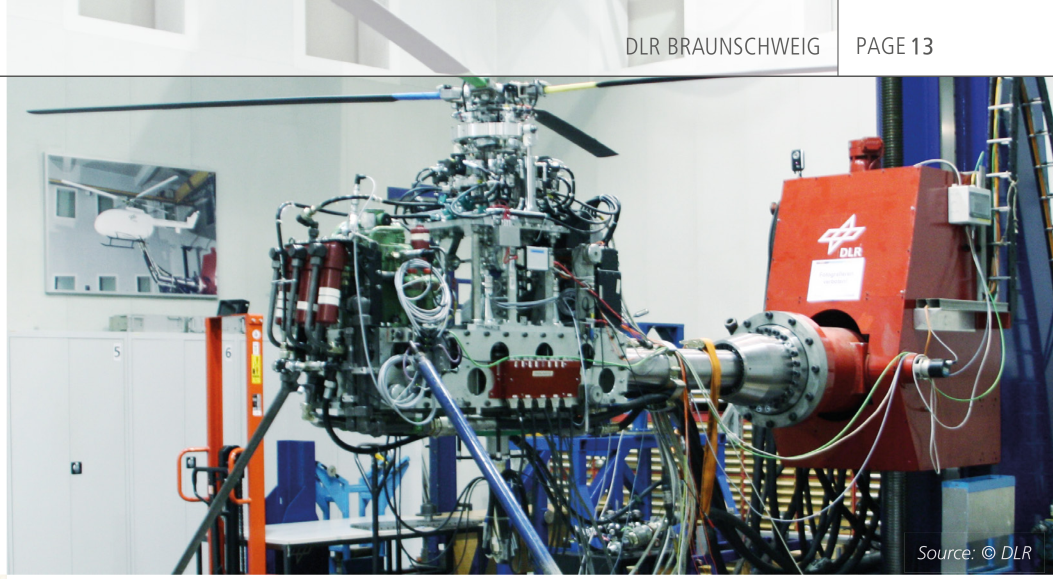
A fast-spinning rotor creates the desired thrust and lift for a helicopter – audible even for the hard of hearing. With a new kind of rotor control, the German Aerospace Center (DLR) proves that a helicopter can soar through the skies with far less noise and vibrations.

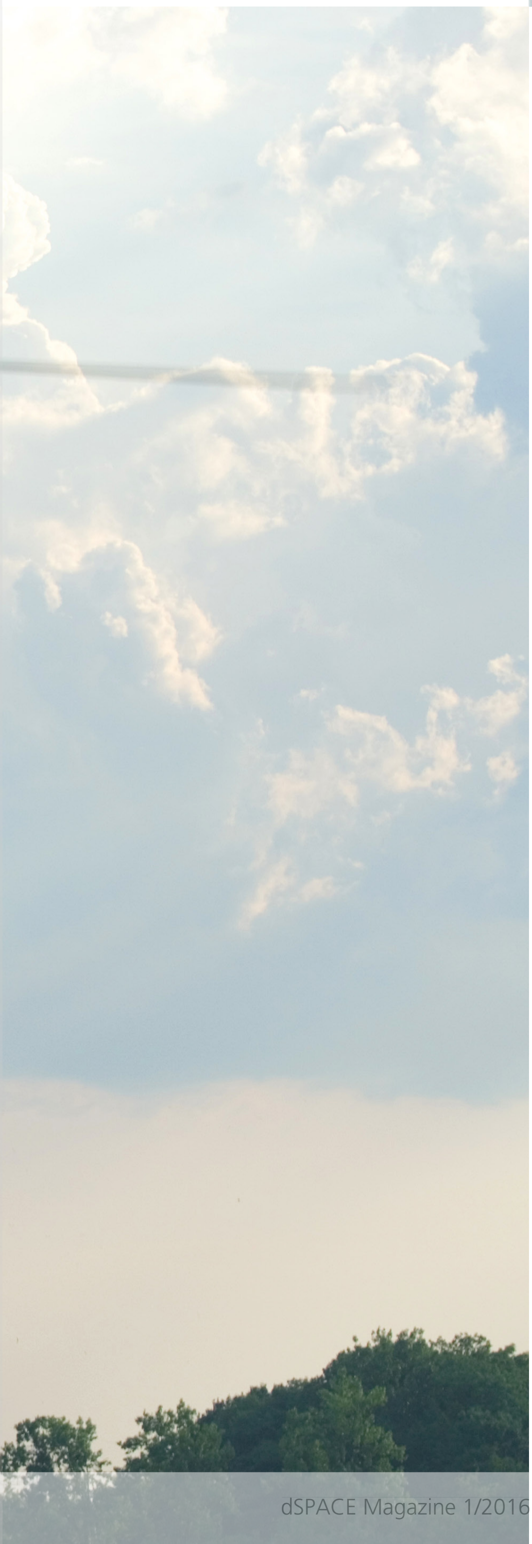
Agile Blades

A multiple-swashplate system for helicopters actively reduces noise and vibrations



Source: © DLR

DLR test setup for developing active controls for helicopter rotors.



For a helicopter in forward flight, the flows resulting from the forward movement of the helicopter and the rotation of the rotor blades overlap. This creates highly unsymmetrical flow conditions within the rotor disk. This causes various aerodynamic, aeroelastic and aeroacoustic effects, such as dynamic stall, noise, and vibrations. These effects usually occur periodically with the rotor's rotational frequency and integer multiples thereof (rotor-harmonic frequencies). One approach to counter or at least mitigate these effects focuses directly on the helicopter's rotor controls.

Controlling the Helicopter

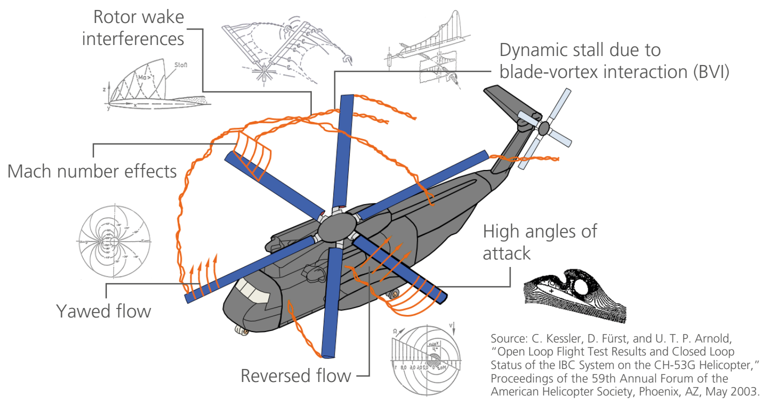
The main mechanical control unit of a helicopter is called a swashplate. It transfers the pilot's commands to the rotating blades. This is done by a combination of collective pitch control, i.e., changing the pitch angle of all main rotor blades to change the lift, and cyclic pitch control to influence forward and sideward thrust. The latter causes a variation of the blades' pitch angles to occur once every revolution of the rotor, or 1/rev.

Taking Action

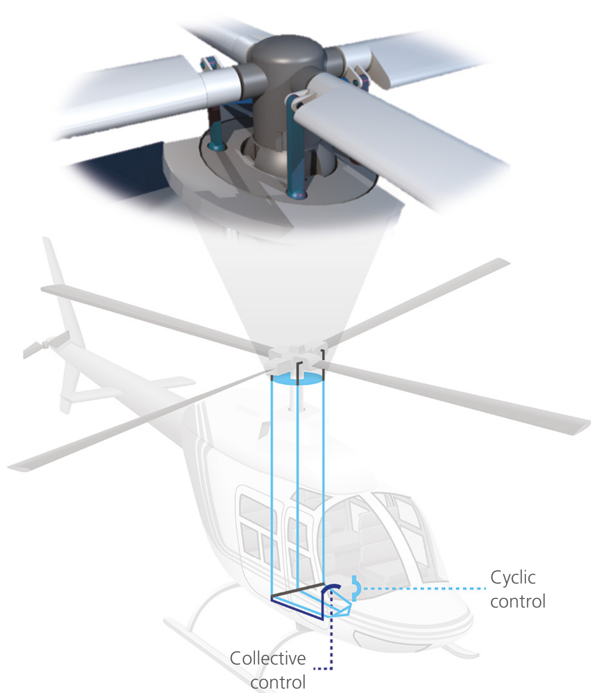
To mitigate undesired effects, the pitch angles of the rotor blades can be modified by stimulating the rotor blades with an integer multiple of the rotor frequency and a low amplitude. To reduce vibrations, the frequency, amplitude, and phase of the control signal is chosen such that vibrations are canceled out by interference. But also noise emissions and the power consumption of the rotor can be positively influenced by this method. Conventional (collective and cyclic) helicopter controls cannot effectively influence the higher harmonics of the undesired aerodynamic effects, and are only used to control the flight attitude. This is why as early as the mid-20th century, researchers tried to counter such phenomena and their effects by means of active rotor control. In addition to the pitch angle changes at all blades that are implemented by the primary controls, active rotor control introduces high-frequency pitch angle changes at a certain multiple of the rotor frequency (rotor-harmonic frequencies). This significantly reduces the vibrations in the helicopter and the noise radiation, and can also improve thrust and lift.

Active Rotor Control

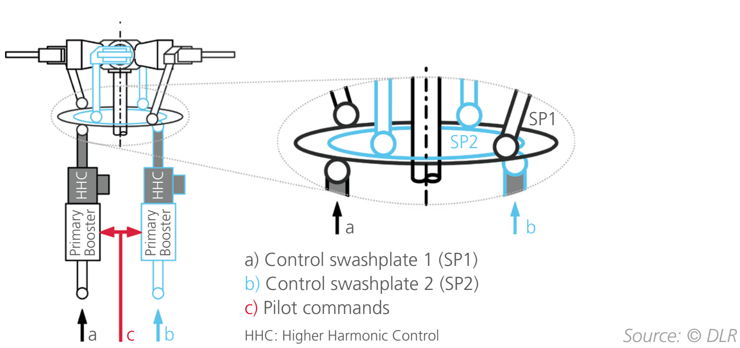
Existing approaches to active rotor control often have significant drawbacks. Systems that create the dynamic pitch angle changes by moving the swashplate (through actuators) are individual-blade-control (IBC)-capable only for rotors with up to 3 blades. For rotors with four or more blades, as are common today, this approach is limited for reasons of swashplate kinematics. Other systems are fully IBC-capable but use actuators in the rotating system that are subject to high loads and have to be supplied with energy and control signals via slip rings, which can pose a major challenge in and of itself. >>



Aerodynamic phenomena of helicopter rotors in forward flight.



The collective and cyclic pitch control of the rotor blades via a swashplate makes it possible to fly a helicopter vertically and horizontally.



How the multiple-swashplate system works: One swashplate controls two opposing rotor blades.

New Approach: Multiple Swashplates

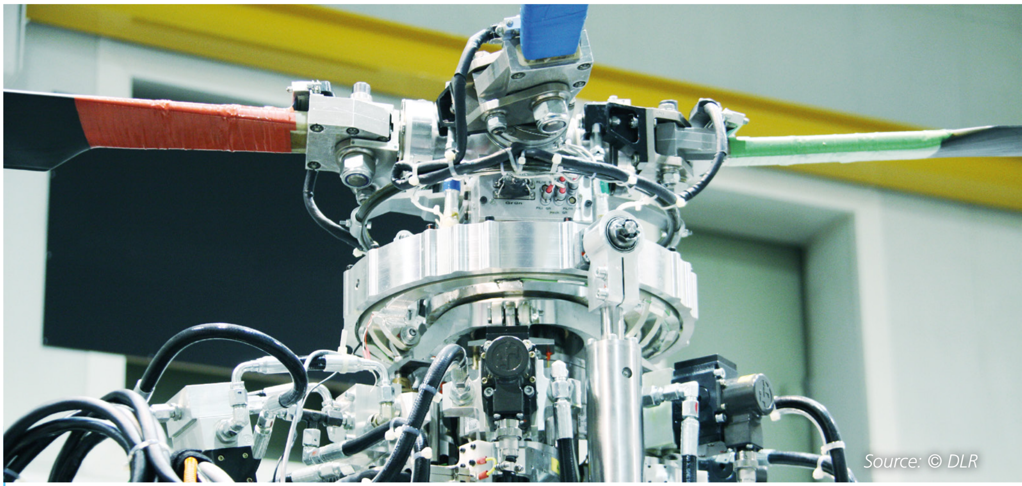
The multiple-swashplate system (META) patented by DLR and tested on a four-blade rotor on the rotor test rig in Braunschweig is a novel approach for an active rotor control. Electrohydraulic actuators induce high-frequency movements of multiple concentric swashplates. The swashplates then generate the desired dynamic changes of the individual blade pitch angles on the rotor. The actuators are installed below the swashplates, which are each connected to two blades. Using multiple swashplates makes the system IBC-capable, i.e., it is possible to modify the pitch angle of each rotor blade individually and with arbitrary control functions and frequencies. META thus combines the advantages of existing approaches without having to suffer from their drawbacks.

Initial Test Setup

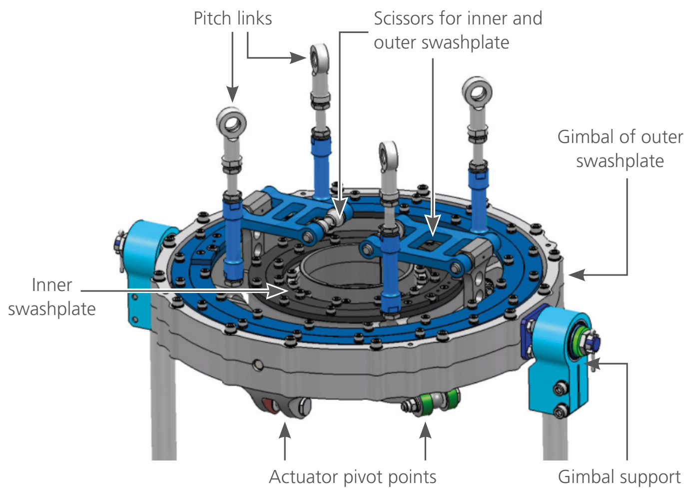
During the VAR-META project (VAR-META = fully active rotor control via multiple swashplates) within the framework of the Federal Aeronautical Research Programme, the multiple-swashplate system was tested for the first time on the rotor test rig at the DLR in Braunschweig. In these tests, a Mach-scaled wind tunnel model of a hingeless Bo105 rotor with a diameter of approx. 4 m was used. The model was equipped with the multiple-swashplate system for the first time. As a result of the Mach-scaling, the flow conditions largely reflect those of the actual helicopter rotor. However, this also increases the rotor speed. A particular challenge of the project was to control the electrohydraulic actuators that position and move the two swashplates. On the one hand, the desired changes to the pitch angles of all four rotor blades have to be translated into the corresponding piston movements of the actuators. On the other hand, these actuator movements have to be controlled actively.

Controller Requirements

The requirements for the open and closed loop control system are high: During testing, the model's rotor spins at 1050 rpm. Therefore, a planned blade control frequency from the first to sixth rotor harmonic results in an actuator frequency range from 0 Hz (static positioning) to 105 Hz, in which a high control accuracy must be achieved (approx. 0.05 mm). The maximum stroke of the actuators is ±4 mm, which corresponds to a pitch angle of approx. ±3.7° at the rotor blade. The pitch angle of a rotor blade always depends on the current azimuth angle of the rotor. Therefore, an angle encoder at the rotor mast is used to create trigger signals that provide information about the current azimuth angle and are used by all open and closed loop controls and measurement systems of the rotor test rig. To achieve the desired control accuracy, the actuators of the multiple-swashplate system are controlled 256 times per revolution. At a rotor frequency of 17.5 Hz, this results in a clock speed of almost 4.5 kHz for the control system. This means that all computations for the control of six actuators and their closed loop control have to be calculated at this speed, including signal processing and analysis as well as filters and feedforward control.



Prototype construction of the multiple-swashplate system.



Mechanical construction of the multiple-swashplate system. Source: © DLR

Developing the Controller Model

First, the entire system kinematics were modeled in MATLAB®/Simulink® to derive the real-time-capable control laws. The actuator movements required for the desired control case are computed via control matrices (some with > 50 columns) that convert individual pitch angle modifications (and coupling terms) into the corresponding control signals for the actuators. The subsequent actuator control consists of a PID controller with a feedforward loop. Because this feedforward control contains a complete harmonic signal analysis and a digital 8th-order low-pass filter, the simultaneous computation of a control signal for six actuators is also very demanding. After an actuator model

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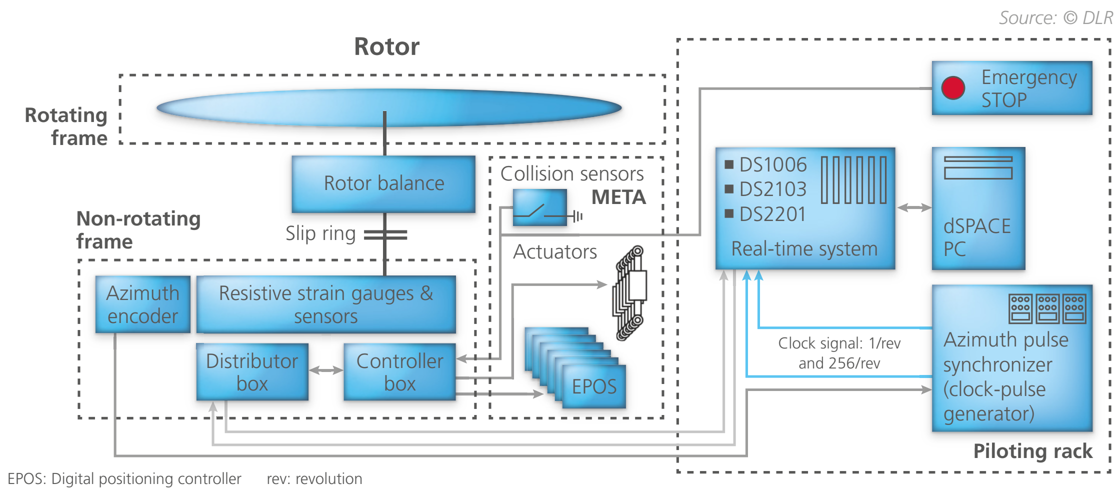
> "With the powerful dSPACE real-time system, we were able to extensively test the algorithms of our active rotor control and successfully prove the functionality of our multiple-swashplate concept."
>
> *Philip Küfmann, DLR*



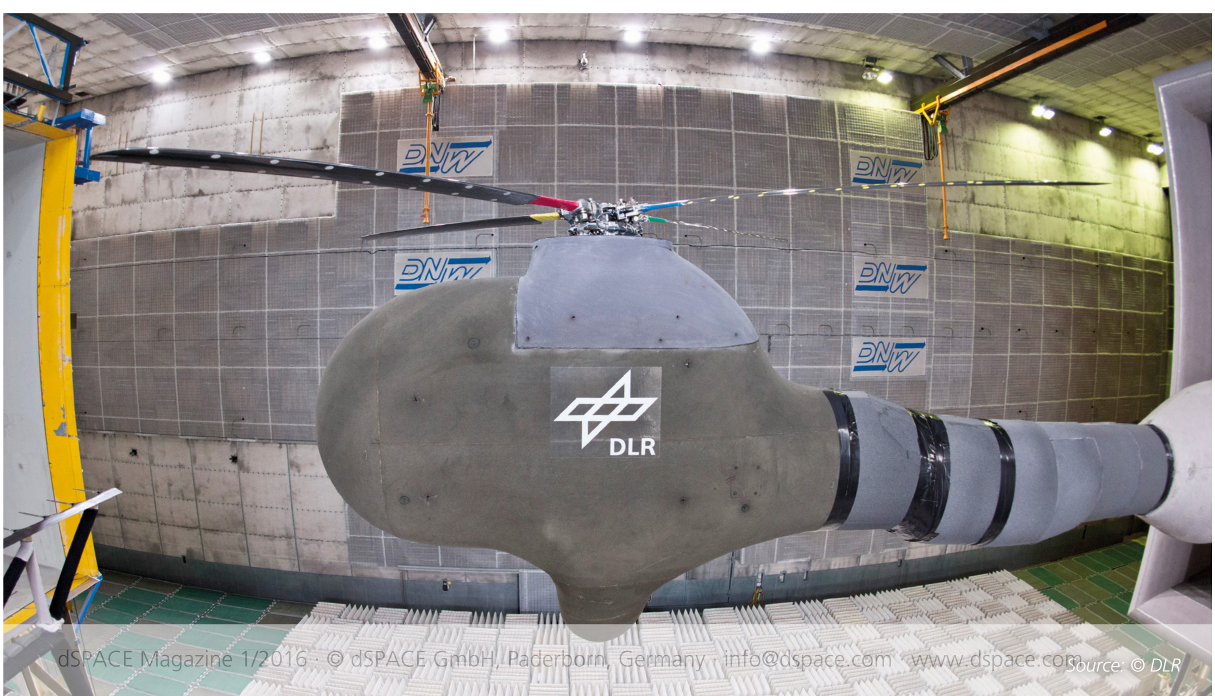
Signal flow chart of the test setup.

and the open and closed loop controls were modeled and validated in Simulink, the system had to become real-time-capable to control the hardware during actual tests.

Designing a Real-Time-Capable Control

The open and closed loop control of the multiple-swashplate system was implemented on a dSPACE system with a quad-core DS1006 Processor Board and the I/O boards DS2103 and DS2201. An Ethernet module was used to be able to communicate with measurement computers and data servers during the tests. The controls modeled in Simulink were distributed across multiple processor cores. One core each was used for the open loop control, closed loop control, and other tasks (such as network communication). Real-Time Workshop™ was used to compile the controls and run them on the dSPACE system. The signals of the angle encoder are used to trigger the program via hardware interrupts so the program runs synchronously to the remaining control and measurement hardware. Thus, it was possible to fulfill the high requirements for the clock speed of less than 250 µs per control step and achieve the desired control accuracy. Developers can use ControlDesk® Next Generation and a specially designed graphical user interface therein to access all the important parameters during a running operation, such as the controller gain,

Experimental setup in the wind tunnel.



Control and monitoring systems for the wind tunnel test, with two ControlDesk layouts (on the right).

> "We use dSPACE ControlDesk to carry out all of the measurement and control tasks needed for the dynamic operation of META efficiently and conveniently."
>
> *Philip Küfmann, DLR*

feedforward parameters, control frequencies and amplitudes.

Conclusion and Further Steps

The tests and proof of the system's IBC capability at the DLR in Braunschweig helped bring the VAR-META project to successful completion. After the hardware and software were updated and developed further, the multiple-swashplate system completed its first wind tunnel test in the low-speed wind tunnel of German-Dutch Wind Tunnels (DNW) in September 2015. The wind tunnel test was conducted within the FTK-META project (FTK = advanced swashplate concepts) and took nine days. The aim of the tests was to prove the influence of active rotor control on noise, vibration and performance, as well as a first function test of the multiple-swashplate system under various simulated flight conditions. The active rotor control strategies realized with META proved to reduce noise emissions by up to 5 dB and vibrations by up to 90% (in individual components). In rapid forward flight, the required rotor power was reduced by up to 4%. The system consisting of actuators and a dSPACE real-time PC operated without errors during the entire test. In the follow-up project SKAT (= scalability and risk minimization of technology with innovative design), the multiple-swashplate system will be used to research active rotor control concepts on the new five-blade rotor system. The project will also test a new controller developed on a dSPACE system that detects undesired vibrations at the model and balances them out by corresponding control commands at the two swashplates. ■

Philip Küfmann, DLR

Watch META in the wind tunnel: www.dspace.com/go/dMag_20161_META_E

The Multiple Swashplate System was invented by Prof. Dr. Berend van der Wall und Mr. Rainer Bartels at the DLR Institute of Flight Systems and was patented in 2008 (Pat. Nr.: DE-10-2006-030-089-D).

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