DEVELOPMENT OF AN ACTIVE FLAP ROTOR MODEL

M. Höfinger
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Flugsystemtechnik
Lilienthalplatz 7, 38108 Braunschweig, Germany

P. Leconte
Office National d'Étude et de Recherche Aérospatiale (ONERA), Centre de Châtillon
BP 72 – 29, avenue de la Division Leclerc, 92322 Châtillon Cedex, France

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Abstract: *The research organizations ONERA and DLR initiated a common programme supported by Eurocopter (EC) and Eurocopter Deutschland (ECD) as industry partners within the Active Blade Concept (ABC). The content is to investigate in theory and experiment the possible benefits and the phenomena associated with an actively controlled flap located at the trailing edge of a helicopter rotor blade. The main focus is put on the reduction of vibration and noise radiation of the complete helicopter rotor and the expansion of the flight envelope by the use of multi-frequency higher harmonic flap control. The first phase of the research programme was dedicated to the numerical assessment of flap geometry, radial location, and optimal control inputs. The simulations showed best results for a 15% chord flap, with different optimal radial locations, depending on the disturbance considered. A more inboard flap location is most suitable for vibration reduction, while for noise reduction the best results were obtained with a more outboard position. The design, manufacturing and experimental wind tunnel testing of a 4-bladed Mach-scaled rotor model in high speed and descent flight is realized during the second phase.*

1. INTRODUCTION

Increasing crew and passenger comfort, and reducing high frequency dynamic structural loads that increase the wear of components by minimizing the corresponding disturbances, still is an important aim for aerospace engineers. In addition, the increasing interest in environmentally friendly aircraft has led to specifications with continuously decreasing limits for noise emissions. This is especially valid for helicopters because they are often operated in urban environment, e.g. due to police and rescue missions including the hospital approaches.

The helicopter vibrations are high frequency fuselage oscillations. They are mainly excited by periodic forces generated by the main rotor and transferred through the rotor head and the gearbox into the fuselage. In the case of a rotor with identical blades only harmonics of the blade passage frequency N/rev are fed into the fixed fuselage system, with N the number of rotor blades. Although in reality marginal differences between the blades exist, and thus the vibratory frequency content is not restricted to the mentioned harmonic, the vibrations with non-harmonic frequency are negligible in normal operation. The lowest harmonic, the N/rev frequency content of the vibration, generally shows the largest amplitude and represents the most annoying part for human kind.

Different approaches have been explored to achieve a reduction of the helicopter vibration. Passive means, either located in the rotating or fixed system, aim at interrupting the transfer of the exciting forces into the fuselage by especially tuned absorbers (Ref. 1, 2, 3, 4, 5, 6). Structural optimization of the fuselage or dynamic tuning of the rotor blades are important means used during the design process to keep the fuselage vibration at an acceptable level (Ref. 7, 8, 9, 10, 11, 12). With active means the reduction of the exciting forces at the point of origin in the rotating system is possible.

International research activities showed the high potential of active rotor control with a higher harmonic blade pitch variation for vibration reduction (Ref. 13, 14). In this case a blade pitch oscillation with harmonics of the rotor rotational frequency is superimposed to the collective and cyclic blade pitch. Another benefit of this active control technology is the possibility to influence the flight paths of the tip vortices generated by the rotor blades. Especially in descent flight, the interaction of blades and vortices leads to the so-called Blade Vortex Interaction (BVI) noise (Ref. 15, 16). This impulsive noise is characteristic for helicopters in the final approach. As an example Figure 1 shows data from the Higher Harmonic Aeroacoustic Rotor Test (HART, 1994). The increased vortex miss distance as influence of the HHC input for minimum BVI can be seen clearly in the z-y-plane (diagram bottom left). Active rotor control can therefore lead to vibration reduction and reduced noise emission in the environmentally important mission elements. But also shock and stall effects in high speed flight resulting in high power consumption due to increased drag components can be influenced. Increased performance is the benefit.

The first realization of an active rotor control was the Higher Harmonic Control (HHC) system (Ref. 17, 18, 19, 20, 21, 22, 23). The control signal was fed into actuators located beneath the swashplate, see Figure 2 left. With this technique the blade pitch variation in the rotating system is restricted to N/rev and (N±1)/rev . The encouraging experimental results led to the development of the Individual Blade Control (IBC) system (Ref. 24, 25, 26, 27, 28, 29, 30, 31, 32, 33). By replacing the original pitch links located above the swashplate by hydraulic actuators, as indicated in Figure 2 right, the input frequency is no more restricted. Both technologies work with a higher harmonic excitation of the blade pitch at the blade root. Since helicopter blades are flexible in torsion the gain of the local blade pitch at the outer section of the blade depends on the input signal frequency and the aerodynamic loading, respectively the flight condition, and the natural frequency of torsion.

With an active trailing edge flap the excitation is not introduced at the blade root, but locally at a definite radial section of the blade. As a consequence, direct influence on the local blade pitch, the aerodynamic loading and furthermore the blade motion by adapting the blades to the local flow condition, is possible.

Therefore ONERA and DLR, supported by EC and ECD, initiated a common research activity within the Active Blade Concept (ABC) to investigate theoretically and experimentally the benefits of an active trailing edge flap for vibration and noise reduction and performance improvement of a helicopter rotor. It consists of two phases. During the first phase numerical simulations were conducted at DLR and ONERA to study the benefits and to define optimal flap size, position and deflection laws. The second phase consists of the manufacturing and wind tunnel testing of a Mach-scaled rotor model covering forward and descent flight to validate simulation results and investigate the aerodynamic and dynamic phenomena.

2. NUMERICAL SIMULATION

The numerical evaluation of the trailing edge flap was made using a full-scale 4-bladed medium-class helicopter rotor, with Advanced Technology Rotor (ATR) blades with advanced tip geometry, see Figure 3 (Ref. 34). The numerical model was dynamically adapted to the data of the original reference rotor delivered by industry. The focus was set on the first torsion mode as well as the first and second flap bending and the first lead-lag mode in order to allow the transfer of the numerical results to the real rotor. The presence of the actuators, flap, driving mechanisms etc. was simulated by adding a mass distribution along the flap length and centered on the quarter chord axis.

The flap deflection law to be optimized is

$$\delta_{flap} = \sum_{i=0}^{5} \left[\delta_{ic} \cdot \cos(i \cdot \Psi) + \delta_{is} \cdot \sin(i \cdot \Psi) \right] \tag{1}$$

with δ>0 when the flap is deflected downward.

At ONERA, the optimization variables were the static value δ_{c0} and the harmonic coefficients δ_{iC} and δ_{iS} up to the fourth harmonic (4/rev). At DLR, the static and 1/rev control coefficients were not considered since it was assumed that they will affect the trim and will therefore not be used in an operational system. The higher harmonic flap deflections 2/rev up to 5/rev were optimized by DLR.

Flap deflection effect on Blade Vortex Interaction (BVI) noise

Two main principles can be considered to achieve a BVI noise reduction. Either the strength of the vortices impacting on the following blades can be reduced and/or the path followed by the vortices, i.e. the wake convection, can be modified. The first solution essentially requires changing the spanwise lift distribution on the blade, resulting in modified tip vortex strength. In case of an active trailing edge flap additional vortices at the root and tip of the flap itself are created. The combination of blade and flap vortices can contribute to changes of the overall tip vortex strength. When changing the vortex convection, either upward or downward, the blade vortex missdistance is increased. A significant effect on BVI noise requires that the torsion excursion of the whole blade is modified. This can be obtained at best by combining a large aerodynamic pitching moment generated by the flap deflection and a rather low first torsion mode frequency of the blade. At the start of the project, two different flap chords were considered, respectively of 25 and 15% of the local blade chord. Numerical simulations showed that BVI noise could be reduced with both configurations. Based on the simulation results industry selected the small flap chord to be investigated in a full-scale flap equipped rotor (Ref. 35). The same geometrical configuration was chosen for the rotor model. Additional simulations with a blade with low natural torsion frequency at wind tunnel scale showed the risk of aeroelastic instabilities. The torsion stiffness tuning resulted in a first torsion frequency of 4.3/rev. Figure 4 illustrates for a given flap deflection law the noise reduction as calculated for various flap radial positions.

Flap deflection effect on vibration

As already mentioned above, the vertical N/rev force is one of the terms to be reduced, along with the (N-1)/rev in-plane moment in the rotating frame. The latter creates rolling and pitching movements of the helicopter fuselage. As described in Ref. 36, optimizations were carried out to minimize the unsteady terms. At first, it was assumed that different effects would act on the dynamic behavior of the rotor depending on the chord of the flap: a direct lift effect for the large chord flap and a servo-flap effect for the small flap configuration. The simulations finally showed that in fact both effects can be encountered during a single rotor revolution with both the small or large chord flap. Depending on the flight conditions, optimal flap deflection laws were calculated, leading to reductions of more than 90% for the vertical 4/rev force and 45% of the 3/rev in-plane moment. Simulations with the most inboard flap position (70-80% blade radius) showed the highest reduction levels.

3. ABC MODEL BLADE HARDWARE

For the phenomenological investigation in the wind tunnel a fully articulated main rotor with four Mach-scaled blades of 2.1m radius based on the ATR geometry is designed and manufactured. The maximum blade chord is 140mm. The flap dimensions at wind-tunnel scale are 210mm in span and 21mm in chord. The hardware design includes an adjustable radial location of the flap. Three radial positions will be experimentally investigated, 70-80%, 75-85%, and 80-90% radius, see Figure 3. The baseline rotor rotational frequency will be 103.15rad/s (16.42Hz).

The internal structure of the wind-tunnel blade consists of a main spar made of uni-directional glass fibers (Figure 5), milled foam and especially designed additional elements (Figure 6). A stiffening frame made of high modulus carbon uni-directional fibers accommodates the active flap system, i.e. actuator, driving mechanism, and hinge system (Figure 7). The skin is made of several carbon fiber layers of different orientation and contributes to the torsion stiffness of the blade. Balancing weights made of tungsten are located in the leading edge area.

It takes several steps to manufacture the ABC model blades. The main spar, the skins, the flaps and all interior elements are manufactured separately. After the assembling of the main spar and the carbon frame (Figure 8), the final curing of the blade is made. In order not to encounter serious problems due to thermal expansion of the different materials during the several heating and cooling processes a blade mould made of carbon fiber, especially developed at DLR, is used instead of a steel or aluminum mould (Figure 9).

Flap actuation

The actuation of the flap is provided by the use of a piezoelectric actuator. The experimental assessment is described in Ref.37. Pre-stressed stacks made of piezo material are located along the major axis of a metallic elliptic frame, see Figure 10. The stacks expand when power is delivered. As a consequence the minor axis of the elliptic frame is shortened. One side of the minor axis is clamped to the carbon fiber reinforcing frame. The other end of the minor axis is connected to the flap via a metallic lever blade. It is screwed to the flap off the rotation axis by a small distance, producing an amplification effect. Flap and blade are connected by a hinge blade made of composite material, thus suppressing any conventional bearing that could be affected by high centrifugal loads. The actuator used is an off-the-shelf type manufactured by the French company CEDRAT Recherche. It is slightly modified for the present application. Some data concerning the actuator is given in Table 1.

Table 1: Data of piezoelectric actuator for ABC program (CEDRAT APA500L).

Voltage	0-200V
Mass of actuator	208g
Blocked force (F)	570N
Maximum Stroke (X)	0.5mm
Stiffness	1.140 10^6 N/m
Resonance frequency	450Hz
Energy to weight ratio	342.5 10^{-3} Nm/kg
Width (chord axis)	55mm
Length (span axis)	145mm
Thickness	10mm

The power amplifier used to supply the actuator is limited to 200V and 1A current. A strain gauge bridge implemented on the elliptic frame of the actuator allows measuring its stroke. Two Hall effect sensors per flap measure the deflection angle. The corresponding magnets are glued to the flap and the sensors are located in the blade trailing edge.

4. ABC WIND-TUNNEL TESTS

The experimental testing with the active flap rotor model will be made in two different wind tunnels. The first test campaign will be conducted in the ONERA wind tunnel S1MA in Modane. The testing is primarily dedicated to vibration reduction and performance improvement in forward flight.

The focus of the second test campaign, carried out in the Large Low-Speed Facility (LLF) of the German-Dutch Wind Tunnels (DNW) is put on noise reduction in descent flight conditions including the use of a flow visualization and measurement technique to analyze the complex vortex behavior.

Wind tunnels

The S1MA wind-tunnel combines a large test section (8 meters in diameter) and wind speeds ranging from almost 0 to Mach 1. The test apparatus for isolated rotor models is electrically driven and features hydraulic power to control the rotor (collective and cyclic pitch). The shaft can be tilted to a maximum angle of 90° to simulate hover flow conditions. Steady and unsteady forces acting on the rotor are measured with a balance mounted below the rotor. In addition, a large number of unsteady quantities can be measured in the rotating system, such as flap, lead-lag and pitch angles, accelerations at the hub, pressure distribution on the blades, blade deflections, pitch-link loads… As the tests for the flap-equipped rotor will be highly sophisticated, the possibility to run the rotor on the rig in the cart but outside the aerodynamic circuit will be used at best during the preparation phase to maximize the wind-tunnel slot productivity.

DLR has a long tradition of rotorcraft wind tunnel testing in the LLF of the DNW (Ref. 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49). Prior to the wind tunnel tests the complete test set-up, including the model, the control container, data gathering and all additional supporting systems are fully assembled, prepared, and checked in the preparation hall at DLR, Institute of Flight Systems in Braunschweig. It includes a replica of the DNW sting support and comprises all facilities to operate the rotor, calibrate the balances and the sensors, and check all hard- and software. After successful functional testing the facilities are disassembled and transferred to the DNW. As in the S1MA the three dimensional static and dynamic rotor loads in the fixed system are measured with a rotor balance located beneath the rotor hub. Data from the rotating system are transferred via a 250 channel slip ring. A 135kW hydraulic motor drives the main rotor. The tests will be conducted in the acoustically damped DNW test chamber using the 8m by 6m open jet configuration with a microphone array and a common support for flow measurements.

Test content

The first ABC test, dedicated to vibration reduction and performance improvement, will use open- and closed-loop control. Forward flight conditions with advance ratios ranging from μ=0.3 to 0.45 with different rotor loadings will be tested, see Figure 11. The inboard flap position is of highest priority, since the numerical simulations showed that this configuration appears most suitable for vibration reduction.

For each test condition reference data without flap deflection are measured. Following are sweeps of the harmonic flap deflection parameters phase, amplitude and frequency. Since this is a time consuming procedure (approximately 6min per test point) it can only be realized for selected rotor conditions. The optimal flap deflection control laws for vibration reduction and performance improvement as obtained from the numerical simulations will be validated.

The DNW test is mainly dedicated to BVI noise reduction in descent flight condition. But vibration and performance parameters are measured continuously and are therefore available for analysis. The investigation will cover flight path angles from γ=+2° to -12° at μ=0.15, see Figure 11. Besides noise measurements the DNW test data of the flap and blade tip vortices flight paths will be gathered using the Particle Image Velocimetry (PIV) flow measurement technique (Ref. 50). The outer flap position is of highest priority, since the corresponding numerical results indicated the highest potential for noise reduction. Because of the time consuming noise and PIV measurements the middle flap position (75-85% radius) will not be tested and flap control will be open-loop only.

Flap control

The flap deflection control system used during the wind tunnel tests in S1MA is based on a dSPACE solution. It can be used to establish the sensitivity matrices of the whole active flap rotor, perform sweeps with respect to the flap actuation parameters, deliver prescribed flap deflection laws, and perform on-line optimization of the flap deflection law to minimize the vibration level. The dSPACE system also generates the signals needed to retrim the rotor if the introduced flap deflection law has an influence on the flight condition. Two human validation steps are kept in the control process due to safety reasons. One is related to the flight condition and one to the delivery of an optimized flap deflection law. The closed loop configuration used to decrease the vibration level is based on strain gauges data from one blade. Analysis of previous rotors featuring such gauges (see blade deflection paragraph below) showed that the evolution of the vibration level according to various flight conditions could be well depicted.

The flap deflection control in the DNW will be open loop only. Single frequency parameter sweeps will be made to identify the effect of the dedicated frequency on the output signals. The pre-calculated optimal control laws that will be validated are of multiple frequencies. The input signals are commanded via PC with the possibility to manually adjust single parameters.

Data gathering

In addition to the non-permanent acoustical and flow field measurement in DNW, some data are recorded throughout the tests. From the rotating system, besides the flap deflection data, these are strain gauge signals from every blade for blade motion analysis, two root pitch sensors, shaft bending moments and all pitch link forces. These data are pre-amplified and transmitted via a slip-ring system. In the non-rotating system the shaft inclination, rotor azimuth, balance forces, power, basic rotor control, actuator forces and displacements, swash plate accelerations and temperatures are measured.

After setting the wind tunnel and the rotor on operational condition as specified in the test matrix, the wind tunnel data (air data, model position) are provided and recorded together with the rotor and balance data. Immediately afterwards the blade pressure data are recorded and in DNW the microphone or PIV measurements start. During PIV measurements no acoustic data is recorded because it is not possible to install the microphone traverse and the common support for PIV simultaneously in the test section.

Noise measurements

A moveable and height adjustable array of 13 laterally mounted microphones is used for the noise measurement in the DNW LLF. The microphones will be located at a distance of 1.5 rotor radii beneath the rotor hub center. The traverse is starting at the most upstream position and traveling downstream in increments of 0.5m with a stop for measurement. At each stop up to 100 rotor revolutions are recorded continuously at a sampling rate of 2048/rev (approximately 33.6kHz). The data acquisition is triggered to the 1/rev rotor signal. From these data the mid-frequency noise (6-40 times the blade passage frequency = 24-160/rev, appr. 400-2600Hz) will be computed and the influence of the flap control analyzed.

Blade deflection measurements

During the tests in both S1MA and DNW the flapping and torsion deflections of the blade will be evaluated with the SPA (Strain Pattern Analysis) method, developed by ONERA. This method is based on data from strain gauges implemented on the rotor blades. A specific calibration performed prior to the tests by vibrating the blades at their natural frequencies allows to record the mode shapes and correspondent strain gauge responses. The gauge signals recorded during the tests are then projected on the modal base, providing generalized coordinates. Combined with the modal shapes the actual blade deflections can be computed.

Vibration measurements

The static and dynamic hub loads are measured by a rotor balance, calibrated statically with respect to the rotor hub. A Fourier analysis of the dynamic signal gives the frequency content and the corresponding vibrations. With a sampling rate of 128/rev, up to the 64th harmonic of the rotor rotational frequency (approximately 1kHz) can be analyzed. However, only the 4/rev will be used for vibration analysis.

PIV measurement

The most important question concerning the flow field behind the rotor blade, if equipped with trailing edge flaps, is how the different vortices will develop in space and time. Uncertainties remain in theory if the tip vortex and the outer flap vortex merge and when. But this can have a direct impact on the intensity of the BVI noise radiation and on the optimal flap control input. With PIV it is possible to observe the time evolution of turbulent vortex structures such as vortex convection, line and sheet formation, merging, and dissipation.

In order to cover the proposed vortex locations with the PIV measurement, a common support with three traverses (in x, y, and z direction) plus a central hinge for rotations about the vertical axis will be installed in the test section. The laser beams are directed vertically into the flow field from the lower platform. The camera systems are mounted on the z-traverses on the vertical tower. In three components (3C) stereoscopic PIV measurements, two cameras are used to cover the three velocity components of the flow field. For the ABC test two component (2C) PIV is sufficient, since the focus is on the general behavior of the vortices. Provided that a high resolution is available it is possible to cover the entire radial range of 30% rotor radius (0.63m) from tip to the most inboard flap vortex with one camera.

Blade pressure measurement

The ABC model blades will be equipped with altogether 168 absolute pressure sensors, distributed on the four blades. From 72.5% to 97.5% rotor radius pressure sensors are located at the leading edge (9% chord) with increments of 5% radius. In addition sensors are located at 50% and 62.5% radius. High gradients in the leading edge pressure, indicating BVI events, can be observed with these sensors. Figure 12 shows the leading edge pressure data from a former wind tunnel test with HHC. For the case of minimum BVI the high parallel gradients, present in the first quarter of the rotor disk for the baseline case without HHC, are avoided. Although the pressure and the gradients are increased at around 90° azimuth, the parallel interaction of vortices and blades and as a consequence the BVI noise radiation is reduced. At five radial positions (50%, 72.5%, 77.5%, 82.5%, 87.5% radius) data from a chordwise distribution of 20 pressure sensors are measured to be able to analyze the flap influence on the sectional aerodynamic loading.

Blade pressure will be measured in parallel to noise. The pressure measurement starts when the reference blade passes the 0° azimuth position. The sample rate is 2048/rev as for the microphone data. Data from the pressure transducers will be recorded for 64 revolutions.

5. CONCLUSION AND OUTLOOK

DLR and ONERA both have longtime experience in the theoretical and experimental research of helicopter technology. Active rotor control is known to be a highly successful means to reduce disturbances such as vibration and noise radiation by influencing the aerodynamic excitation and the dynamic reaction of the main rotor blades. The investigation of Higher Harmonic Control (HHC) as well as Individual Blade Control (IBC) in the past led to the improvement of the simulation codes and the understanding of underlying phenomena such as Blade Vortex Interaction (BVI) noise. Both technologies have in common that a higher harmonic blade pitch is introduced at the blade root. Continuing the successful cooperation on Active Rotor Control, DLR and ONERA initiated a common Active Blade Concept (ABC) programme to investigate the potential of active trailing edge flaps on helicopter rotor blades for vibration and noise reduction and performance improvement. In the first phase of the programme the optimal flap size and position as well as control laws were evaluated for a full-scale ATR (Advanced Technology Rotor). As far as vibrations are concerned, gains of up to 90% on the 4/rev vertical force or 45% on the 3/rev in-plane moment in the rotating frame (inducing pitch and roll movements), without penalty on other unsteady forces, could be numerically obtained. Some of the physical phenomena, which contribute to noise alleviation, need to be experimentally demonstrated, such as the combination of blade tip vortex and flap tip vortex. Therefore, a highly instrumented four-bladed rotor model will be manufactured and tested in both S1MA (high speed for vibration) and DNW (low speed for noise) wind tunnels in order to validate the numerical simulations.

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FIGURES

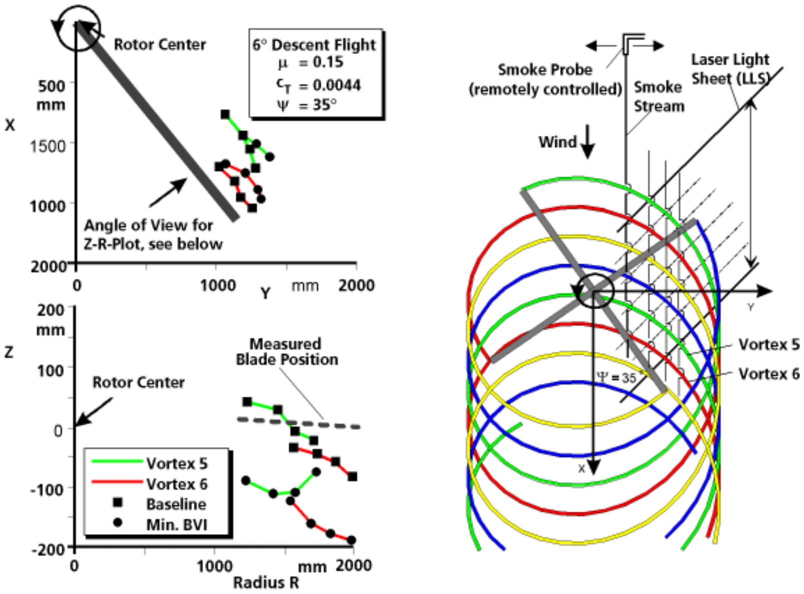


Figure 1: Influence of HHC on vortex flight path; data from HART, 1994.

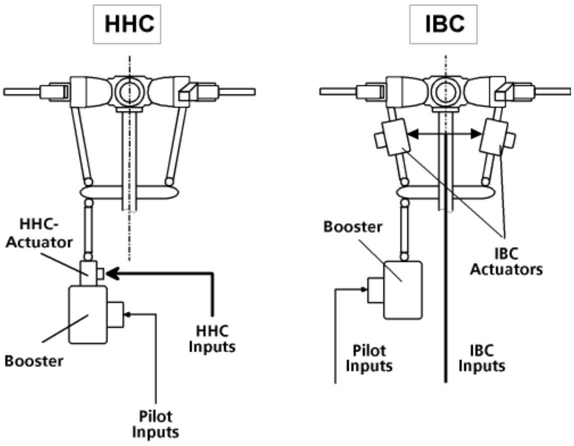


Figure 2: Schematic HHC-IBC comparison.

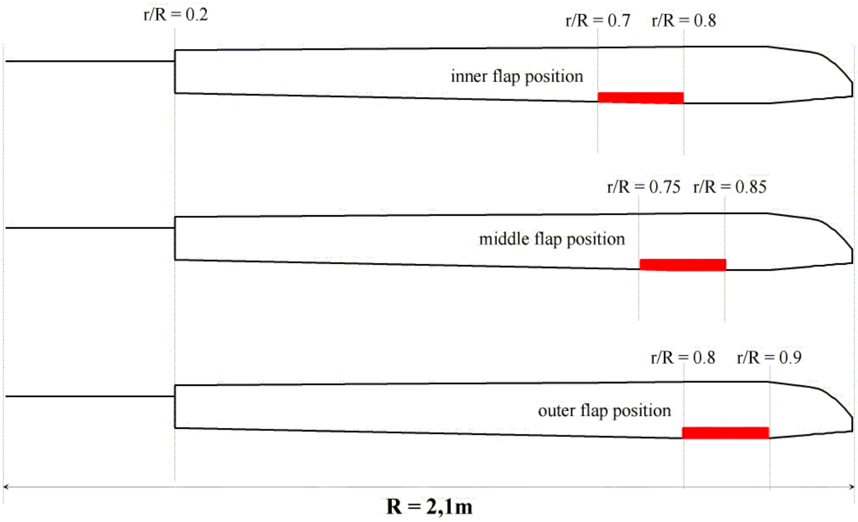


Figure 3: ATR blade geometry with active trailing edge flap locations.

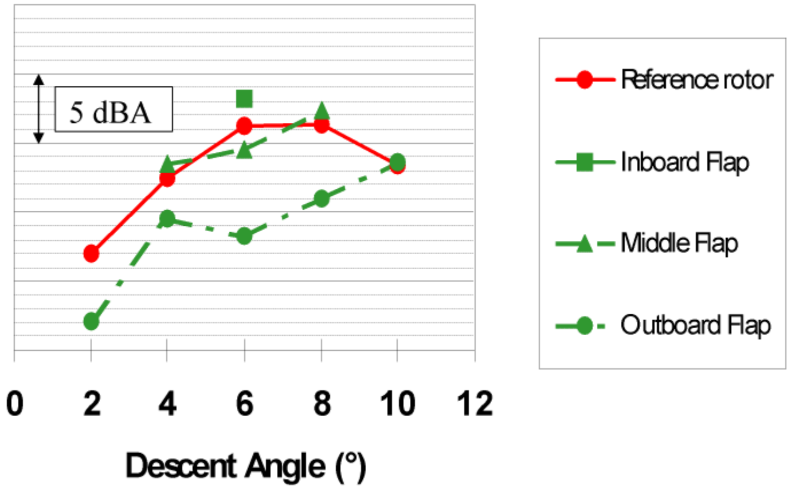
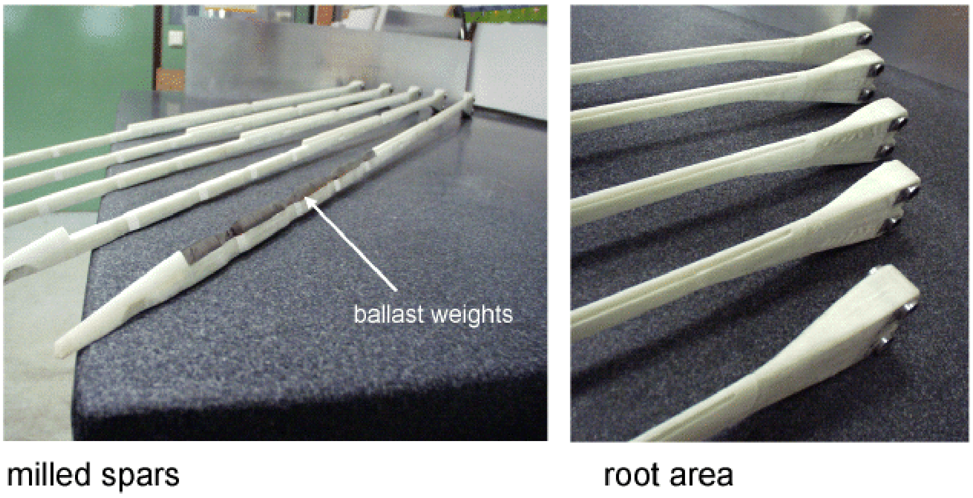


Figure 4: Predicted noise reduction (results from numerical simulations with 15% chord flap).



milled spars

root area

Figure 5: Milled main spars for the ABC model blades (4+1 spare).

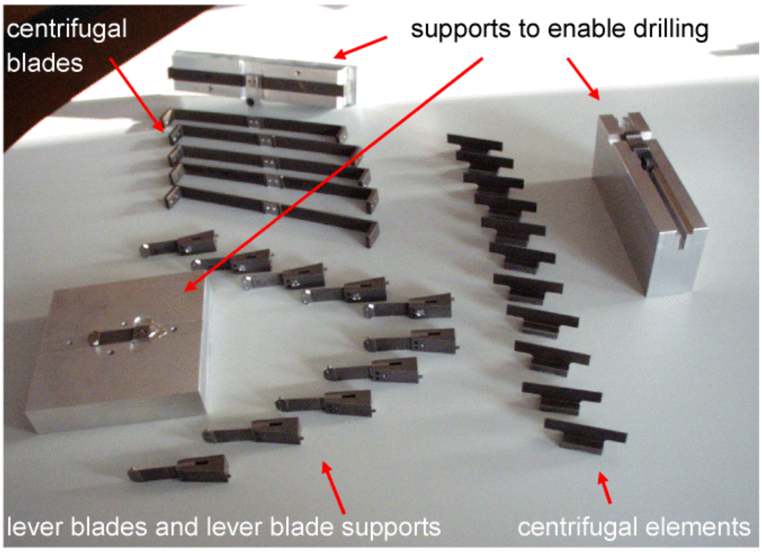


Figure 6: Additional elements as part of the ABC model blade active flap system design.

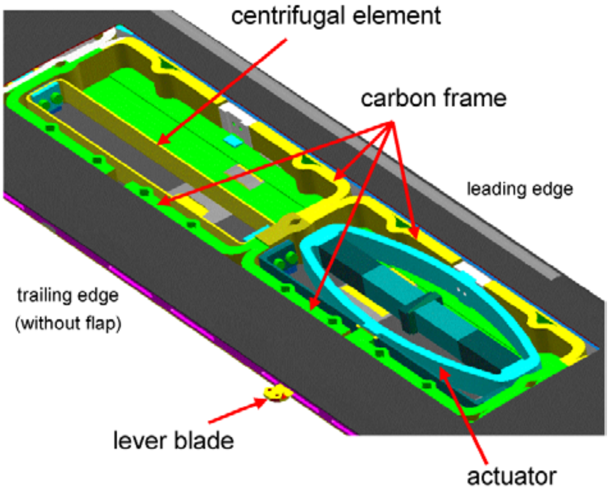


Figure 7: Inner ABC model blade design of flap area including carbon frame and piezoelectric actuator.

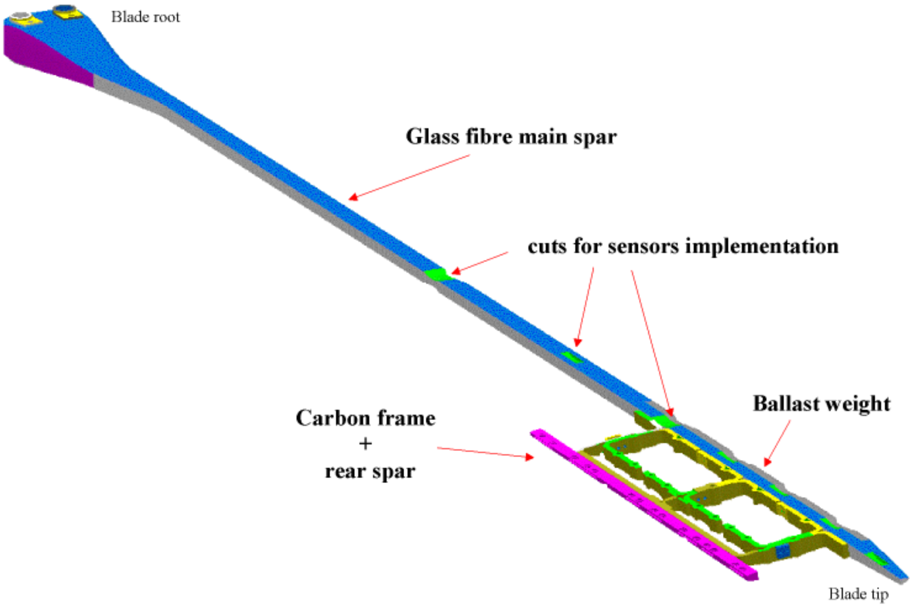


Figure 8: Assembled carbon frame and main spar.

Figure 9: Upper and lower part of the carbon fiber blade mould.

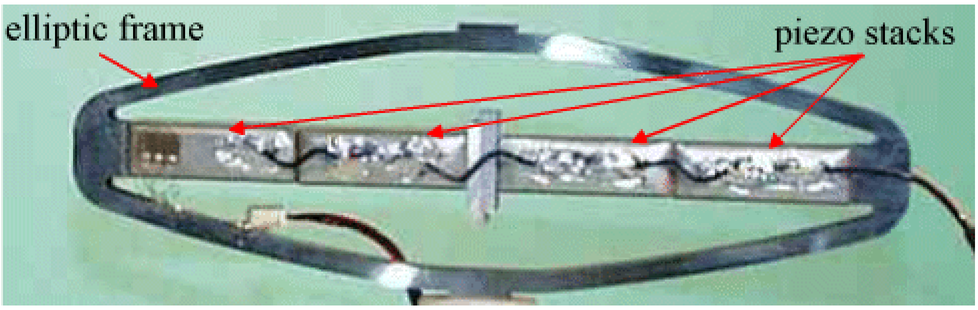


Figure 10: Piezoelectric actuator used to drive the ABC active trailing edge flap.

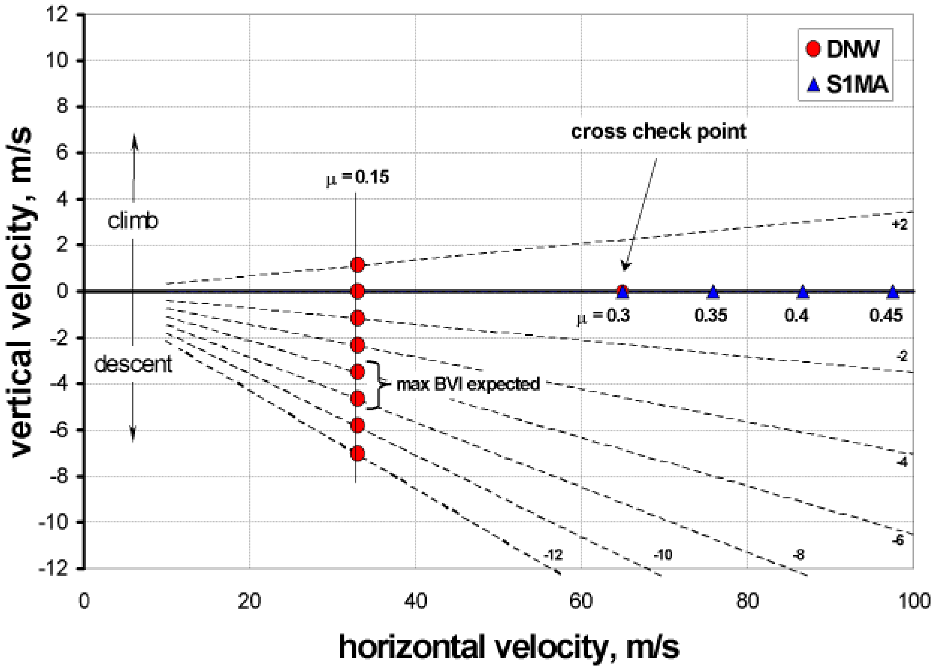


Figure 11: Test matrix of ABC active trailing edge flap programme.

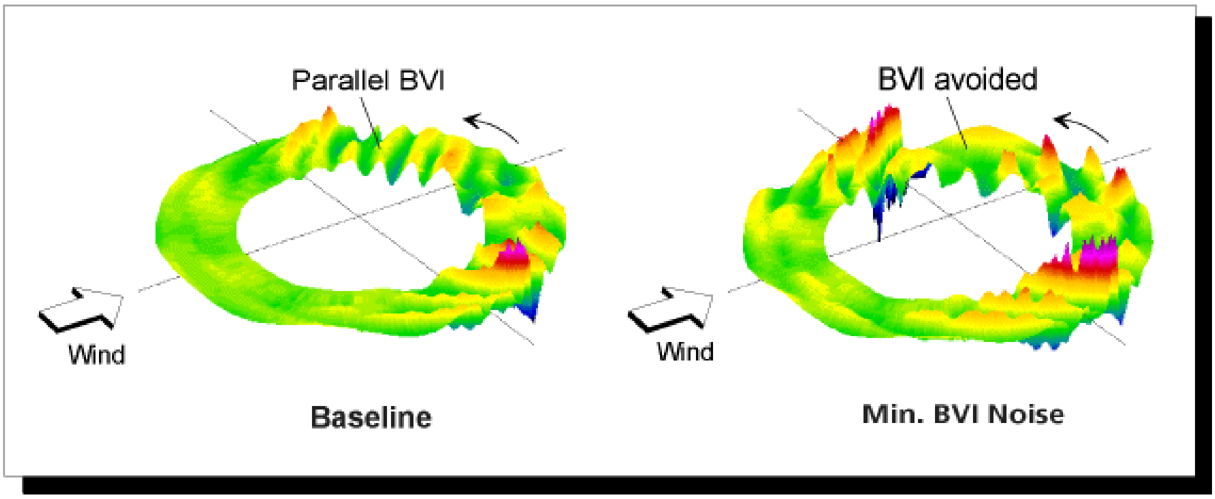


Figure 12: Effect of HHC on leading edge pressure distribution (HART 1994, 6° descent flight).