occasions, significant height was lost during the encounters with turbulence. The pilot commented that had this happened in flight, he would have experienced far more motion in the heave axis, to give the sensation of 'falling'.

Table 6 and Table 7 show the TS and RQ ratings awarded by the pilot during the evaluations. These are shown with respect to flight speed and turbulence model. For all flight speeds, a single assessment run was performed. For the RQ ratings, two cases show two ratings. For these cases, the pilot awarded two ratings to reflect the situation experienced. Using the RQ scale, it is possible to award more than one rating for each test run to give more information about the RQs experienced. For example, in the case at 60 kts with medium turbulence, the pilot commented that moderate disturbance was frequently experienced during the test run. However, in addition, he also experienced one occasion of severe aircraft disturbance. For this reason, he awarded 2-C and 3-A for this test point.

Table 6: Turbulence Air Scale (TS) ratings awarded during evaluation campaign in AVES

Turbulence Model	Hover	30 kts	60 kts	90 kts
LOW	4	4	4	6
MEDIUM	5	4	5	6
HIGH	7	9*	6	6/7

**Due to loss of control towards the end of the test run*

Table 7: Ride Qualities (RQ) ratings awarded during the evaluation campaign in AVES

Turbulence Model	Hover	30 kts	60 kts	90 kts
LOW	2-C	1-D	2-B	3-B, 4-A
MEDIUM	2-D	2-B	2-C, 3-A	3-B
HIGH	3-C	4-B	3-B	3-C

As shown, the ratings awarded by pilot generally correlated with the expected trend with respect to turbulence severity. The RQ scale was found to give a broader range of ratings compared to TS. The suitability of the RQ scale was supported by the pilot, who consistently struggled to awarded ratings to describe turbulence with the TS scale. Using the RQ ratings, turbulence intensity was found to increase with flight speed. This is consistent with the models

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

identified. Furthermore, for almost all cases, the correct trend between turbulence model intensity and pilot RQ rating was observed. For one case (Low, 90 kts), the pilot commented that the LOW model felt more intense than the MEDIUM model.

At lower speeds (Hover, 30 kts), the pilot commented that the yaw motion induced by the turbulence was too strong and did not reflect real flight. On one occasion (30 kts, high turbulence), the yaw motion was so strong that that pilot effectively lost control of the aircraft. This is reflected in the ratings awarded by the pilot (9, 4-B). During this case, the turbulence was acceptable for most of the test run until a very strong yaw motion was experienced. For this reason, the pilot awarded 4-B as it was not experienced for the complete run. For this reason, ratings for the HIGH turbulence model at low speed are higher than those at higher speed. At 60 kts and 90 kts the yaw motion was not found to be a significant problem.

Ratings show that generally the turbulence experienced was stronger than expected. The pilot also commented that the disturbance experienced was larger than in-flight. There are a number of reasons hypothesized shown in the following section.

5.3. Discussion

5.3.1. Turbulence Test Procedure and Extraction

One issue that was found during the flight test was the difficulty to ascertain conditions of constant turbulence. In previous CETI investigations, flights were conducted only at hover. In this case, the aircraft is in a constant location. This is of course not the case during forward flight tests. For this reason, frequent changes in the turbulence intensity occur, due to local weather conditions.

For sufficient frequency content to extract CETI models, as stated earlier in this paper, test points between 60–90 seconds are recommended. Consistently during the flight test, pilots commented that within the period of 60 seconds, large differences in the turbulence intensity were apparent. This could not be avoided. During the CETI extraction process, which is conducted using analysis methods in the frequency domain, this aspect is not considered. The result of the extraction process will be an average turbulence level. For this reason, sporadic periods of extreme turbulence may be overlooked during the process. Results from this research effort however suggest that the generated turbulence models reflect conditions experienced during flight, despite this limitation.

5.3.2. Turbulence in Fixed-based Simulation Facilities

Tests performed were conducted using the motion platform of the AVES facility. This was found to be of high importance when awarding TS and RQ ratings. In previous tests, the pilots consistently stated that the turbulence felt unrealistic when performing tests in the fixed-base simulation. Without motion it was very challenging to differentiate between motion directly from the control of the helicopter and the external motions. In addition, the higher frequency disturbances were almost imperceptible without the use of vestibular feedback. With the motion active, the scenario was much more realistic and reflected turbulence expected in-flight.

An aspect that was not addressed in this research effort is the influence of motion parameter tuning on results obtained. For this evaluation, relatively low motion gains were selected. This was due to the large motions experienced during the completion of each test point. To ensure that the motion platform did not reach any travel limits, which would cause false cues, the motion gains in both primary rotational and translational axes were set to 0.2 for the tests. This is 20% of actual accelerations which would be experienced in flight. In previous work concerning fidelity of motion settings, Ref. [21], the motion settings used were found to be suitable when performing low speed rotorcraft mission task elements, with pilots stating high benefit from the motion, reflecting well real flight.

For the cases investigated in this research effort, the pilot stated that the turbulence was stronger than in flight tests. However, increasing motion gains further may lead to an even greater mismatch between the experience in-simulation and in-flight. Currently the influence of motion on the overall perception of turbulence in simulation has not been thoroughly researched and should form part of future efforts. Experience in this research effort shows that motion is of high importance when conducting tests in simulation concerning turbulence.

5.3.3. Turbulence Intensity and Model Deficiencies

One aspect that may have influenced ratings awarded by the pilot in the simulator is the helicopter model characteristics. The model used in this investigation represents the ACT/FHS aircraft used for the flight tests and the extraction of turbulence models. However, the characteristics of the AVES model are not identical to the ACT/FHS aircraft over the flight envelope. Efforts are currently under way to improve the AVES representation of the ACT/FHS as described in Ch. 7.2 of Ref. [22]. Differences between simulator model and aircraft flight characteristics may lead to a larger disturbance during the interaction with turbulence.

In particular, the AVES model of the ACT/FHS features a conventional tail rotor and not a Fenestron model as the aircraft. In the pilot tests, it was frequently commented that the yaw motion (at lower flight speeds) induced from the turbulence, was too

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021

large and unrealistic. This may have resulted from the model deficiencies and should be investigated in future efforts.

Furthermore, any deficiencies of the aircraft models used for the CETI extraction also influence the quality of the turbulence simulation. These models were derived from system identification and exhibit some deficits in the low frequency range. This might also have negatively influenced the turbulence intensity.

6. CONCLUSIONS

This paper presents new Control Equivalent Turbulence Input (CETI) models for both hover and forward flight. Turbulence models were extracted from flight tests performed with the ACT/FHS at four speeds and at different altitudes.

The results presented in this paper show that the CETI approach, originally developed for modeling turbulence in hover and low speed conditions, is also applicable to modeling turbulence over the flight envelope, including both with respect to forward flight and altitude. An overall model, valid for hover to forward flight could be developed using the same model structure as previously used for hover. The identified model parameters change smoothly with speed and turbulence level. A preliminary approach to account for altitude variation was developed.

The extracted CETI models were tested in a research simulation facility. Tests over the flight envelope of the ACT/FHS helicopter received favorable comments from the assessing test pilot. The use of four models over the flight range and linear interpolation between these points was considered sufficient to adequately simulate the turbulence in real-time simulation. Altitude variation will be tested in the future.

Pilots awarded turbulence ratings both in-flight and during simulator testing. The use of the structured feedback approach allowed cases to be grouped, to determine three suitable levels of turbulence (low, medium, high). Ratings obtained during simulation tests reflected those obtained during flight, giving further justification to support the correct modeling of turbulence.

Through pilot comments and experience, a large amount of feedback was collected regarding the suitability of the models, test methods and simulation set-up. Pilot feedback led to the development of the Ride Quality (RQ) scale as an alternative to the TS for turbulence rating.

The CETI models presented in this paper are suitable for use with the ACT/FHS aircraft. Using the methods proposed in Ref. [14], scaled CETI models for a large helicopter were developed. These models will be tested in the future.

7. ACKNOWLEDGEMENT

The investigations were conducted under the auspices of the national research project CORINNE (Comfort Of Ride Improved eNgiNEering) funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) within the German Aviation Research Program LuFo V-3.

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

The authors would like to thank the pilots involved in both flight test and simulation campaigns. Additionally, thanks are extended to all who supported the planning, preparation and execution of the flight tests and the simulator study.

8. REFERENCES

[1] Berger, T., Ivler, C., Berrios, M.G., Tischler, M.B., "Disturbance Rejection Handling Qualities Criteria for Rotorcraft," AHS 72nd Annual Forum, West Palm Beach, FL, USA, May 2016.

[2] Juhasz, O., Lopez, M.J.S., Berrios, M.G., Berger, T., Tischler, M.B., "Turbulence Modeling of a Small Quadrotor UAS Using System Identification from Flight Data," 7th AHS Technical Meeting on VTOL Unmanned Aircraft Systems, Mesa, AZ, January 24-26, 2017.

[3] Lehmann, P.H., Jones, M., Höfinger, M., "Impact of turbulence and degraded visual environment on pilot workload," CEAS Aeronautical Journal volume 8, pp 413-428, 2017, https://doi.org/10.1007/s13272-017-0246-3.

[4] Hoblit, F. H., "Gust Loads on Aircraft: Concepts and Applications, Washington, DC: AIAA Education Series, American Institute of Aeronautics and Astronautics," 1988, Chap. 13.

[5] McFarland, R. and Duisenberg, K., "Simulation of Rotor Blade Element Turbulence," NASA Technical Memorandum 108862, Jan. 1995.

[6] Gaonkar, G., "Review of Turbulence Modeling and Related Applications to Some Problems of Helicopter Flight Dynamics," Journal of the American Helicopter Society, vol. 53, no. 1, pp. 87-107, Jan 2008. https://doi.org/10.4050/JAHS.53.87.

[7] Baillie, S. and Morgan, J., "An in-flight investigation into the relationships among control sensitivity, control bandwidth and disturbance rejection bandwidth using a variable stability helicopter," 15th European Rotorcraft Forum, Amsterdam, Netherlands, September 1989.

[8] Lusardi, J., Tischler, M. B., Blanken, C. and Labows, S., "Empirically derived helicopter response model and control system requirements for flight in turbulence," Journal of the American Helicopter Society, vol. 49, no. 3, p. 340, 2004. https://doi.org/10.4050/JAHS.49.340.

[9] Lusardi, J., Blanken, C. and Tischler, M., "Piloted Evaluation of a UH-60 Mixer Equivalent Turbulence Simulation Model," AHS 59th Annual Forum, Phoenix, Arizona, May 6-8, 2003.

[10] Lusardi, J., von Gruenhagen, W. and Seher-Weiss, S., "Parametric Turbulence Modeling for Rotorcraft Applications - Approach, Flight Tests and Verification," Rotorcraft Handling Qualities Conference, The Foresight Centre, University of Liverpool, UK, 4-6 Nov. 2008.

[11] Seher-Weiss, S. and von Gruenhagen, W., "Development of EC 135 turbulence models via system identification," Aerospace Science and Technology, vol. 23, p. 43-52, 2012. https://doi.org/10.1016/j.ast.2011.09.008.

[12] Seher-Weiß, S. and Jones, M., "Control Equivalent Turbulence Input Models for Rotorcraft in Hover and Forward Flight," Journal of Guidance, Control, and Dynamics, Published Online: 7 May 2021, https://doi.org/10.2514/1.G005931.

[13] Malpica, C.A., Lawrence, B., Lindsey, J. Blanken, C.L., "Handling Qualities of a Large Civil Tiltrotor in Hover using Translational Rate Command," American Helicopter Society 68th Annual Forum, Fort Worth, TX, May 1-3, 2012.

[14] Hess, R. A., "A Simplified and Approximate Technique for Scaling Rotorcraft Control Inputs for Turbulence Modeling," Journal of the American Helicopter Society, vol. 49, No. 3, pp. 361-366, Jul 2004. https://doi.org/10.4050/JAHS.49.361.

[15] Seher-Weiß, S., "ACT/FHS System Identification Including Rotor and Engine Dynamics," Journal of the American Helicopter Society, vol. 64, No. 2, p. 022003, 2019. https://doi.org/10.4050/JAHS.64.022003.

[16] Tischler, M.B., Remple, R.K. (2012), "Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples", 2nd ed. American Institute of Aeronautics and Astronautics, Reston, VA.

[17] Anon., "Defence Standard 00-970, Design and Airworthiness Requirements for Service Aircraft, Part 7 - Rotorcraft, Issue 3," Ministry of Defence, Glasgow, UK, 2010.

[18] Anon., „U.S. Military Specification MIL-F-8785C," US, 1980.

[19] Ştefănescu, I.-B. and Stoica, A.-M., "An Atmospheric Turbulence Model for the Puma SA 330 Helicopter", UPB Scientific Bulletin, Series D: Mechanical Engineering, Jan. 2017.

[20] Gottschlich, J. and Jones, M., "Online Trimming of Flight Dynamics Models Using 2Simulate Real-Time Simulation Framework," AIAA Modeling and Simulation Technologies Conference, SciTech, Orlando, Florida, 2018.

[21] Jones, M., "The Suitability of Objective Motion Criteria for Rotorcraft Manoeuvres," AIAA Scitech 2019, San Diego, CA. https://doi.org/10.2514/6.2019-0180

[22] Tischler, M. B., White, M. D., Cameron, N., D'Agosto, S., Greiser, S., Gubbels, B., Guner, F., He, C., Horn, J., Hui, K., A., Jones, M., Juhasz, O., Lehman, R., Miller, D., Myrand-Lapierre, V., Nadeau-Beaulieu, M., Nadell, S., Padfield, G. D., Pavel, M., Prasad, J. V. R., Ragazzi, A., Richard, S., Scepanovic, P., Seher-Weiß, S., Stroosma, O., Soong, J., Taghizad, A., Tobias, E., M., Xin, H., Yavrucuk, I., and Lee, O., "Rotorcraft Flight Simulation Model Fidelity Improvement and Assessment", STO Technical Report, North Atlantic Treaty Organization, 2021. https://doi.org/10.14339/STO-TR-AVT-296-NU

Presented at 47th European Rotorcraft Forum, United Kingdom, 7-9th September, 2021