IMPLEMENTATION AND TEST OF A SEMI-CLOSED LOOP HHC-ALGORITHM WITH THE DLR'S MULTIPLE SWASHPLATE SYSTEM

Philip Küfmann
German Aerospace Center (DLR), Lilienthalplatz 7,
Institute of Flight Systems
38108 Braunschweig, Germany

Claudio Brillante
Politecnico di Milano, via la Masa 34,
Dipartimento di Scienze e Tecnologie Aerospaziali
20156, Milano, Italy

Abstract

This paper discusses the design, integration and test of a Higher Harmonic Control algorithm capable of both vibration control and in-flight blade tracking in conjunction with DLR's multiple swashplate control system (META). The design of the control algorithm is described in detail and the results of coupled numerical investigations with both MbDyne and DLR's comprehensive rotor code to determine the algorithm's performance, are presented. The integration of the control-algorithm into the realtime control software is shown for the META system, where for safety reasons a semi-open loop approach was implemented. First tests of the controllers in-flight tracking mode to reduce $1/rev$ loads during hover have successfully been conducted at the DLR's rotor test facility, yielding a 94.2% reduction in $1/rev$ vibratory loads while maintaining constant rotor thrust.

Notation

b	blade number index
$\mathbf{C}$	matrix used for parameter limitations
d	vector of control signal limitations
$F_{x,y,z}$	hub forces (non-rotating frame)
$\underline{F}$	vector of hub load harmonics
$\underline{g}$	linear coefficient vector
$\underline{g}_{QP}$	linear coefficient vector reformulated for solution via quadratic programming
$\mathbf{H}$	quadratic coefficient matrix
$\mathbf{H_{QP}}$	quadratic coefficient matrix reformulated for solution via quadratic programming
$\mathbf{I}$	unity matrix
J	quadratic const function
$\mathbf{K}$	gain matrix
$M_{x,y,z}$	hub moments (non-rotating frame)
N_b	number of blades
$\mathbf{P}$	covariance error matrix
$\mathbf{T}$	transfer matrix
$\mathbf{W}_{\mathbf{z},\underline{\gamma},\mathbf{\Delta}\underline{\gamma}}$	weighting matrices
x^+, x^-	reformulated version of $\underline{\gamma}$ or $\underline{\gamma}_0$ for solution via quadratic programming
$\underline{\gamma}$	vector of blade pitch harmonics
$\underline{\gamma}_\mathbf{0}$	vector of individual blade pitch offsets
$\bar{\delta}$	limitation for harmonic inputs
Θ	primary control input
$\Theta_{c,s}$	sine and cosine blade pitch components
ϑ	individual blade pitch angle
μ	advance ratio
Ψ	azimuth angle
Ω	rotor frequency

Abbreviations

AHD	Airbus Helicopters Deutschland
APS	azimuthal pulse-synchronizer
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DNW	Deutsch-Niederländischer Windkanal (German-Dutch Wind Tunnels)
EPOS	Easy-to-use positioning system
FTK	Fortschrittliche Taumelscheibenkonzepte (advanced swashplace-concepts)
GUI	graphical user interface
HART	Higher-harmonic-control Aeroacoustics Rotor Test
HHC	Higher Harmonic Control
IBC	Individual Blade Control
LLF	Large Low-Speed Facility
META	Mehrfach-Taumelscheibe (Multiple Swashplate Control System)
RHA	recursive harmonic analysis
RTP	real-time processor
RTR	Rotor test rig
TEDAS	transputer-based extendable data acquisition system
VAR	Voll-Aktive Rotorsteuerung (fully active rotor control)

1. INTRODUCTION

Despite their unique set of capabilities - such as hovering, vertical take-off and landing as well as excellent low speed flight performance - which have made them irreplacable for many civil and military operations, helicopters still lag behind their fixed-wing counterparts in several aspects. The main reason are the problems helicopters still suffer from, the most important of which are:

- high level of vibrations,
- high noise generated by the rotor,
- high power required in high speed forward flight,
- low range and limited speed of flight.

Since the middle of the last century, dramatic improvements have been made regarding vibration levels using utilizing passive means such as dampeners and bifilars [1]. Similar improvements were made regarding noise emissions by employing new, optimized blade designs [2]. However, reductions beyond current regulatory goals [3, 4] seem to be out of reach with purely passive measures.

Active rotor control technologies such as Higher Harmonic Control (HHC) [5] and Individual Blade Control (IBC) are capable to further reduce noise and vibration levels, which has been proven in various wind-tunnel and flight tests. [6–16] Besides these objectives, flight tests in 2004 and wind tunnel tests in 2009 also demonstrated the potential of active rotor control to improve rotor performance [17, 18]. During the wind tunnel tests, rotor power reductions of about 5% were measured using $2/rev$ blade pitch inputs at high forward speed. A survey of the different well-known active control systems and some selected results are given in [19] and [20].

With the DLR's patented multiple swashplate control system (META) [21–24] it is possible for the first time to realize fully individual blade control on a rotor with up to six blades while all necessary actuators remain in the non-rotating system below the swashplates. This setup eliminates issues connected with on-blade actuation systems and IBC approaches with (hydraulically) actuated control rods, such as high complexity, energy and signal transfer via slipring and high centrifugal loads acting on the actuation system. After first successful tests in the DLR's rotor testing facility [25], the system is scheduled to undergo extensive wind tunnel tests in the large low-speed facility of DNW (Deutsch-Niederländischer Windkanal, German-Dutch Windtunnels) in late 2015. During these tests, which are carried out within the framework of a National research project in cooperation with Airbus Helicopters Germany, the influence of various IBC strategies on vibrations, noise levels and rotor performance will be investigated using Mach-scaled Bo105 blades as well as newly developed blades with a more modern blade geometry.

In preparation for these tests, a modified HHC algorithm was designed and implemented for use in conjunction with the META-system. By exploiting quadratic programming theory [26], the controller is able to deliver optimized control signals for vibration reduction and for in-flight blade tracking while at the same time taking into account the specific actuator limitations of the META-system's hardware.

The following chapters describe in detail the process of designing, implementing, integrating and testing the modified HHC algorithm as well as first preliminary test results obtained during hover tests at DLR's rotor testing facility.

2. HHC Control Implementation

With the aim of vibration reduction by active methods in mind, the higher harmonic control algorithm represents a very simple and effective solution and has been widely used in the past years. An adaptive version of this controller is presented here and particular care is given to the actuators limitations, which are taken into account by a constrained optimization procedure during the computation of the control signal as described in [26].

2.1. Model Identification

The rotor subsystem can be approximated for step k using a quasi static linear transfer function between the cosine and sine amplitudes of the blade pitch harmonics Θ_{S_n,C_n} $(n = 2, 3, 4, 5)$, represented in the vector $\underline{\gamma}$ and the vector $\underline{F}$ comprising specific cosine and sine amplitudes of harmonic hub loads such as the vertical force F_Z, lateral forces F_X and F_Y as well as roll and pitch moments M_X and M_Y:

$$\underline{F}_{k+1} = \underline{F}_k + \mathbf{T}_k \left(\underline{\gamma}_{k+1} - \underline{\gamma}_k \right) \tag{1}$$

where the transfer matrix $\mathbf{T}_k$ has to be properly identified. Since the helicopter rotor exhibits a strong nonlinear behavior depending on the swashplate orientation and the flight condition, an adaptive on-line identification algorithm is the best choice to compensate these effects and achieve better performance during the controller implementation. The Recursive Least Squares (RLS) [27] method is used in this work and the transfer-matrix $\mathbf{T}$ can be updated at each step k with the following equations:

$$\begin{aligned} \mathbf{K}_{k+1} &= \frac{1}{\left(\alpha + \triangle\underline{\gamma}_k^T \mathbf{P}_k \triangle\underline{\gamma}_k\right)} \triangle\underline{\gamma}_k^T \mathbf{P}_k \\ \mathbf{T}_{k+1} &= \mathbf{T}_k + \left(\triangle\underline{F}_k - \mathbf{T}_k \triangle\underline{\gamma}_k \right) \mathbf{K}_{k+1} \\ \mathbf{P}_{k+1} &= \mathbf{P}_k \left(\frac{1}{\alpha}\mathbf{I} - \triangle\underline{\gamma}_k \mathbf{K}_{k+1} \right) \end{aligned} \tag{2}$$

where $\mathbf{K}$ is the gain, $\mathbf{P}$ is the covariance error matrix, $\triangle\underline{F}_k = \underline{F}_k - \underline{F}_{k-1}$, $\triangle\underline{\gamma}_k = \underline{\gamma}_k - \underline{\gamma}_{k-1}$ and α is the exponential window parameter acting as forgetting factor. Note that the step k is updated after a certain number of rotor revolutions (3 or 5 for example) in order to reach a steady state condition without transients and allow the quasi static assumption of the rotor behavior of Eq. (1).

2.2. Control Algorithm

After having computed an accurate estimate of the transfer matrix $\mathbf{T}_k$, the classical HHC algorithm computes the cosine and sine amplitudes of the control signal harmonics ($\underline{\boldsymbol{\gamma}}_k$) by minimization of a quadratic cost function J using the analytical solution of the minimization process. The prediction of the magnitude of the computed signal is a crucial aspect of the classical approach since the actuators may reach the saturation point or undesirably high controls inputs may occurr during the experiments. This issue is usally mitigated by increasing the weight imposed on the control signal coefficients in the cost function J or truncating or scaling the signal in time domain. However, these approaches can generally lead to a significant reduction in controller performance.

A more elegant way to handle actuator constraints has been proposed by [26], where the HHC cost function is minimized through a constrained optimization imposing the actuator limitations.

$$\begin{aligned} min_{\underline{\boldsymbol{\gamma}}}\, J \quad &= \quad \frac{1}{2}\Big(\underline{F}^T_{k+1}\mathbf{W}_F\underline{F}_{k+1} + \underline{\boldsymbol{\gamma}}^T_{k+1}\mathbf{W}_{\gamma}\underline{\boldsymbol{\gamma}}_{k+1} \\ &\qquad + \triangle\underline{\boldsymbol{\gamma}}^T_{k+1}\mathbf{W}_{\triangle\gamma}\triangle\underline{\boldsymbol{\gamma}}_{k+1}\Big) \\ with \quad & \quad |\Theta_{C,n}| + |\Theta_{S,n}| \leq \bar{\delta} \end{aligned} \tag{3}$$

In Eq. (3) the matrices $\mathbf{W}_F$, $\mathbf{W}_{\underline{\gamma}}$ and $\mathbf{W}_{\triangle\underline{\gamma}}$ are the weights applied to the the hub loads to be reduced, the control signal harmonics and to their increment, respectively. The constraints on the control signal are taken into account by imposing a limitation $\bar{\delta}$ on the magnitude of each harmonic n composing the signal. Since in this paper the control problem is addressed using Quadratic Programming [28], where constraints have to be expressed as linear inequalities, the non-linear form of the constraints $\sqrt{\Theta^2_{C,n} + \Theta^2_{S,n}} \leq \bar{\delta}$ was not applicable. Instead, a stricter set of linear constraints formulated as the sum of the absolute values $|\Theta_{C,n}|$ and $|\Theta_{S,n}|$ is used. This formulation is also implemented when the same algorithm is employed to the blade tracking problem and the constraints on the harmonics are replaced with a limitation of the static blades pitch $|\Theta_{0,b}| \leq \bar{\delta}$, where N_b is the number of blades and the subscript b is the blade number index.

In order to obtain a set of linear inequalities necessary for the implementation using Quadratic Programming, the linear constraints are again reformulated with the following change of variables:

$$\underline{\gamma} = \underline{x}^+ - \underline{x}^- \tag{4}$$

with the new introduced variables $\underline{x}^+$ and $\underline{x}^-$ (derived from the contents of $\underline{\gamma}$, Θ_{C_n,S_n}) always positive. Now the sum of the absolute values and the constraints of Eq. (3) can be written as:

$$\begin{gathered} -\left(x^+_{c,n} + x^-_{c,n}\right) - \left(x^+_{s,n} + x^-_{s,n}\right) \geq -\bar{\delta} \\ with\ \underline{x}^+ \geq 0 \wedge \underline{x}^- \geq 0 \end{gathered} \tag{5}$$

After substituting the quasi static approximation of the rotor model of Eq. (1) into Eq. (3) we obtain:

$$\begin{aligned} min_{\underline{\boldsymbol{\gamma}}_{k+1}} J =& \frac{1}{2}\Big[\left(\underline{F}_k + \mathbf{T}\triangle\underline{\boldsymbol{\gamma}}_{k+1}\right)^T \mathbf{W}_F \left(\underline{F}_k + \mathbf{T}\triangle\underline{\boldsymbol{\gamma}}_{k+1}\right) \\ & + \underline{\boldsymbol{\gamma}}^T_{k+1}\mathbf{W}_{\gamma}\underline{\boldsymbol{\gamma}}_{k+1} + \triangle\underline{\boldsymbol{\gamma}}^T_{k+1}\mathbf{W}_{\triangle\gamma}\triangle\underline{\boldsymbol{\gamma}}_{k+1}\Big] \\ with\ & \triangle\underline{\boldsymbol{\gamma}}_{k+1} = \underline{\boldsymbol{\gamma}}_{k+1} - \underline{\boldsymbol{\gamma}}_k \end{aligned} \tag{6}$$

Since it is a minimization problem it is possible to ignore all terms independent from $\underline{\boldsymbol{\gamma}}_{k+1}$ and without loss of generality the cost function J can be written in a compact form, considering only the quadratic ($\mathbf{H}$) and the linear terms ($\underline{g}$), as shown in Eq. (7):

$$min_{\underline{\boldsymbol{\gamma}}_{k+1}} J = \frac{1}{2}\left(\underline{\boldsymbol{\gamma}}^T_{k+1}\mathbf{H}\underline{\boldsymbol{\gamma}}_{k+1} + \underline{g}^T\underline{\boldsymbol{\gamma}}_{k+1}\right) \tag{7}$$

Inroducing the change of variables of Eq. (4) and adding the constraints of Eq. (5), the resulting problem (Eq. (8)) can now be solved by Quadratic Programming techniques.

$$\begin{aligned} min_{\underline{x}}\, J \quad &= \quad \tfrac{1}{2}\underline{x}^T\mathbf{H_{QP}}\underline{x} + \underline{\mathbf{g}}^T_{QP}\underline{x} \\ with \quad & \quad \mathbf{C}\underline{x} \geq \underline{d} \end{aligned} \tag{8}$$

where $\mathbf{H_{QP}} = \begin{bmatrix} \mathbf{H} & -\mathbf{H} \\ -\mathbf{H} & \mathbf{H} \end{bmatrix}$, $\underline{g}_{QP} = \begin{Bmatrix} \underline{g} \\ -\underline{g} \end{Bmatrix}$, $\underline{x}$ is the vector containing the new variables $\underline{x}^+$ and $\underline{x}^-$, $\mathbf{C}$ is the constraints matrix composed of $+1$ and -1 and the vector $\underline{d}$ contains the control signal harmonics limitations $\bar{\delta}$. To solve this control problem at each step k an Interior Point algorithm has been developed, which can solve the problem in a very efficient way within few iterations and hence is suitable for implementation in the META's control software (see section 4). Further details on the optimization method can be found in [28].

3. Simulation Results

Numerical simulations are needed to test the capability and performance of the proposed HHC method before carrying out experimental tests. Numerical data of the HART II blade, a Mach-scaled model of a four-bladed Bo105 rotor with a radius of 2 m, are considered and two test cases are simulated. In the first example the controller is validated for blade tracking in hover using the multibody software `MBDyn` [29] while in the second one the DLR's comprehensive rotor simulation code `S4` [30,31] is coupled with `Matlab` to reduce the dynamic hub vibrations of the vertical force F_Z

and the roll- and pitch moments (M_X and M_Y) are reduced in forward flight. In conjunction with forces, moments and pitch angles, the term n/rev is used to denote the n^{th} harmonic of the rotor, or the n^{th} multiple of the rotor frequency Ω.

3.1. Blade Tracking

A numerical model of the HART II rotor is approximated here using the software `MBDyn`, a general purpose multibody code developed by the Aerospace department of Politecnico di Milano [29]. In addition to the rigid bodies simulation, `MBDyn` also provides flexible components, such as nonlinear beams and plates, as well as basic aerodynamic theories for the simulation of helicopter rotors, such as the blade element theory coupled to uniform/linear inflow models. In this example rigid bodies are used to represent the hub and the pitch hinge while five nonlinear finite volume beams [32] discretize the blade. The META system is not modeled for reasons of simplicity, since we are only interested in the blade pitch angles that are imposed directly.

To simulate a rotating imbalance and thus to artificially create the need of a blade tracking control, a set of random masses is distributed on three of the four blades at different spans and the pitch links' lengths are altered as well. The resulting simulated imbalaces are much higher than in reality and therefore unerealistic, but provide an ideal foundation to test the controller capability. Moreover, thanks to the nonlinear beams and the multibody formulation, nonlinear effects such as great diplacements and the dynamic response are taken into account.

`MBDyn` also provides a module that allows the coupling with `Matlab/Simulink` using bidirectional socket communications, therefore the HHC controller is implemented within the `Simulink` environment. The rotor is trimmed in hover at a vertical thrust setting of $F_{z,ref} = 3300$ N and the tracking controller aims to reduce the $1/rev$ harmonics of the hub forces F_X and F_Y that arise due to the blade unbalance by changing the static pitch of all N_b blades $\vartheta_{0,b}$. During the minimization of the hub loads using the static pitch of the individual blades it is not guaranteed that the rotor thrust remains constant and there is the possibility to move into another trim configuration. To overcome this issue, the control objective has been modified by imposing the minimization of the difference between the rotor thrust and its desired value $\triangle F_Z = F_Z - F_{Z,ref}$ together with the in-plane hub loads harmonics. The $\mathbf{T}$-matrix is recursively identified every three rotor revolutions and after a good estimate is obtained, the controller is activated. Results after few controller iterations with a constraint of $\pm 5°$ for individual blade pitch offsets are shown in Fig. 1. It is interesting to note that the magnitudes of the hub forces F_X and F_Y are almost halved by the controller even if the blades strongly differ from each other due to the random mass placement and different pitch link lengths. These results are very promising for the experimental tests in which imbalances occur mainly only due to structural and aerodynamical blade-to-blade dissimilarities.

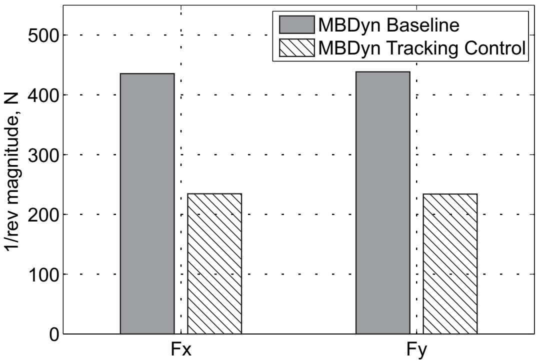


Figure 1: Tracking control results.

3.2. Vibration Control

In this example the controller's performance is investigated for a reduction of the vibratory hub loads in forward flight. The same data for the numerical model of the HART II rotor is considered and the comprehensive rotor simulation code `S4` developed by DLR is used for the forward flight simulation. `S4` approximates the blades' structure using linear finite element beam elements and the aerodynamic loads are computed with an unsteady blade element theory considering both the Wagner- and the Küssner-functions to estimate the unsteady loads. The rotor wake can be approximated with several different inflow models up to the Beddoes' prescribed wake method [33] in a modified form [34], which is the one used in this work and provides a good prediction of vibratory loads.

Since `S4` is not equipped with a general interface to communicate with external programs, it has been coupled with `Matlab` using the `Matlab` engine, a functionality that allows `Fortran` and `C` based codes to call the `Matlab` solver and exchange data within its environment. It is then possible to implement the HHC controller by Matlab functions that are called from `S4`, which acts as the master program.

The rotor is trimmed at an advance ratio of $\mu = 0.318$ (equivalent to the maximum cruise speed of a Bo105 helicopter), such that it produces thrust, propulsive and lateral forces equal to $F_Z = 4330$ N, $F_X = 530$ N and $F_Y = -260$ N with a shaft angle of $\alpha = -8.7°$. This trim solution was derived from free-flight simulations of a full-scale Bo105 helicopter conducted with the Helicopter Overall Simulation Tool (`HOST`) [35], the results of which were scaled down to fit the Mach-scaled rotor model and transformed for use within a wind tunnel axis system. Since the HART II rotor model has four blades, the controller is implemented so to reduce the $4/rev$ harmonic coefficients of the hub loads F_Z, M_X and M_Y by changing the higher harmonics of the blade pitch from the $2/rev$ up to the $5/rev$ and each harmonic of the control signal has been limited below $10°$. Figure 2 shows the loads alleviation achieved compared to the baseline condition. All vibrations are strongly reduced by the HHC controller, especially considering the hub shear force F_Z, which is reduced by 90% with the imposed constraints. Again, the simulation results look promising, and vibration controller's capabilities will be further investigated during wind tunnel tests (see section 6).

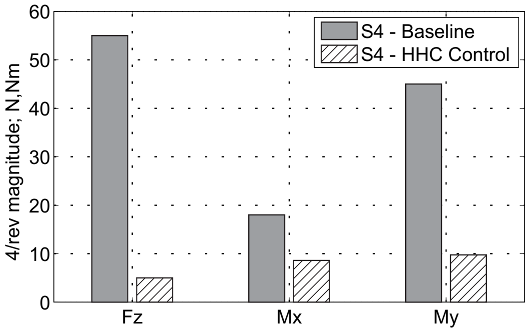


Figure 2: Vibration control results.

4. EXPERIMENTAL SETUP AND CONTROLLER INTEGRATION

The DLR's Institute of Flight Systems has now been operating it's own rotor test rig (RTR) since 1976. It is used for phenomenological investigations of Mach- and dynamically scaled rotors or complete helicopter configurations [36,37] and has been successfully applied in numerous wind tunnel tests [13,15]. In the course of the national research program VAR (fully active rotor control) the RTR has been upgraded with the patented [23,24] Multiple Swashplate Control System (META) which is capable of true IBC for rotors with up to six blades using actuators within the non-rotating frame.

4.1. Test setup for operation with META

In the course of the project *FTK-META* (advanced swashplate-concepts - META), a successor to the aforementioned research program *VAR* in cooperation with Airbus Helicopters Germany, the META system will be used to study the effects of different IBC strategies on vibrations, noise, and rotor performance in the DNW's large low speed facility. A major part of the tests is concerned with vibration reduction in different flight attitudes by means of IBC. Both the reduction of $4/rev$ loads by mixed mode $(2-5/rev)$ HHC as well as reduction of $1/rev$ rotor imbalances by way of in-flight blade tracking are goals of the wind tunnel test. During the preparation phase for the wind tunnel tests the control algorithm described in section 2 was added to the control structure of META within the RTR. A simplified overview over the RTR setup for operation of the integrated META system is shown in Fig. 3.

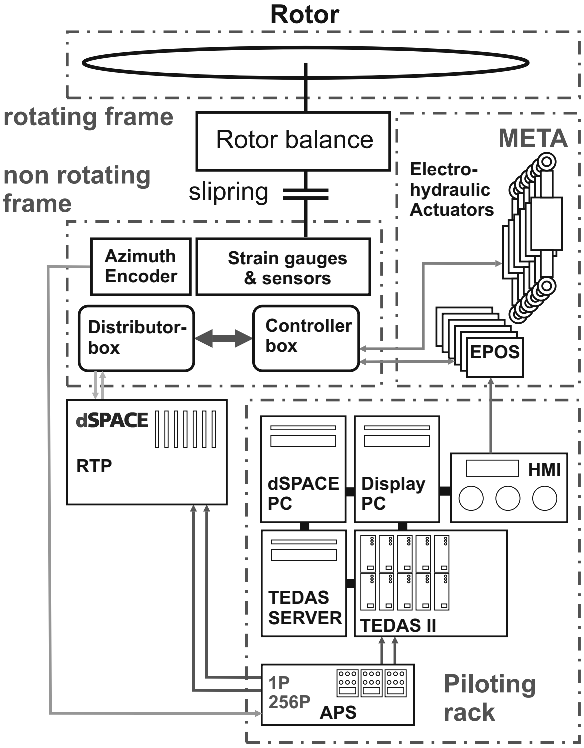


Figure 3: Simplified setup of the RTR for operation with META

The primary rotor controls (collective and dynamic pitch) of META are set by the test operator at the piloting rack for both swashplates simultaneously using comparatively slow, but highly accurate electric motors controlled by "‘Easy to use Positioning System"’ (*EPOS*) -modules, which are part of the META's actuation system. The second, hydraulic part of the actuation system, which has less control authority but is capable of moving with frequencies up to $100\ Hz$, is needed to realize the dynamic blade control signals for HHC, IBC and in-flight blade tracking. The control software for these hydraulic actuators - and thus, the META system - runs independently on a dedicated *dSPACE* real-time processor (RTP) and can be accessed through a graphical user interface (GUI), running on a separate display PC. Signal measurement and recording is handled by the DLR's own second-generation Transputer-based extendible data acquisition system (*TEDAS II*), which is capable of recording up to 250 channels at sampling rates of $2048/rev$.

4.2. Integration of the control algorithm

The control software for the META-system is compiled from a `Simulink`-model using the `Matlab/Simulink`-compiler and then distributed among the four individual cores of the processor used in the RTP-unit. The cores are assigned the following dedicated tasks:

core 1: calculation of IBC signals and conversion to actuator strokes

core 2: hydraulic actuator piston position control, measurement and signal routing

core 3: dedicated (otherwise inaccessible) core for network communications

core 4: miscellaneous

Since they are directly tied into the rotor control system, cores no. 1 & 2 have to run at a frequency equal to $256/rev$ (4.48 kHz) synchronously to the model rotor in order to ensure correct phase settings for the control signals. This is achieved via an external trigger signal from the RTR's azimuthal pulse synchronizer (APS), see Fig. 3. Due to the relatively high sampling rate and the complexity of the tasks, those two cores have little margin with regards to task execution time, and were thus deemed unsuitable for the addition of more functionality. Cores no. 3 and 4 run largely independently and can be set to any arbitrary sampling rate best suited for the assigned task. In order to decouple the task of vibration control from the most computationally demanding functions and to avoid issues with synchronization or task execution times the HHC control algorithm was integrated to run solely on core no. 4 with a base sampling rate of 400 μs (2500 Hz).

The `Simulink`-model representation of the HHC algorithm (see section 3), which has been modified for the use with META can be rougly divided into three parts or steps: Signal handling and sorting, $\mathbf{T}$-Matrix identification, and the core control algorithm itself. Figure 4 shows a schematic representation of the final model which was integrated into META's control system. To prepare the necessary inputs for the controller algorithm, first the time-domain signals from the RTR's six-axis rotor balance are converted into higher harmonic sine and cosine-coefficients by means of recursive harmonic analysis (RHA) on core no. 2 and then internally routed to core no. 4. Depending on the control mode (vibration control or in-flight blade tracking) a selected subset of those signals is then combined into an input vector ($\underline{F}_{k-1}$) used for both $\mathbf{T}$-matrix identification and actual vibration control. Simultaneously, all harmonic control coefficients for HHC and blade-individual offsets for tracking are received from core no. 1 and similarly selected and prepared as input vector $\underline{\gamma}_{k-1}$.

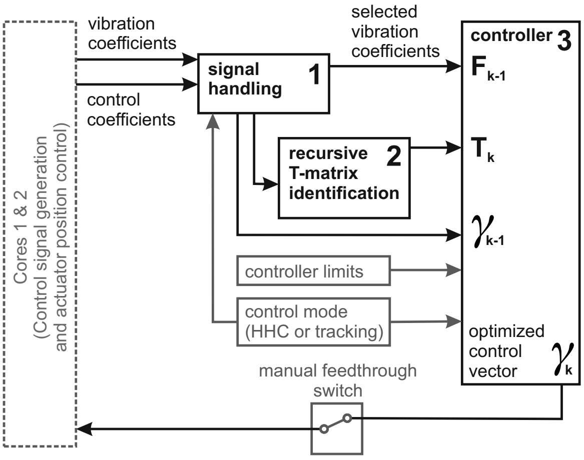


Figure 4: schematic representation of controller's simulink model

Both the vibration and the control coefficients can then be used to identify a transfer matrix $\mathbf{T}$ in the frequency domain using the recursive identification technique from [27] previously described in section 2. To allow enough time for transients to settle down after changing the control signals, an identification step is only triggered if at least one second (or 17.5 rotor revolutions) has passed and the dynamic response of the rotor system has stabilized. The identification cycle is programmed to operate automatically - as soon as an identification step is finished, a new set of randomly generated control signals (either mixed-mode HHC or blade tracking) is calculated and realized by the META system. Once the transients have died down, a new identification step is triggered and the cycle continues until stopped manually. Once fully identified, $\mathbf{T}$-matrices can then be stored on hard disk and, if necessary, reloaded into the control software.

For controller operation, the identified transfer-matrix is then passed along together with the current control inputs to the HHC algorithm. The respective amplitude limits for HHC operation or maximum collective offsets can be set by the user prior to each controller run. Since the HHC algorithm itself includes optimization loops (see [28]) and thus can differ in execution time, an internal rate transition was introduced into the `Simulink` model in order to allow enough time for the full and successful execution of the algorithm. First simulations showed that a maximum execution time of five seconds ($\approx$90 rotor revolutions) is suitable for controller operation and offers a large execution time margin in case of possible deviations. When an optimization run is finished, the calculated control coefficients can be manually adopted and passed on to the META's control task, which then synthesizes the corresponding blade control signals and drives the hydraulic actuators accordingly. This semi-closed loop approach was selected to ensure the safe operation of the experimental model. This way, all control solutions proposed by the control algorithm can be manually checked for inconsistencies or limit exceedance before being realized as highly dynamic control signal in the META-system. Provided that the first test runs of the controller are successful and without problems, switching to closed loop operation of the controller remains an option.

5. TEST OPERATION AND RESULTS

During May 2015, the newly integrated HHC algorithm was tested in conjunction with the META system in the DLR's rotor testing hall in hovering condition. The tests included both mixed-mode HHC operation for reduction of $4/rev$ vibratory forces at 2/3^{rds} of nominal thrust (2500 N) and in-flight blade tracking to reduce $1/rev$ rotor imbalances at a further reduced thrust setting of 1500 N. For in-flight blade tracking, the controller output (individual blade pitch offset) was limited to $0.3°$, while during HHC operation all amplitudes were limited to a maximum of $0.2°$. While the in-flight tracking test was highly successful, the test of the controller's ability to reduce $4/rev$ vibrations by application of mixed-mode HHC yielded inconclusive results due to the confined testing space, as explained later.

5.1. Controller operation

The control algorithm as well as the $\mathbf{T}$-matrix identification is operated from the same GUI as the manual META controls, which allows for manual input of the controller's limits, starting / stopping all controller-related functions and automatically (although manually triggered) adoption of the control solution proposed by the algorithm.

For in-flight blade tracking, the sine and cosine coefficients of the $1/rev$ vibrations measured by the four Z-force transducers of the RTR's rotor balance (see Fig. 5) are displayed and also visually represented in an "'imbalance plot"' for quick assessment by the operator, see also Fig. 6. For a rotating imbalance, the distribution of the four points within the plot resemble the mechanical arrangement of the four z-force transducers around the rotor shaft. Similarly, the time histories of all calculated hub forces and moments in the non-rotating system (excluding rotor torque M_z) are plotted in real-time and displayed for observation during vibration control via HHC.

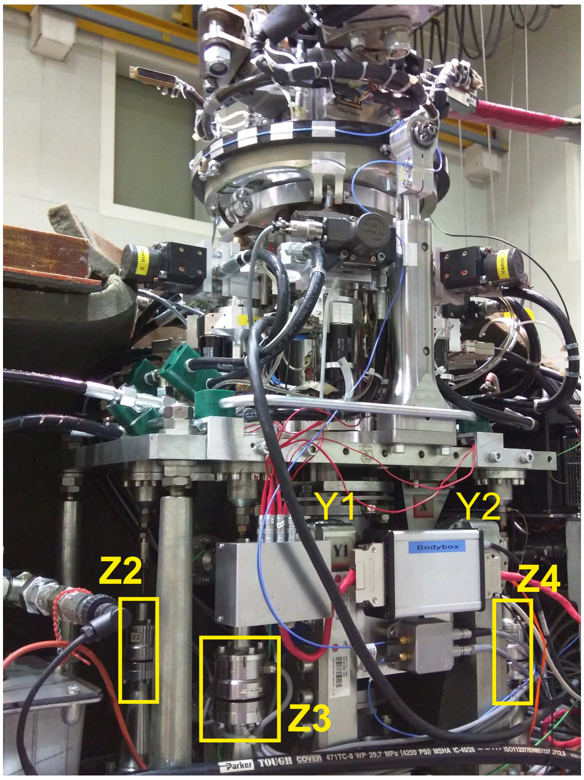
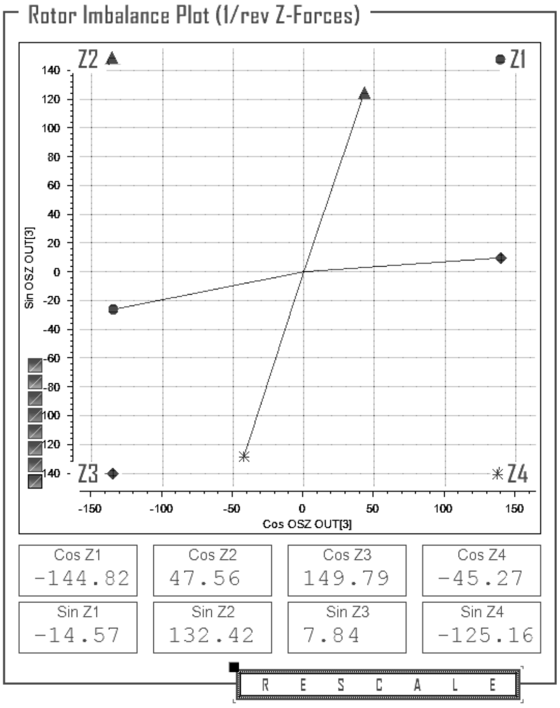


Figure 5: The RTR's six axis rotor balance below the META, Z-force transducers 1,2 and 3 visible


Rotor Imbalance Plot (1/rev Z-Forces)

Cos Z1	Cos Z2	Cos Z3	Cos Z4
-144.82	47.56	149.79	-45.27

Sin Z1	Sin Z2	Sin Z3	Sin Z4
-14.57	132.42	7.84	-125.16

Figure 6: Screenshot of the GUI's imbalance plot used during in-flight blade tracking showing the $1/rev$ sine and cosine components of the Z-forces

5.2. In-flight tracking test results

The first mode of the new control algorithm tested was the reduction of $1/rev$ rotor imbalances via in-flight tracking of individual blades. For operation within the rotor testing hall, the DLR's Bo105 model rotor had already been mechanically tracked and balanced for a thrust setting of 2500 N. However, due to structural and aerodynamical blade-to-blade differences, the remaining imbalances depend on the rotor thrust and increase for rotor thrust values above or below the setting used for the track- and balance process. With this in mind, the rotor thrust was reduced to 1500 N in order to obtain realtively high imbalances in the form of $1/rev$ vibrations and thus a good starting point for the in-flight tracking process.

In this baseline configuration, all Z-force transducers showed $1/rev$ force amplitudes between 128 N and 135 N. For $\mathbf{T}$-matrix identification, random blade offsets (within the predetermined controller limits of $0.3°$) were automatically introduced into the system to produce and measure a corresponding change in rotor imbalance neccessary for the identification process. For reasons of conformity (see section 5.3), the size of the transfer matrix is fixed at 8×8, leaving four columns unpopulated in case of in-flight tracking control (four blade offsets, eight $1/rev$ coefficients for four Z-force transducers). After 10 consecutive random identification steps, the only partly populated transfer matrix was assumed to be identified with sufficient accuracy and saved to hard disk.

In the next step, all dynamic actuator inputs were set so zero and the HHC algorithm was activated. After each completion of the algorithm the proposed individual blade offsets were displayed in the GUI and then manually adopted and applied to the META system. While a total elimination of the rotor imbalance was impossible due to recirculation occuring in the closed space of the test hall, a reduction of the $1/rev$ Z-forces measured by the rotor balance to 8.66% of the baseline level was achieved after four consecutive controller runs.

Figure 7 shows both part of the identification process as well as the four controller steps leading to the final control solution. Each point in the plot represents the average $1/rev$ vibration component of Z-forces measured by the four sensors on the rotor balance for one set of individual blade offsets. Data points depitcted by circles belong to the identification phase and thus represent random settings for individual blade offsets. Data points no. 291-294 (triangles) show the subsequent development during the four controller runs, each further reducing $1/rev$ vibration levels. The final tracking solution and the resulting reductions in $1/rev$ vibratory Z-forces are summarized in Tables 1 and 2.

Table 1: pitch control offsets

blade	$\Delta\vartheta_0$, deg
1	$+0.31°$
2	$+0.03°$
3	$-0.07°$
4	$+0.33°$

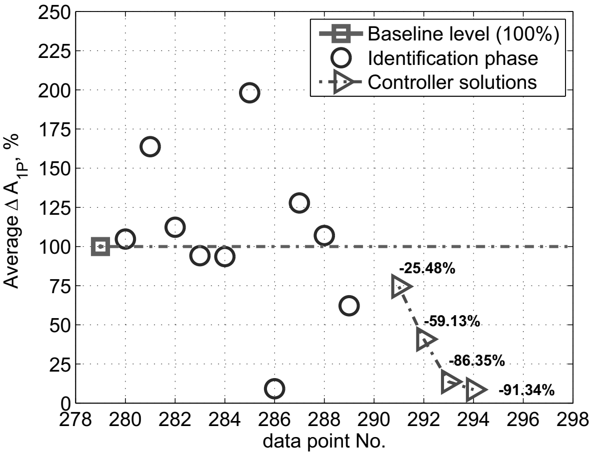


Figure 7: Progression of average $1/rev$ Z-force measured during testing

Table 2: reductions in 1/rev z-force amplitudes

transducer	$A_{1,baseline}$	ΔA_{1P}, N	red., $\%$
$Z1$	131.9	-122.0	-92.5
$Z2$	134.0	-121.1	-90.4
$Z3$	135.0	-121.0	-89.6
$Z4$	128.1	-119.1	-93.0

Since the desired thrust setting for the rotor is not directly communicated to the dSPACE-system running the controller algorithm, the method described in section 3 to keep the thrust setting constant during operation could not be realized. As a result, the individual blade offsets led to a net increase in rotor thrust of 115 N (7.7%). The severity of the rotor imbalances partly depends on rotor thrust and this effect can bias the results in either direction. To prevent, or at least mitigate this effect in the future, a feed-forward thrust compensation has been added within the control software, automatically lowering the collective pitch setting by $1/4^{th}$ of the sum of all individual blade offsets. The control and identification algorithms still use the unchanged individual pitch offset values which leads to a different transfer matrix, but does not affect the controller's performance in an adverse manner.

With the thrust compensation enabled, a second test was performed, again at a reduced thrust setting of 1500 N and with blade offsets limited to a maximum of $0.3°$ After the initial identification phase using random inputs, the controller algorithm was able to reduce $1/rev$ Z-forces by 87.4% after the first step, with a final reduction of 94.2% after three controller runs. The individual blade offsets measured during the third controller run are listed in table 3. The sum of all individual blade offsets in this case equals zero, thus keeping the thrust nearly constant during the test without need for further manual inputs by the operator. Accordingly the maximum thrust offset during the application of the last controller solution was measured at -11.8 N, equaling less than 1% of baseline thrust.

Table 3: pitch control offsets with equalized thrust

blade	$\Delta\vartheta_0$, deg
1	$+0.15°$
2	$-0.18°$
3	$-0.18°$
4	$+0.21°$

5.3. Vibration control test results

For the second tested control task, the $4/rev$ content of the hub loads were set as targets for vibration reduction by mixed mode HHC. Because the $\mathbf{T}$-matrix has a fixed size of 8×8, only four different hub loads (2 coefficients for each) can be accounted for. In this test, the hub forces F_X,F_Y and F_Z as well as the roll-moment M_X were chosen as controller input. The sine and cosine components for all HHC frequencies were limited to a maximum of $0.2°$. In contrast to the in-flight tracking test described before, this test was conducted at a thrust setting of 2500 N equal to $2/3^{rds}$ of the nominal thrust for the Bo105 model rotor in hover.

After setting the limits and trimming the rotor system, the identification cylcle was started, again introducing arbitrary control settings into the META system, resulting in changes of $4/rev$ vibrational loads. In this test the 8×8 transfer matrix was fully populated (eight control coefficients for four frequencies, as well as eight vibration coefficients for four rotor forces and moments), the identification cycle was allowed to run 20 times to be able to identify the transfer matrix with sufficient accuracy.

While both the control altgorithm itself and the identification functioned correctly and as expected based on the previous software simulations (see section 3), the results of this test were found to be inconclusive. During the identification phase, the $4/rev$ vibration coefficients of the measured rotor forces and moments failed to stabilize and remain at constant levels for the baseline case and also for any given tracking input, resulting in an insufficiently identified transfer-matrix. As a result, the "'solutions"' calculated by the control algorithm failed to produce notable reductions in $4/rev$ vibratory loads.

Two main reasons were identified, which contributed to the problem: Since the model was tested inside an enclosed space, recirculations effects and aerodynamic disturbances occur due to the proximity of the floor and walls to the rotor. The severity of those effects is coupled to the thrust setting - however at reduced thrust the $4/rev$ forces measured were too small to make a successful test of the vibration controller possible. At a nominal thrust of 2500 N, the recirculation effects strongly influence the rotor and thus the forces and moments measured by the rotor balance especially at higher frequencies, causing the aforementioned instability of the $4/rev$ coefficients.

Furthermore, the operation of high-powered electrical equipment (such as hydraulic pump motors) in close proximity to the model caused electromagnetic interferences with a frequency of 50 Hz. While this is hardly a problem for the measurement of $1/rev$ signal components ($1/rev$ equals 17.5 Hz), these interferences have a significant effect on the measured $3/rev$ (52.5 Hz) and also $4/rev$ (70.0 Hz) components.

Both of these problems are part of the testing environment used for the tests presented in this paper and will not be present during the upcoming wind-tunnel tests in the DNW's LLF. Due to the large size of the test section of the tunnel (8 m$\times 6$ m) and the flight attitudes to be tested (landing approach and level flight), recirculation effects like those experienced within the close test hall at DLR cannot occur. Furthermore, during the wind tunnel campgaign the hydraulic power units and other high-powered electrical equipment will be seperated much far enough from the measurement system to eliminate or at least reduce electromagnetic signal interferences to a minimum.

6. CONCLUSIONS AND OUTLOOK

As part of the ongoing preparations for a wind tunnel test campaign within the national research project *FTK-META*, a new HHC-based control algorithm was designed for use in conjunction with the DLR's novel multiple swashplate control system META. Capable of optimizing active rotor control signals for both vibration reduction and in-flight blade tracking while respecting user-defined limits, this algorithm was first tested by means of coupled numerical simulations with `MbDyn` and DLR's comprehensive rotor code `S4` and then subsequently integrated into the DLR's rotor test rig. In May 2015, the first tests of the control algorithm were conducted in hover conditions. Major findings are:

- Through the application of quadratic programming theory, reliable adherence of the control algorithm to user-specified limits was achieved while eliminating the need for the balancing of different wheighing matrices or other techniques such as signal scaling or truncation methods.
- Coupled numerical simulations performed with `MbDyn` (Politecnico di Milano) as well as with `S4` (DLR) were successfully conducted and used as proof-of-concept before the integration into the rotor test rig.
- For in-flight blade tracking, applicable transfer matrices were successfully identified by means of recursive identification methods both with and without automatic thrust compensation.

- At a reduced thrust setting of 1500 N, the occuring $1/rev$ rotor imbalances could be reduced by 94.2% using individual pitch offsets of up to $0.21°$ while maintaining a nearly constant thrust setting without further manual input.
- The test of the controller for the reduction of $4/rev$ vibratory hub forces and moments via mixed mode HHC $(2-5/rev)$ at $2/3^{rds}$ of nominal thrust yielded inconclusive results due to recirculation effects caused by the limited available space in the DLR's rotor test hall and electromagnetic interference.
- Based on the simulation results and also the successful test of the in-flight tracking mode of the controller, the algorithm is expected to perform as planned in HHC-tests during the upcoming wind-tunnel campaign.

Future work will focus on incremental steps to improve controller performance, primarily to try to reduce the number of controller runs necessary to achieve an optimal solution within given limits. Another goal is to further reduce the processing time needed to perform one controller iteration on the dSPACE real-time system. Parallel to the current semi-open loop approach, which necessitates an active user input for the application of each new control soution, a closed loop variant of the algorithm will be considered as well.

The upcoming wind-tunnel tests of the DLR's META-system are scheduled for late September 2015. During those tests, the control algorithm presented in this paper will be extensively used for both vibration control as well as in-flight blade tracking in various different flight attitudes, including a $6°$ descent and high speed forward flight.

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