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SKAT – A LUFO V-1 PROJECT ON SCALING TECHNIQUES FOR ROTORCRAFT DESIGN

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Abstract

Family concepts are not easily transferable to rotary wing design. Kit and platform approaches have been only applied partially for helicopter design, for example to modular subsystems such as avionics. An important point to realize family concepts is scalability of specific technologies. Quick realization of innovations for a whole product range and the minimization of risks which accompany innovations is enabled by extended scalability and improved extrapolation capabilities. Therefore the LuFo V-1 project SKAT (Skalierbarkeit und Risikominimierung von Technologien bei innovativem Design) aims on the scalability of the main rotor system with respect to aerodynamics, acoustics and structural dynamics aspects to expedite the kit and platform approaches within the aeromechanics topics. The project includes two independent proposals. One proposal was made by Airbus Helicopter, which will be discussed in further detail here and the other one by DLR FT (Institut für Flugsystemtechnik), dealing with effectivity of higher harmonic control and individual blade control for five bladed rotors.

To push the before mentioned approach with respect to scaling within the rotorcraft design domain several subtopics are addressed for main rotors within the LuFo V-1 project SKAT. The first large topic is dedicated to the enhancement of methodologies to predict scaling effects in pre-design. This task comprises the investigation on aerodynamics phenomena for scaling, an improved rotor pre-design process and the definition of design spaces of dynamics parameters for pre-design phase. The second area, which is addressed, is methods for innovative rotor design, including main rotor scalability investigations with respect to aerodynamics, aero-acoustics, performance and limitloads as well as transition investigations, scaling laws for aeroelastics models and the establishment of an improved blade design process. The third part of the project deals with similarity of interfaces of the main rotor. The influence of the overall system on scaling of fatigue loads and existing load spectra was investigated. From an interfaces point of view the drive train was taken under closer considerations by modelling of low and high frequency torsion oscillations, investigations of the influence of the drive train, gear box suspension and rotor controls on the main rotor. For easier modelling of main rotor interfaces studies on model reduction were made. Also scalability with respect to aeromechanics stability, vibratory hub loads, active rotor control and vibro-acoustics transfer was investigated. Finally, the results obtained within the project will be assessed with respect to its industrial applicability especially for pre-development tasks, rotor aerodynamics and the overall main rotor system.

1. INTRODUCTION

The feasibility of family concepts for helicopters is strongly connected to the scalability of specific technologies. However, such concepts were not easily transferrable to rotary wing design due to the complexity and the large variety within the helicopter industry. Compared to the automotive world where kit and platform approaches are widely used to increase competitiveness, these approaches have been considered to be only partially applicable to helicopter design. Thus, they have been applied to modular subsystems, such as avionics.

For innovative designs, on the one hand, the capability of extended scalability allows quick realization of an innovation for a whole product range. On the other hand, the risks which accompany innovations will be minimized by increased capabilities of extrapolation. The LuFo V-1 project SKAT (Skalierbarkeit und Risikominimierung von Technologien bei innovativem Design) aims on the scalability of the main rotor system with respect to aerodynamics, acoustics and structural dynamics aspects to expedite the kit and platform approaches within the aeromechanics topics.

The project includes two independent proposals. One proposal was made by Airbus Helicopters, which will be discussed in further detail here and the other one by DLR FT (Institut für Flugsystemtechnik), dealing with effectivity of higher harmonic control and individual blade control for five bladed rotors.

The Airbus Helicopter proposal of SKAT is composed of several work packages, see FIG 1. The content of each of this work packages will be described in more detail in the following sections. The project duration was planned to be three years. However an extension of nine month was granted by the project funding organization. Four subcontracting partners take part in the project:

- Chair of Helicopter Technology of Technical University of Munich
- Institute of Aerodynamics and Flow Technology of DLR
- Flight Mechanics and Controls Lab of University of Stuttgart
- Institute of Engineering and Computational Mechanics of University of Stuttgart.

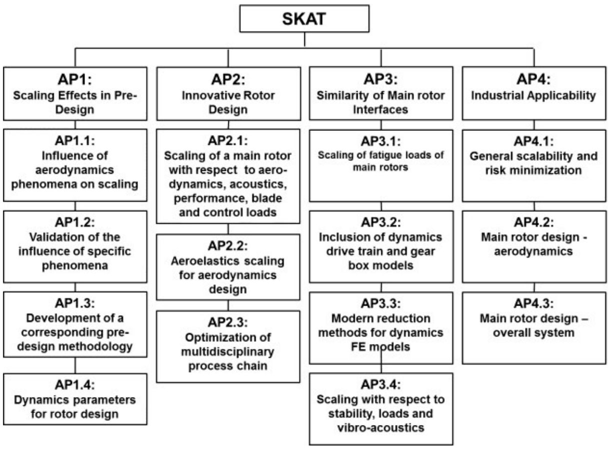

FIG 1: SKAT work packages of Airbus Helicopters' proposal

2. SYMBOLS AND ABBREVIATIONS

ART	Articulated rotor
BMR	Bearingless main rotor
c	Rotor blade mean chord
CFD	Computational fluid dynamics
HMR	Hingeless main rotor
ISA	International standard atmosphere
LoCAR	Low Cost Advanced Rotor System
Ma	Mach number
MR	Main rotor
OAT	Outside air temperature
R	Rotor radis
Re	Reynolds number
SDM	Simulation data management
SL	Sea level
TR	Tail rotor
U	Rotor blade tip speed
ρ	Density

3. SCALING EFFECTS IN PRE-DESIGN

In early stages of development, scaling of existing systems or components has been shown to be an adequate means for fast establishment of a new design. For helicopter rotors a solely geometric scaling law inherits a risk, as aerodynamics phenomena like Reynolds, Mach or solidity effects are neglected.

The investigations are targeting to expand the existing methods and tools environment in pre-design.

In pre-design within the range of performance prediction the modelling of the main rotor is essential to represent relevant physics. Adverse requirements have to be fulfilled. On the one hand high prediction quality is requested, resulting in highly complex numerical calculation methods which have to be validated against bench and flight tests. On the other hand a large number of concept and parameter studies are necessary during pre-design process. This results in the requirement to minimize calculation effort and complexity. This is in contrast to the previous requirement. This dilemma is extensively discussed in [1], where it is called the “problem of size”. Additionally the choice of modelling approach for performance calculations in the early development process also has to be adapted to other fields of interdisciplinary helicopter design. For example the mass estimation, which is derived empirically based on existing helicopter data, naturally is limited with respect to its accuracy and therefore the use of highly complex main rotor performance calculations is questionable. [2] supports this statement with the conclusion that for helicopter pre-design high fidelity calculations are not necessary. It is recommended not to use the most complex modelling, but to use the minimum complexity, necessary to reach the target. With respect to rotor scaling during pre-design consideration of subsystem level, low calculation effort, moderate modelling effort and prediction quality at least at level of mass estimation are requirements for modelling of main rotors. The desired consideration of subsystem level (engines, rotor, gear boxes …) excludes the use of simplest empiric design and calculation methods [3]. Typically, for modelling within helicopter pre-design the so called energy method is used. This method is extensively described in literature ([4], [5], [6], [7]). Also the use of the design and performance calculation tool “NDARC” [2], published in 2009 confirms the suitability of the energy method for helicopter pre-design.

The investigation on scaling effects in pre-design is divided into four subtopics:

- Influence of aerodynamics phenomena on scaling
- Validation of the influence of specific phenomena
- Development of a corresponding pre-design methodology
- Dynamics parameters for rotor design

3.1. Influence of aerodynamics phenomena on scaling

The previous considerations with respect to requirements for modelling physical effects within helicopter pre-design can be applied on the discussion of relevant aerodynamic phenomena. A similar analysis regarding the relevance of these phenomena was made.

Generally speaking, the flow field of a helicopter rotor is highly unsteady and complex. FIG 2 depicts schematically some aerodynamics phenomena for a helicopter in forward flight.

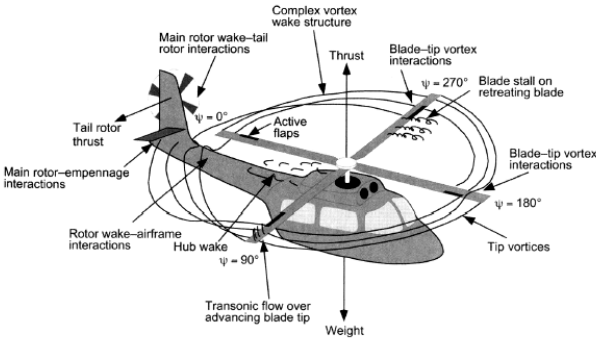

FIG 2: Scheme of aerodynamics phenomena within the flow field of a helicopter in forward flight [6]

Of special interest are the rotor related phenomena, some of which are discussed in more detail in the following.

- The rotor blades work in the wake of the leading blades and therefore under disturbed inflow conditions which leads to performance losses.
- At high forward speed transonic flow conditions can occur at the advancing blade causing a significant increase of power required accompanied by an increase of vibration levels and (control) loads [6], [7].
- At the retreating blade the local inflow speed can be drastically reduced up to reverse flow in the inner area of the rotor radius. Large angles of attack are necessary to compensate, leading to flow separation at the retreating blade for extreme conditions. Vibration and load levels as well as power required increase significantly.

Beside of these rotor phenomena, further relevant phenomena for helicopter pre-design were identified:

- Dependence of mean blade drag on lift
- Reynolds effects
- Effects at high advance ratio (forward / tip speed)
- Induced power losses

Based on this, the phenomena which were judged as significant with respect to scaling effects were investigated in further steps. This was of importance to be able to perform appropriate prioritization of parameter variations for risk mitigation and increase of efficiency for the validation of the influence of specific phenomena. For example, the compressibility can have strong adverse effects on power required. A steep increase of drag coefficient versus speed at high Mach numbers demonstrates the high priority of this phenomenon for helicopter design.

3.2. Validation of the influence of specific phenomena

This work was performed by Chair of Helicopter Technology of Technical University of Munich as subcontractor within the SKAT project.

The work, described in the previous section, results in the aim to determine or analyze performance data of the isolated rotor in dependency of rotor parameters subjected to scaling and the aerodynamics environment. To generate data suitable for pre-design processes, the evaluation has to be done according to parameters, usually used in the energy method. This requires differentiation in induced power, airfoil section power and parasitic power. The test procedure foresaw investigations within a parameter space around a defined reference rotor and condition. The parameter space can be divided into aerodynamics parameters (Re, Ma, ρ …) and rotor characteristic (R, c, U …). These two parameter spaces establish the calculation matrix for preliminary and final studies. The chosen tool for modelling is CAMRAD II [8].

As reference for the investigations the Airbus Helicopters H135 family was chosen, because a broad data base for different main rotor systems and validated models of different quality are available. A CAMRAD II model of the H135 was provided to Chair of Helicopter Technology by Airbus Helicopters. The CAMRAD II model was validated with respect to performance calculations by comparing CAMRAD II results to results computed by the performance calculations tool GENSIM. The successful validation establishes the reference model for following parameter variations.

The feasibility of the calculations was verified by a systematic exploitation of a preliminary calculation matrix. The end of the preliminary study was the definition of the final calculation matrix under consideration of preliminary results, convergence behavior and necessary calculation times. For the final calculation matrix the outer ranges of the atmospheric parameters (e. g. hot and high conditions) were defined as optional with low priority. For inflow modelling it was chosen to use uniform inflow and prescribed wake settings of CAMRAD II to save calculation time.

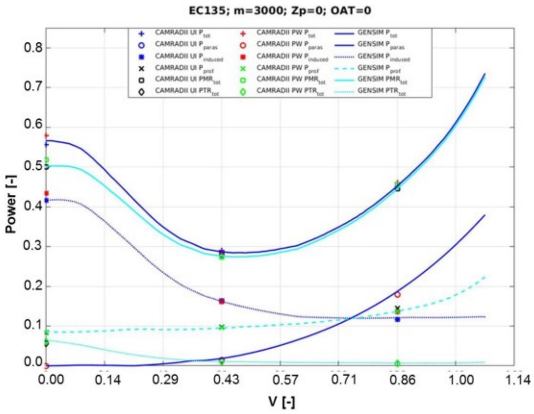

FIG 3: Comparison GENSIM versus CAMRAD II for m=3000 kg, Zp=0 ft; OAT=0°C

FIG 3 shows the parameters, used for validation of the CAMRAD II model. The total power and its components, divided into their physical origin are shown, related to reference power. The comparison comprises CAMRAD II (uniform inflow and prescribed wake) calculations for two forward flight speeds and hover, represented by symbols, with the according characteristics, derived by GENSIM models, represented by lines, which show good agreement with flight test results. The comparison shows satisfactory agreement for pre-design purposes.

All CAMRAD II results, inclusive a special program for data evaluation were handed over to Airbus Helicopters by Chair of Helicopter Technology for further usage within the project SKAT.

3.3. Development of a corresponding pre-design methodology

Based on the theoretical basis and data, generated by the previous tasks, a suitable pre-design method for rotor scaling shall be established.

First the models developed for consideration of effects of aerodynamics phenomena on scaling were introduced in the pre-design software CHOPPER. For this the models had to be adapted to the CHOPPER software architecture. Afterwards a validation was performed to ensure comparable results between CHOPPER and the original modelling. Discrepancies of up to 4% were detected and are subject to further investigations.

In a second step the analysis of the before mentioned CAMRAD II calculation results was started. Up to now the analysis is limited to the baseline case of the EC135 T2. The results for total power, airfoil section power and induced power for uniform inflow and prescribed wake inflow models were compared to each other to get an overview about the accuracy, which can be achieved by CAMRAD II.

FIG 4 shows exemplary results. The total power results showed sufficient agreement, but the other two power components are outside the desired accuracy. Further investigations on the reason will be made.

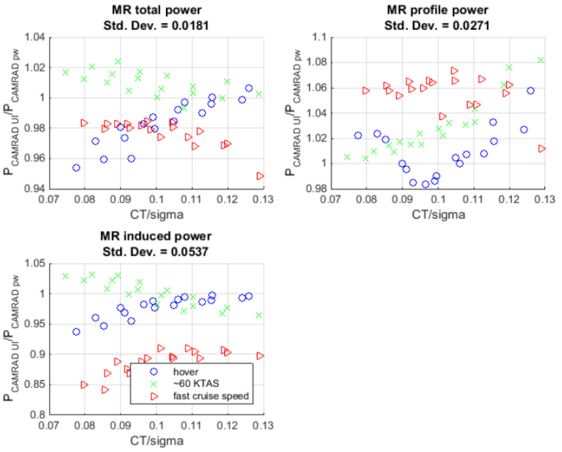

FIG 4: Comparison CAMRAD II uniform inflow and prescribed wake

As the quality of the planned pre-design scaling methodology is directly influenced by the validity and physical significance of the available data the analysis of the data base got a higher priority than originally planned. The validation with flight test data up to now was only possible for the baseline EC135 T2 rotor. Therefore all scaled cases are not validated and methods for a subsequent validation were searched for:

- Comparison to CFD calculations
- Comparison to validated GENSIM calculations
- Comparison to flight test results

The largest significance is expected for comparison with CFD results, meaning the largest time and cost effort. Direct comparison to flight test results only is of limited significance, as the full break down into all power portions is not available by these measurements. Therefore it primarily was decided to use existing GENSIM results. Here validated results for the main rotor, investigated in the first steps as well as results for the H135 and for a prototype rotor with radius of 5.4 meters are available. In dependency on the validation results a decision whether to use CFD calculations or not shall be taken and the pre-design method shall be finished.

3.4. Dynamics parameters for rotor design

To support pre-design, usually design corridors are defined for main rotor development. In contrast to already existing design corridors for mission profiles risk mitigation for pre-design based on design corridors for dynamics parameters was established. Dynamics parameters are meant to be parameters, which have significant meaning for evaluation of rotor dynamics.

First, relevant dynamics phenomena, related to helicopter main rotors were used to identify associated parameters. 32 parameters were identified, corresponding to the eight dynamics fields, listed in TAB 1.

Stability	**Forced Response**	**Others**
Ground and air resonance	Critical speeds	Track and balance
Rotor-structure-coupling	Vibratory loads	General parameters
Stability of drive system		

TAB 1: Dynamics fields for parameter evaluation

This number of parameters is too large and a lot of them are not available during pre-design phase. Therefore several filtering processes were performed to reduce the number of parameters to a reasonable value. Especially the parameter reduction performed in co-work between dynamics and pre-design departments gave a significant reduction. Out of the original 32 parameters seven suitable parameters for pre-design were filtered out and design windows were defined.

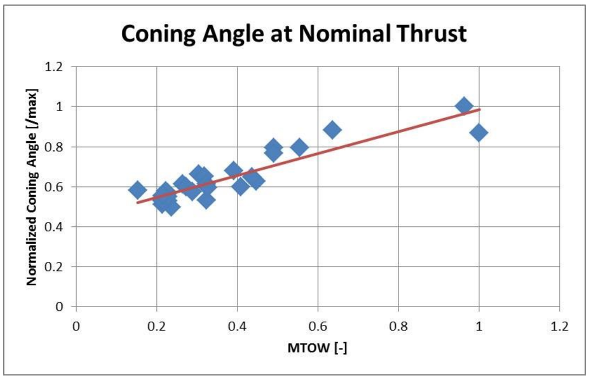

FIG 5: Coning angle versus maximum take-off weight

Here, as example for a design corridor the coning angle is presented. A large coning angle can give a hint on air resonance issues in later flight test stages. Generally, large helicopters have larger coning angles. During maneuvers with large vertical acceleration the coning angle increases and careful flight testing with respect to air resonance tendency has to be performed to ensure stability. FIG 5 shows the normalized coning angle for nominal thrust versus maximum take-off weight (related to max. in fleet) for a significant part of the Airbus Helicopters fleet. The characteristics nearly represent a straight line. The actual coning angle shall not be significantly larger than indicated by this line for a given take-off weight.

4. INNOVATIVE ROTOR DESIGN

The second area, which is addressed, is methods for innovative rotor design.

4.1. Scaling of a main rotor with respect to aerodynamics, acoustics, performance, blade and control loads

This task has the aim to enable fulfillment of different requirements for a helicopter by using scaling laws and performance predictions, enhanced by consideration of transition effects. These requirements incorporate work on modified mission scenarios for an existing helicopter as well as the development of a new helicopter based on already existing models. Therefore scaling of rotors and transition effects were investigated and their influence on aerodynamics, aeroacoustics, performance and limit loads was analyzed.

4.1.1. Investigations on scaling of main rotors with respect to aerodynamics, acoustics and performance

Performance

For new main rotor designs a reliable calculation model for prediction of power requirements is necessary. A modelling approach which enables scaling of existing, validated models is chosen. By gradually adapting the existing rotor model a new calculation model is generated.

The initial and the target rotors were chosen in a way that they differ in specific, known parameters. The most important parameters were rotor diameter (+10%), blade twist (+100%), tip speed (-5%) and planform shape. Additionally the used airfoils differed for the two rotors.

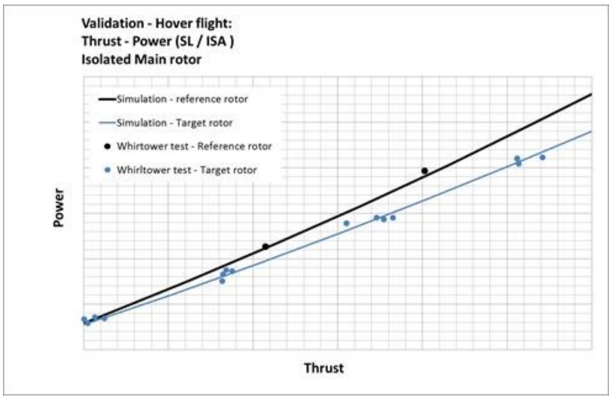

FIG 6: Validation of models with whirltower test data

The validation of the models is based on the hover power requirement of the isolated rotor. The test data was taken from whirl tower test results and cover a variation of rotor thrust. FIG 6 shows the comparison between calculations and test data. A good representation of the test data by the models can be seen and the models can be used as baseline for further investigations.

Based on the initial model a stepwise adaption to the target rotor was performed. First the radius was increased, than the blade twist. Afterwards the airfoils were changed, followed by tip speed and chord. The modification of thrust-power characteristics for hover flight condition in 10000ft ISA for these steps is shown in FIG 7. The diameter increase lead to a decrease of power required by 10%, the twist increase to 3% power decrease and the new airfoils to 0.8%. The rotor speed reduction showed no effect, as it had to be covered by an increase in mean chord.

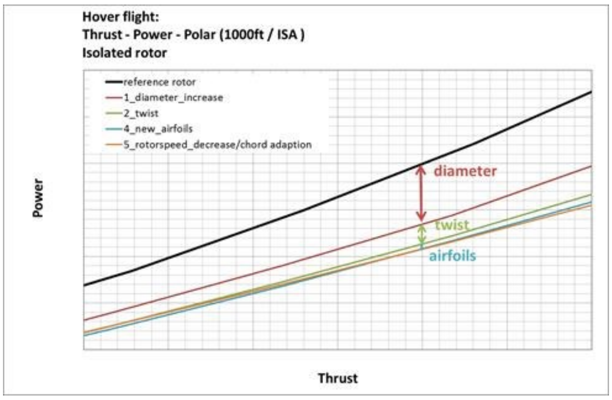

FIG 7: Influence of rotor blade parameters on hover power requirement

Acoustics and aerodynamics

The aim of this task is to increase acoustics predictability, using two known rotors and their corresponding calculation models. Numerical simulations in the fields of aerodynamics and acoustics were performed. For fly over conditions a higher order WENO method within the CFD code FLOWer was used. The combination of this method with fine resolution in time and space enables detailed acoustics evaluation of the results. To check on the differences in predictability for different rotors, the H135 rotor as well as the BLUECOPTER™ rotor were modelled and investigated. For approach flight conditions, CAMRAD II models with free wake were used. For both methods the acoustics part is treated by the ACCO code. To compare simulation and measurement results, a breakdown of source terms was performed.

FIG 8 shows mean EPNL levels (mean value from retreating, center and advancing microphone) for BLUECOPTER™, H135 and H145 during ICAO approach. The predictability of the calculations is judged well.

For fly over condition forward flights speed of 90 % of level flight speed with maximum continuous power was used. FIG 9 shows the flow field around the BLUECOPTER™ rotor in level flight condition, calculated by FLOWer with WENO.

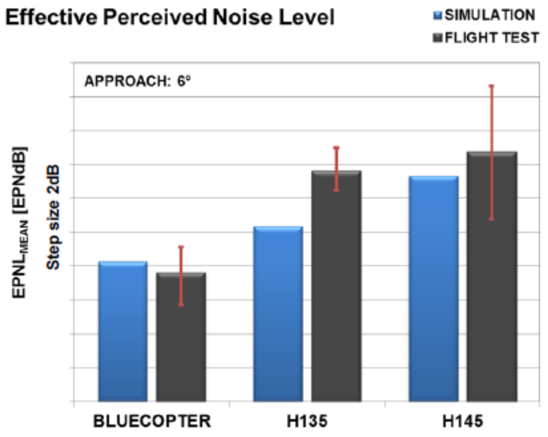

FIG 8: Mean EPNL levels for different helicopters

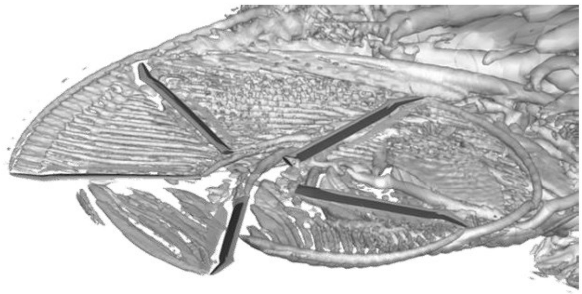

FIG 9: Numerical aerodynamics simulation

The tonal part of the main rotor is represented well, when evaluating the ACCO results. The broad band noise parts are missing. This explains a constant offset of several dB, when comparing simulation and test. Broad band noise will be treated in another LuFo project named CHARME to fill this gap.

4.1.2. Investigation on transition at main rotor blades

In order to increase the accuracy of performance calculations, future performance prediction should include boundary layer transition effects. Therefore, a new laminar-turbulent transition prediction tool was implemented in the CFD solver FLOWer. In addition, whirltower tests (FIG 10, left hand side shows the blades mounted on the whirltower) with transition detection by infrared thermography measurement were performed to study the transition occurring on blade, and the experimental data was used to validate the CFD tool. The work on boundary layer transition on the main rotor blades was done by Institute of Aerodynamics and Flow Technology of DLR.

The measurement of the transition position was performed using two infrared cameras, simultaneously recording images from the lower and the upper sides of the blade. For effective measurements, one of the blades was heated up to 60°C by means of hot air to achieve a temperature difference between the blade surface and the airflow. Due to the different magnitude of heat transfer from the rotor blade into the air in laminar and turbulent flow, respectively, a temperature difference between laminar and turbulent zones appears which can be evaluated by infrared recordings. FIG 10, right hand side, shows an instantaneous infrared image of the blade's upper side for a hover condition, with dark and bright greyscales representing cold and warm temperatures, respectively. The erosion protection at the blade leading edge can clearly be identified by the black stripe (due to reflection on the metal surface). Downstream in chord direction, an area of laminar flow can be seen (light grey, warm), followed by a larger area of turbulent flow (darker grey, cool). The change from warm to cool temperatures indicates the location of the laminar-turbulent transition. The quantitative evaluation of the transition position was performed based on a planar view of the rotor blade which was recalculated by an automatized image reconstruction of the infrared recordings.

Foto: DLR AS©

FIG 10: Rotor on whirltower (left hand side) and infrared picture of upper side of blade (right hand side)

For the numerical simulation of the transitional flow around the blades, a new transition prediction tool for rotor blades was developed based on empirical criteria, and was implemented in the CFD code FLOWer. The code was adapted to industrial needs and validated against the experimental results. In general, a good agreement with the experiment is reached. Deviations can mainly be observed in the inner part of the rotor blade's lower side. A reason for this is seen in the influence of the root vortex effects between the experiment on the whirltower and the numerical simulation with a rigid blade in a simplified setup. The numerical transition prediction within the code FLOWer is performed in three steps based on flow data along airfoil sections.

- Determination of local inflow conditions
- Calculation of laminar boundary layer parameters
- Prediction of laminar-turbulent transition by evaluation of transition criteria

Due to the calculation of laminar boundary layer parameters along the mesh lines of the airfoil sections some limitations arise within the usual method. To overcome the limitations, the newly implemented transition prediction within SKAT uses the approach to share the missing block data and flow parameters between all involved processes. Therefore the data structures were extended and the exchange of mesh coordinates established. The combined coordinates and flow parameters are handed over to the transition module. Finally the position of the laminar-turbulent transition is transformed into the original block structure. While the chosen concept of the data exchange causes limitations for the mesh topologies to be used, it is ensured that the FLOWer meshes for rotor blades existing at Airbus Helicopters can be used without modification. The only task is to define the mesh blocks, which are combined into a group for transition prediction, within the FLOWer topology data file.

The implementation of the transition prediction within FLOWer was tested by DLR for several example cases:

- Steady flow around a wing
- Harmonic oscillation of a 2D airfoil
- Helicopter rotors in hover and forward flight condition

4.1.3. Investigation on scaling of main rotor limit loads

The scaling of limit loads was investigated in this task. The influence of design parameters as plan form, blade chord distribution, blade twist and airfoils on limit loads was focused on. The process to determine and scale blade loads was divided into three steps:

- Geometric scaling
- Loads calculation with in-house tools
- Establishment of a new scaling process to determine blade loads with CAMRAD II

Dynamic stall at the retreating rotor blade causes strong, non-linear effects, dimensioning the rotor controls due to its influence on blade torsion. Therefore the scaling of control loads was a significant part of the task. The process for scaling of control loads was divided into two steps:

- Geometric scaling
- Establishment of a new scaling process to determine blade loads with CAMRAD II

An improved rotor model for the LoCAR (LuFo V-3 project) rotor for highly loaded flight conditions was validated. Special focus was set on the proper adaption of the dynamic stall models according to the airfoils used for this rotor. By means of this model the quality of the scaling process for limit loads was validated.

By means of the process, developed in SKAT, blade and control loads for complex rotor blade geometry can be predicted even for aerodynamic demanding flight conditions in future. Also highly loaded flight conditions can be considered in the loads prediction. Therefore this process is suited to predict limit loads.

4.2. Aeroelastic scaling for aerodynamics design

Within this work task the aerodynamic and aero-acoustic main rotor design process shall be improved by establishing aeroelastic scaling laws. For example, when modifying blade chord of a reference blade also structural properties as moments of inertia, stiffness, mass distribution, etc. are modified. The aim of this work is to enable quick adaption of dynamics parameters for a new rotor blade, based on an existing reference rotor blade and therewith speed up optimization processes.

Up to now a simple geometrical scaling of structural parameters as stiffness, mass and inertia based on a dynamics CAMRAD II model was used for optimization tasks within aerodynamics and aero-acoustics. For scaling purposes the blade’s cross section had to be simplified to enable scaling according to section length and thickness. Geometric parameters like reference axes directly had to be taken from the blade design and had to be adapted.

Within SKAT this scaling procedure was extended. Additional design parameters like blade twist were included for scaling. Also a radius scaling procedure was introduced. Here geometric parameters of the reference model are scaled by consideration of radius changes. The importance here lies in the modelling technique where all distances are related to radius. As different CAMRAD II versions enable the usage of different reference coordinate systems the scaling tool also was adapted to switch reference systems to handle different software versions.

As validation a hover flight case for the upgrade of the H135’s rotor was chosen. Here the rotor radius was increased by 2%. Originally, to generate a CAMRAD II model the existing rotor model was extended in the outer radius range and a lot of parameters had to be corrected manually, as they were related to rotor radius. With the procedure, derived from SKAT the rotor radius change could be implemented automatically. For validation purposes the figure of merit was used. The calculation results for the scaled rotor were within numerical accuracy of CAMRAD II, compared to the original dynamics model of the larger rotor.

4.3. Optimization of multidisziplinary process chain for aeroelastic rotor models

An efficient and fast establishment of aeroelastic rotor calculation models is essential for checking on scaling properties for various disciplines like aerodynamics, aero-acoustics, performance, loads and stability. The industrial approach is to use highly specialized codes, using multibody systems and elastic beam theory on structural dynamics side and lifting line methods with different inflow models on aerodynamics side. For high accuracy and large detail requirements a coupling of the rotor codes to CFD is performed. To set up the aeroelastic rotor models a main task is to provide cross section data for the elastic beam theory, as well as blade aerodynamics data for the lifting line theory, both based on blade design. A large potential to improve the establishment of aeroelastic models is seen within the fields of standardization and automatization. The task is divided into two subtasks: The establishment of an automatized process chain and of a suitable database for aeroelastic rotor models.

4.3.1. Highly automated process chain for rotor blade design

To establish an automatized process chain, involving the disciplines design, stress, dynamics, loads and aerodynamics, the actual rotor blade design process was analyzed in depth. Interfaces between departments were identified and inputs and outputs were defined. The process and interface identification resulted in an extensive document, describing the cooperation between the five departments, mentioned before, and giving advice how to improve the processes. The analysis of the process revealed the need of a common data base including a strict version management. Another potential improvement was identified within harmonization of coordinate system definitions. A standardized reference system for each task reduces the risk of errors within data exchange and eases the usage of data, originated by other disciplines.

This process chain was investigated with respect to its suitability for automatization and an optimization took place. The goal was to stick to existing commercial or in-house tools of each discipline and connect them via a commercial simulation data management (SDM) tool. The aim is a reduction of development time and cost as well as the reduction of calculation errors, caused by insufficient data exchange. To select a proper SDM tool first a search was performed and then four suppliers for such software were invited to present solutions. Afterwards a requirement specification document was established. The suppliers all gave an answer to the specification. A decision matrix based on the requirements document and on considerations regarding costs and support offers was established. The matrix was harmonized between the involved departments and several members of each department filled the matrix with ratings. A favorite supplier was found by this way. However, after deciding for one supplier the process management strategy for design at Airbus Helicopters was changed and the acquisition of a SDM tool was postponed and finally cancelled. Instead of using a software tool the process chain was tested without automatization by manual control of data exchange. FIG 11 is a schematic view how the process chain works by personal exchange of data with distinct nomenclature and defined structures and formats.

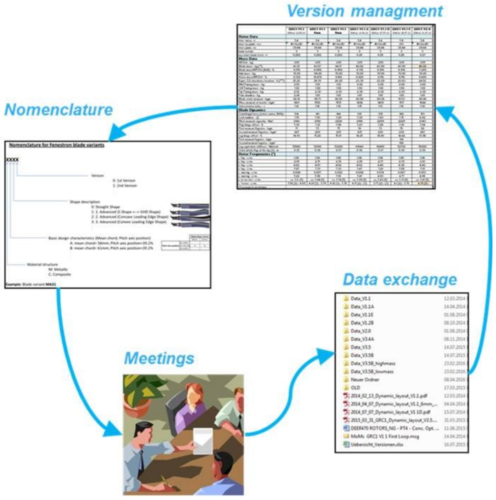

FIG 11: Implementation of rotor design process chain without SDM

The implementation of the manual process brought improvements within development speed and costs. The demonstration took part within the developments for the GRC1 rotor of Cleansky project and the IFR-HeliCo demonstrator rotor. For all contributors clear efficiency increase for the investigation of lots of versions during interdisciplinary rotor design was observed. During process evaluation the clear definition of process steps and data conventions were highlighted as large advantage, compared to the previous procedures. Also a clear formulation of the design specification and the early and close involvement of all contributors were identified as essential. Further improvement possibility was identified within the documentation of data, exchanged between different contributors.

4.3.2. Aeroelastics main rotor model data base

An aeroelastics main rotor model database was defined and established to ease multidisciplinary usage of the models within the design process. First a requirement specification document for the data base was generated. Beside the requirements for the data base itself, the document also gives a detailed description of the modelling process and the associated data for the rotor code CAMRAD II. The data base also should have been connected to the SDM system, described in the previous chapter. However, as explained before, the SDM system was not implemented. Of course, the data base also can be used without SDM system and as it was judged to be an important feature in process data management it was finally set up. A modular setup of the data base was defined, which is also able to include airframe data management.

5. SIMILARITY OF MAIN ROTOR INTERFACES

The third part of the project deals with similarity of interfaces of the main rotor.

5.1. Scaling of fatigue loads of main rotors

During helicopter operation main rotor and main rotor controls are subject to severe dynamic loads. For an efficient design an analysis of parts lifetime is necessary at an early stage of development. The load spectra, required for lifetime calculations, cannot be derived by simulations. Instead load spectra derived by flight tests have to be adapted to new designs. Beside of scaling the main rotor design, scaling of existing test data has also to consider the design of the overall helicopter.

5.1.1. Scaling of load spectra

The transferability of load spectra, based on flight test data of existing helicopters, was investigated. The following strategies were defined:

- Physical / scientific approach:
  Based on physical relations a given load spectrum is scaled for a new rotor
- Statistic approach:
  The load spectrum is derived from load spectra of similar rotors
- Mixed approach:
  Both previous approaches are combined

To establish a rule for scaling based on rotor geometry a suitable strategy for each case was chosen from the above mentioned and validated by existing flight test data. Scaling matrices were set up to scale existing rainflow matrices under consideration of according time spectra.

5.1.2. Influence of overall helicopter on fatigue loads

The influence of modifications of the helicopter on fatigue loads of the main rotor and its controls was investigated. The modifications in focus were maximum take-off weight, center of gravity range, the aerodynamic configuration and maximum flight speed. These parameters determine the trim of the helicopter and therewith the mast moment. A scaling rule for all relevant main rotor loads with respect to all relevant flight conditions was established.

5.2. Inclusion of dynamics gearbox and drive train models

The dynamic system of a helicopter consists of main rotor, main gear box, intermediate gear boxes, engines, tail gear box and tail rotor. The drive train (shafts and gear boxes) distributes the power from engines to rotors. The main gear box with its mounting struts and/or membranes transfers main rotor forces and moments to the airframe. The drive train influences the torsional dynamic behavior of the main rotor in the low frequency range. As rotary speed and torque conversion normally is performed via several gear stages a high frequency excitation occurs due to gear intermeshing. Therefore this excitation is of relevance for vibro-acoustics. The gear boxes transmit vibration excitation from main rotor to airframe in the low frequency range via its mounting. This is of special relevance for crew and passenger comfort. These vibrations often are reduced by anti-vibration systems.

Within this task models and calculation approaches for different frequency ranges of aeroelastics/aeromechanics and vibro-acoustics shall be developed, which consider the influences of drive train and main gear box suspension.

5.2.1. Modelling of a helicopter drive train system for low frequency torsional behavior

A simple dynamic drive train model was established to enable the simulation of low frequency torsion oscillation behavior. As simulation environment SIMPACK multibody simulation software was chosen. The drive train model was combined with a main rotor model to achieve an overall drive system model. The main parameters for the SIMPACK model (see FIG 12) are:

- Gear box architecture (positions of axes)
- Material and geometry of shafts, gears and bearings
- Equivalent data for bearing stiffness modelling

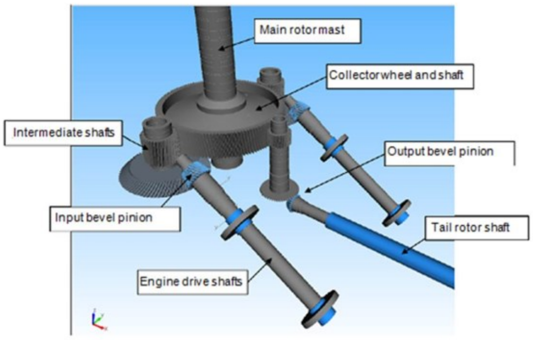

FIG 12: SIMPACK model of H135 drive train

The validation of the overall SIMPACK model was done by evaluation of torque step inputs from simulation and tests. The resulting transfer functions were compared. The difference in eigenfrequencies was below 5%.

5.2.2. Influence of drive train on main rotor

The main influence of the drive train on the elastic main rotor is the interference between structural dynamics rotational degree of freedom and corresponding torque at the rotor hub. Typically, the main rotor oscillates against the rest of the drive train. Due to elasticity of the drive train the lowest eigenfrequencies are in the range of several Hertz and a significant influence of the drive train on dynamic blade loads and stability occurs.

To establish modelling requirements, first a comparison of existing drive train architectures was done to identify suitable parameters. Corresponding technical data for Airbus Helicopters drive trains and dynamics phenomena of interest were collected. The outcome was that the drive train is relevant for torsional stability (low frequency, within bandwidth of engine control), stability of first rotor blade lead-lag mode and the frequency placement of higher rotor blade modes (influence on vibratory rotor loads). Also a categorization (serial or demonstrator, main rotor hub technology, tail rotor type, main gear box type, number of engines, tail rotor drive shaft type) of helicopters was considered. The final requirements were gathered in a document.

Based on these data the scaling of model parameters was investigated. As example the overall inertia of the drive train versus MTOW is presented in FIG 13. The helicopter categorization with respect to main rotor hub technology is shown by different colors of the markers. Concluding from the graph it can be stated that a clear dependency between inertia and maximum take-off weight exists and that the type of main rotor hub has no influence. When defining a design corridor, following the data of FIG 13, a first estimation of drive train inertia can be done in a very early stage of helicopter design. Analog to this, several other parameters were investigated regarding their suitability for scaling. For defining design corridors, sometimes the categorization, mentioned before, had to be respected. For example, the stiffness of a supercritical tail rotor drive shaft is significantly higher than that of subcritical shafts. Therefore the design corridors for each category are shifted with respect to each other. An outcome of this work also was a list of guidelines for choice of minimum degrees of freedom to establish a model for scaling. These results enable the simplification of drive train models.

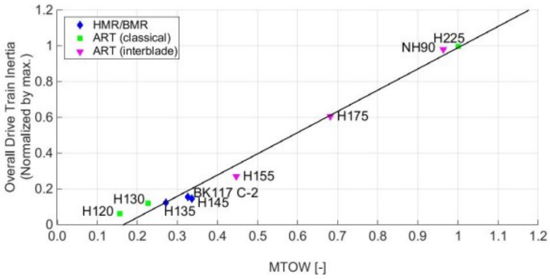

FIG 13: Dependency between drive train inertia and maximum take-off weight (related to maximum in fleet)

5.2.3. Influence of rotor suspension on main rotor

The influence of rotor suspension on the elastic main rotor mainly takes part via the interference between structural dynamics degrees of freedom and the longitudinal and lateral movement of the rotor hub with corresponding forces and moments. The suspension of the main gear box typically is done by struts and additionally via a membrane, where appropriate. These elements can incorporate vibration reduction means. Also the connection stiffness of the airframe can influence the dynamic behavior of the main rotor and therefore has to be considered. A second load path via the rotor controls exist. Its structural dynamics influences the torsion dynamics and control loads and thus the whole main rotor behavior by influencing pitch angles of the blade.

The rotor hub’s translatory movement in longitudinal and lateral direction lead to an interdependency with cyclic lead-lag modes of the rotor blades, which clearly can influence dynamics lead-lag loads and lead-lag stability. Rotary degrees of freedom couple with cyclic flapping motions of the blade and therefore can cause stability phenomena similar to whirl flutter.

For scaling of parameters of suspension and rotor controls a requirement set for modelling was established in a first step. The main points were:

- Type of model (Analytic, FEM, multibody simulation)
- Type of suspension (Soft, isolation, stiff)
- Suspension components to be considered
- Controls components to be considered

Then different rotor suspension concepts from Airbus Helicopters fleet were identified and compared. For selected concepts, generic kinematic calculation models were defined and implemented in analytical and FE models. Based on these models, normalized transfer functions, which are easy to scale were determined. A quick assessment of sub component loads also is possible with the generic models. This enables load estimation, when scaling a rotor suspension to different helicopter platforms.

To enhance existing FE-models investigations on the H135 anti resonance vibration isolation system ARIS, which replaces the vertical gear box struts, were performed. A simplified dynamics equivalent model was established to reduce the model parameters for scaling. This model can now be used for generating interface models for coupling of airframe with main rotor models in CAMRAD II or to predict vibration isolation efficiency under consideration of a full system with connection stiffness to airframe.

Within this task also a catalogue of potential rotor control architectures and investigations on scaling of rotor suspension and rotor controls will be made before end of the project.

5.2.4. Extension of drive train models for higher frequency oscillation behavior

Based on the SIMPACK model of the drive train, described in section 5.2.1, a model enhancement was performed to also include higher frequency excitation for vibro-acoustics. For this task, the integration of more sophisticated calculation methods which represent stiffness of gearing contact is necessary. A first check on possible external calculation methods to be included in SIMPACK revealed, that the tools intended to use have deficiencies for the type of gears widely used in helicopter gear boxes. Therefore it was decided to upgrade the existing SIMPACK model by gear meshing stiffness. The gear dynamics simulation in SIMPACK is based on a FE model for determining the stiffness of teeth and wheels. For integration into SIMPACK the FE mesh with stiffness characteristics has to be reduced to master nodes, which act as interfaces to the SIMPACK model. Beside the number and type of elements in the FE model, the main parameters here are the number and position of master nodes and the number of eigenmodes, which are used in the model reduction.

First validation steps with an already validated software showed deficiencies in determining the gear stiffness. A model refinement could improve the situation. However, the effort was judged too high. It will exceed the originally planned work by far. This method would not be used at Airbus Helicopters Deutschland for design of serial products. Therefore the work on this topic was stopped.

5.3. Modern reduction methods for dynamics FE models

The application of modern reduction methods on detailed FE models allows focusing on essential dynamics properties, by a significant reduction of structural dynamics degrees of freedom. Usually this is done for the low frequency range which is of special interest for aeromechanics topics. To apply model reduction for highly flexible structures within a centrifugal field, like main rotor blades, the reduction methods shall be extended by adequate projection of gyroscopic effects.

This work was done by Institute of Engineering and Computational Mechanics of University of Stuttgart.

5.3.1. Consolidation of the NASTRAN-MatMorembs-SIMPACK process

Within the LuFo project COROS suitability of modern model reduction methods for helicopter airframe applications was demonstrated in principle. Within this project it was started to generate a process, directly involving the FE solver NASTRAN, which is widely used in aeronautics. The model reduction itself is performed by the model order reduction program MatMorembs. The tool chain, established within COROS, was consolidated with respect to following topics:

- Robust import of global stiffness and mass matrices as well as according degrees of freedom
- All modelling techniques and finite elements, used in helicopter and component models, shall be covered
- Robust export of SID and FBI files for description of reduced systems within SIMPACK

The process chain, used within SKAT, is depicted in FIG 14. To import the system matrices from the NASTRAN output an import routine was established, which was validated and extended by usage of existing models.

In a second step the model reduction is performed within MatMorembs. Its results are elastic ansatz functions and reduced system matrices. The last step is the export of the reduced system matrices for usage in multibody simulation programs. As multibody software on the one hand CAMRAD II (as in FIG 14) and on the other hand SIMPACK were used. For CAMRAD II an interface already was introduced within COROS and for SIMPACK SID (standard input data) files were used. Their generation was implemented within MatMorembs. For newer SIMPACK versions also an export to so called FBI files was implemented.

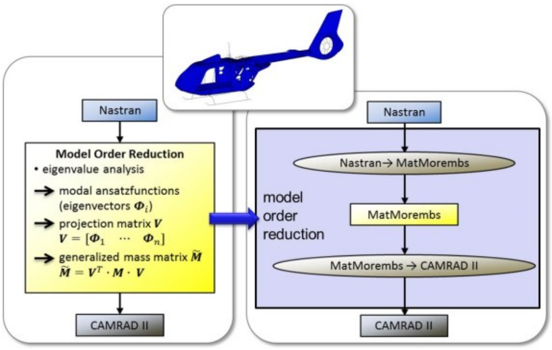

FIG 14: Process chain from FE model to multibody simulation

A validation plan was agreed between Airbus Helicopters and Institute of Engineering and Computational Mechanics. Academic models as well as NASTRAN models of existing airframes were used to cover real helicopter models with some special modelling techniques like static condensation or different coordinate systems for different helicopter components. During validation of the import function the function was improved by some additional features. It also was necessary to extend the import to cope with different binary results data formats for different MSC NASTRAN versions. The robustness of the process chain was demonstrated by installing MatMorembs at Airbus Helicopters and applying it on example models.

5.3.2. Modern reduction methods for rotating systems: main rotor with elastic blades

Helicopter rotors are characterized by their structural mechanics properties that on the one hand the rotor blade loads remain controllable due to blade elasticity and on the other hand the centrifugal stiffening dominates the dynamic behavior via geometric stiffness effects. For a successful application of modern reduction methods for rotor blades a suitable consideration of geometric stiffness within simulations is of essential importance.

A first step is to generate a 3D FE mesh for Nastran. Typically, the blade modelling is done by beam elements with cross section data and not by 3D FE meshes. Therefore a new mesh, based on exemplary 3D design data had to be generated for SKAT. In a second step the NASTRAN data was imported into MatMorembs under consideration of the geometric stiffness. An FBI file was generated by MatMorembs, which can be read by SIMPACK. A validation was done by comparing the results calculated with “MatMorembs FBI files” with results calculated with “SIMPACK reference FBI files” for a generic rotating beam structure. FIG 15 shows a comparison of beam eigenfrequencies. It is shown that the results with MatMorembs are in accordance with the SIMPACK results.

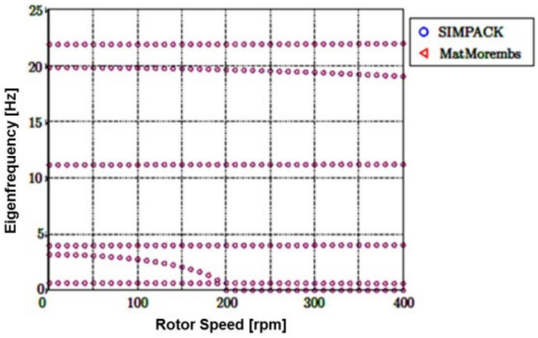

FIG 15: Comparison between calculation with MatMorembs FBI files and SIMPACK FBI files

5.4. Scaling with respect to stability, vibratory loads and vibro-acoustics

The main rotor shall be investigated regarding scaling for dynamics topics. Therefore aeroelastics and aeromechanics stability, vibratory rotor loads and vibro-acoustics transfer are in the main focus of the investigations. For these aspects the interfaces of the main rotor to other systems like drive train or rotor suspension are of interest. The task includes conventional passive main rotor systems as well as active ones.

5.4.1. Scaling with respect to stability of main rotor

Scaling of main rotors with respect to aeroelastics and aeromechanics stability will be treated by different modelling levels. An analysis which dynamics phenomena shall be considered lead to the following list:

- Blade flutter
- Torsional stability
- Air resonance
- Ground resonance
- Whirl flutter or critical bending speeds

The next steps in this task will be a comparison of main rotor dynamics of an isolated rotor with that of a rotor where interfaces are considered, an investigation on scaling requirements for main rotor design with respect to the identified dynamics phenomena and the demonstration by an example.

5.4.2. Scaling of vibratory main rotor loads

Aspects for scaling of main rotors with respect to vibratory rotor loads are investigated, similar to stability issues, on different modelling levels.

At the beginning of the work on scaling with respect to vibratory loads a strategy how to compare different rotors independently of scaling parameter and operational conditions was set up. For example when plotting mast moment versus flight speed for a single helicopter at different operating conditions a large scatter will be obtained. To compare rotor moments a normalization of moments with radius and weight and forward flight speed represented by advance ratio leads to a significant reduction in data scatter. Additional to the before mentioned example, scaling laws were defined for forces and moments in fixed frame. As mentioned before, the comparison of helicopters of the same type demonstrated that data scatter is significantly reduced. Therefore the method also is suitable to compare different helicopter types. Test data of several Airbus helicopters' vibratory rotor loads were collected and summarized to perform the above mentioned scaling for comparisons. However, this work is still ongoing.

To identify parameters with significant influence on scaling of main rotor loads calculations with CAMRAD II were performed. As test case the LoCAR main rotor was used. First the existing model was improved according to flight test data. Afterwards interfaces were implemented.

Drive train
Modelling of the drive train with rotor mast, engines, gear box and tail rotor improves the prediction of collective lead-lag loads. The drive train implementation lead to a significant improvement for the first two drive train modes calculation results.

Airframe
The implementation of an elastic airframe serves to estimate the influence of airframe motion on the rotor hub and therewith on vibratory loads. To do this a FE model of the airframe was used. For low flight speed a clear improvement of calculation results, compared to flight test data could be observed.

Swashplate
The swashplate is able to influence vibratory rotor loads by its kinematics but also by its own dynamics behavior. The implementation of an anisotropic swashplate increased the accuracy of lead-lag moment calculations. However, this improvement could not be observed for all forces and moments. A reason for that could be that some of the swashplate properties only were roughly estimated and that the correct orientation of the swashplates anisotropy could not be represented correctly in CAMRAD II.

In next steps investigations on scaling of requirements for main rotors, considering also its interfaces to drive train, rotor mast, main gear box and suspension shall be made and demonstrated by an example.

5.4.3. Scaling of active rotor systems

When considering an active rotor for scaling with respect to its dimensions no significant structural changes are expected. However, the scaling of blade number could have an impact, as it has direct influence on control variables for many control tasks. These influences shall be investigated with the target to obtain a model for control paths of chosen control tasks for arbitrary blade numbers. Beside the influence of blade number on control tasks the scaling of the main rotor also influences the actuation elements and therewith the active control.

This work was done by Flight Mechanics and Controls Lab of University of Stuttgart.

A part of the task comprises an investigation on actuation for active rotor system with respect to scalability. Qualitative considerations regarding different actuator types were made. Here concepts that directly influence blade pitch angle (like an active control rod) and concepts which influence the blade pitch angle via aerodynamic effects (like active servo flaps) were considered. Based on this, simple models of one blade with actuator to investigate the transfer behavior from actuator input to forces and moments at the blade were established. An exemplary result is that for direct actuation the frequency scatter of the response to a fixed frequency excitation is lower than for a servo flap.

The other part of the work was a generalization of the control path models for three control tasks.

Increase of lead-lag damping
Based on an analytical model for a four bladed rotor [9] with active flaps an analytical model with blade number as parameter was established. By generating mean values of the models in multi blade coordinates linear time invariant systems were created. The location and number of poles of these systems directly depend on the number of rotor blades. Additional poles compared to previous investigations appear, when considering rotors with blade number larger than four. To check the potential impact of these poles on stability the movement of the rotor's center of gravity due to the cyclic modes was investigated analytically for the most critical cases. The conclusion of this investigation was that the additional poles due to increased number of blades are irrelevant for the stability of the overall helicopter. Therewith it further can be concluded that the actual control laws for four bladed rotors for lead-lag damping enhancement can be used for arbitrary blade numbers larger than two. Just the gain has to be adjusted for specific rotors.

Reduction of vibrations at N/rev
For investigations on the effect of blade number on N/rev vibration reduction of active systems a generic analytical model of an N-bladed rotor was established. It allows theoretical examination of the influence of blade number on active quasi-steady vibration reduction. The results lead to the conclusion that the potential for vibration reduction is independent of the number of rotor blades. This conclusion was confirmed by evaluation of flight test data.

Reduction of vibrations due to tracking errors
To investigate on vibration reduction by tracking with actively controlled rotors the transfer behavior of an ideal rotor with arbitrary blade number was modelled by a linear transfer matrix. The transfer matrix represents the influence of constant inputs to the actuation of a single blade to cabin vibrations at rotor harmonics. A basic outcome of this investigation was that the blade number directly influences the number of independently controllable rotor harmonics. For the 1/rev and 2/rev frequency range, traditionally considered, the maximum vibration reduction potential will be achieved for a rotor with at least five blades.

To investigate on the influence of the servo flap's position a mixed model approach with a CAMRAD II model of the rotor blade and a simple model of the servo flap was chosen. The simulation approach was verified by a comparison to a CAMRAD II model with fixed servo flap position. The influence of the radial positon of a servo flap on its vibration reduction potential for the first three rotor harmonics is shown in FIG 16. Here the flap size and the constant flap deflection for tracking were kept fixed.

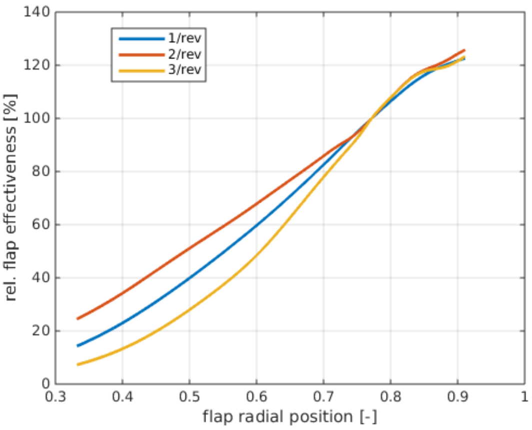

FIG 16: Servo flap effectivity related to baseline configuration versus radial position

Based on this modelling technique, transfer matrix models for different servo flap configurations and also for blade root actuation were established. With these models the implementation of the tracking controller based on the theoretical investigation was tested. Here it could be shown that the generalized tracking controller works for different numbers of blades as well as for different types of actuation.

5.4.4. Scaling of main rotor vibro-acoustics

Within this work task a method to calculate and scale the transfer of dynamic excitations, generated by the main rotor, to the airframe is developed. For this, the modelling and scaling of vibro-acoustics isolation and damping elements, situated in the main gear box struts, are investigated. With the resulting calculation methods one shall be enabled to design, optimize and validate isolation or damping elements, suitable for helicopter applications. An element used at Airbus Helicopters is based on the principle of particle damping. Here the inner volume of the strut can be filled with different granulates.

To validate calculation methods, a suitable experimental data base had to be established. Therefore a main gear box strut of the H145 helicopter was taken to determine vibro-acoustic transfer behavior and damping by an experimental modal analysis. Granulates made of different materials and of different size were tested.

For calculations the FE code NASTRAN was chosen and a large number of modelling approaches with respect to dimensions and discretization was investigated to find the best compromise between accuracy and model size. This was done for the main gear box strut without any granulate filling. Finally a 1D beam model and a 3D solid model were selected.

For correlation the modal assurance criterion MAC was chosen to validate the numerical results with the experimental data. As additional correlation criterion the eigenfrequency difference in percent of a correlated mode pair (experimental and numerical) was used. Both the 1D and the 3D model show good correlation. The MAC for the 1D model is slightly better than for the 3D model. When considering the frequency difference the result is vice versa. In the next steps, the validated models shall be upgraded to also represent the damping properties of a main gear box strut, filled with granulate, as accurately as possible.

6. INDUSTRIAL APPLICABILITY

When all the work packages are finished, the results obtained within the project will be assessed with respect to its industrial applicability especially for pre-development tasks, rotor aerodynamics and the overall main rotor system.

7. CONCLUSIONS

The project SKAT comprises a lot of multidisciplinary tasks from several fields of engineering. Investigations were made to improve the ability to use family concepts, kit and platform approaches within helicopter industry by enabling enhanced scaling capabilities and extrapolation methods. A special focus was set on the main rotor and its interfaces. Several of the methods, developed within the project SKAT are already implemented within industrial processes, even if the project is not finished yet. The finalization of SKAT will take part end of this year.

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