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REDUCTION OF BVI NOISE ON GROUND - IN-FLIGHT EVALUATION OF CLOSED-LOOP CONTROLLER

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1 Abstract

The individual blade root control (IBC) system installed on a BO 105 helicopter has been successfully tested in the open loop configuration. The flight tests have clearly demonstrated the noise and vibration reduction potential of this technology. The further activities were therefore concentrated on the realisation of a closed loop noise and vibration control system.

This paper presents the development and the testing of a BVI (Blade Vortex Interaction) noise control concept. The newly developed control strategy is based on the minimisation of an appropriate BVI index by applying a 2/rev IBC feedback.

The in-flight testing of the controller using on-board microphones for BVI noise detection was performed on the BO 105 test helicopter. The reduction of the noise emission measured on ground is documented for several flight conditions.

2 Introduction

The flight comfort and public acceptance of helicopters strongly depends on the vibration and noise levels inside the cabin and the exterior noise radiation. An extremely annoying noise is the BVI noise, which is primarily radiated during the landing approach, when the helicopter descends into his own rotor wake.

Passive means, e.g. isolation systems or advanced design of rotor blades, do not reduce the vibration loads and the BVI noise emission sufficiently. A more effective technique to significantly minimise vibrations and BVI noise is the application of active rotor blade pitch control like HHC (Higher Harmonic Control) and IBC. HHC consists of a blade pitch control law depending on multiples of the main rotor rotational frequency, whereas IBC allows arbitrary pitch control inputs. There are various ways to realise IBC such as the blade root actuation technology, which will be addressed in this paper, or the piezo-active trailing edge flaps which are currently developed by Eurocopter.

Figure 1 IBC demonstrator aircraft BO105 S1

The active rotor control has been investigated experimentally in wind tunnel and flight tests within the scope of several programmes. Since 1990 EUROCOPTER DEUTSCHLAND (ECD) has devoted a great research effort to the development and improvement of this technology (Ref. /1/ - /10/). An overview of the performed activities is given in Table 1.

One major technical milestone was achieved by the flight tests within the Rotor Active Control Technology (RACT) research programme which was jointly conducted by Eurocopter Germany (ECD), the German Aerospace Center (DLR), the EADS Corp. Research Center (EADS CRC) and ZF-Luftfahrt (ZFL). This open-loop IBC flight tests performed with a highly equipped BO105 IBC demonstrator (Figure 1) provided a comprehensive data base including simultaneous measurements of rotor operational parameters, vibration loads, blade pressures and noise onboard of the aircraft and on ground (Ref. /7/ - /9/).

The current IBC noise control concept was derived from the results and experience gained from this flight test campaign. The concept relies on the noise reduction capabilities of 2/rev IBC feedback control for BVI relevant descent flights, which could be demonstrated in the flight test mentioned before. In this paper, the results of the in-flight testing of this noise controller using onboard microphones for BVI noise detection are presented and evaluated.

Year	IBC Tests	Flight Speed	IBC Ampl./ Harmonics	Objective
1990	***First flight tests*** Open loop single-harmonic input	60 kts/ 115 kts,	0.16° 3/rev, 4/rev, 5/rev	Functionality tests
1991	***Flight tests with increased authority*** Open loop single-harmonic input	60 kts/ 110 kts, 65 kts descent	0.40° 3/rev, 4/rev, 5/rev	Vibration and BVI noise characteristics
1993 / 94	***Wind tunnel tests, NASA Ames*** Open loop single and multi-harmonic input	43 kts ÷ 190 kts	≤ 2.5° 2/rev ÷ 6/rev	Vibration and BVI noise characteristics, performance at high speed
1998	***Flight tests with increased authority*** single-harmonic input	110 kts, 65 kts descent,	0.4° & 1° 2/rev ÷ 5/rev	BVI noise and vibration characteristics
2001	***Flight tests with noise controller*** Closed loop 2/rev noise control	65 kts descent	1.0° 2/rev	BVI noise Reduction

Table 1 Overview of ECD research activities in the field of active rotor control

3 Concept of BVI Noise Control

As already mentioned, the RACT open loop IBC flight tests had an important impact on the development of a noise control concept (Ref. /9/). The main results and conclusions of this campaign are:

- The highest noise reduction for the 4-bladed BO105 test helicopter can be achieved by applying a 2/rev IBC input.
- The noise levels measured on ground for varying IBC phase angles show a pronounced minimum in the region of 60° (Figure 2).
- The BVI noise reductions increase with higher IBC amplitude.
- The noise reductions measured with the onboard microphones are in good correlation with the noise emission on ground and the direct influence of IBC on the pressure distribution could be demonstrated in flight (Figure 3).
- The optimum IBC phase angle is not very sensitive to small changes in the descent angle. Thus small fluctuations in the flight trajectory, which usually occur during the descent phase of the helicopter, could lead to noise peaks but do not affect the noise emission over larger time period.

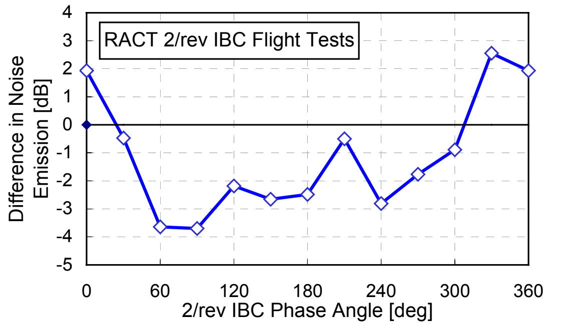

Figure 2 BVI noise reduction versus phase angle for a 2/rev, 1° amplitude IBC input as measured in the RACT flight tests

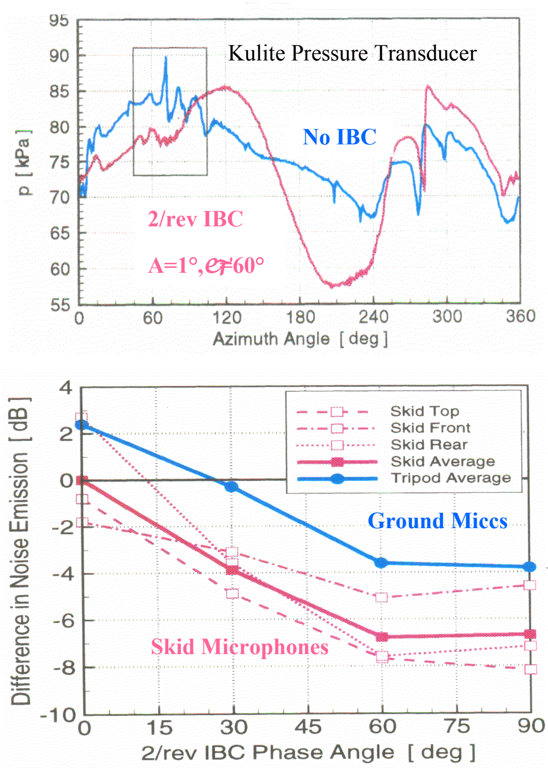

Figure 3 Comparison of all used sensor signals with/without 2/rev IBC input

Based on these results, the present IBC noise control concept has been developed. It is rooted in a new approach for minimising a BVI index (using either blade pressure or onboard microphone signals) by applying a 2/rev IBC feedback control. For the latest test campaign the BVI Index was derived from the onboard microphone signals. The main reason for this choice is the fact that the microphones are part of the non-rotating system and are directly monitoring the acoustic field. The signal processing and the BVI analysis are less complex than for blade-integrated sensors and therefore easier to realise.

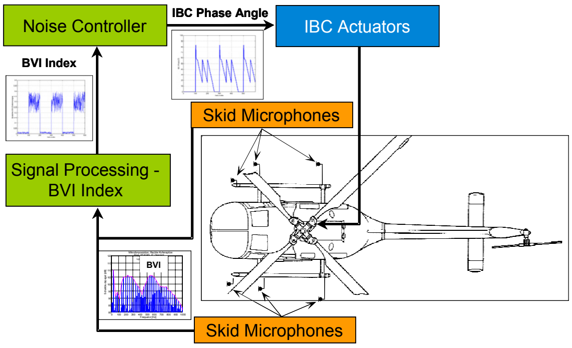

Figure 4 Schematic view of the noise control arrangement

The optimisation of the 2/rev IBC phase angle towards the minimum of this BVI index is carried out by a “Golden Section” algorithm. The optimisation is restricted to the phase angles in the range of 0° - 120° in order to have a fast and efficient control. As indicated by the flight tests, the IBC amplitude was not optimised during the tests and was kept constant at the optimal value of 1°. The schematic of the noise controller is given in Figure 4.

3.1 BVI Detection

There are two main ways to detect the BVI noise. The first method is based on blade integrated sensors measuring the pressure distribution on the rotor blade (e.g. Kulite or piezoelectric sensors). The second method - which is highlighted in this paper - consists in outboard microphones which are directly sensing the acoustic field radiated by the main rotor. For both approaches a BVI index, correlated to the BVI noise emission has to be derived by an appropriate analysis of the sensor signals.

In the case of the onboard microphones the evaluation of open-loop flight tests has shown that the characteristic differences of the noise signals radiated during BVI and "non BVI" flights is their harmonic content. As illustrated in the following figures, a set of higher harmonics appears in the noise spectra (Figure 5), when BVI occurs. This typical BVI noise signature can not be seen for non BVI flight conditions (Figure 6).

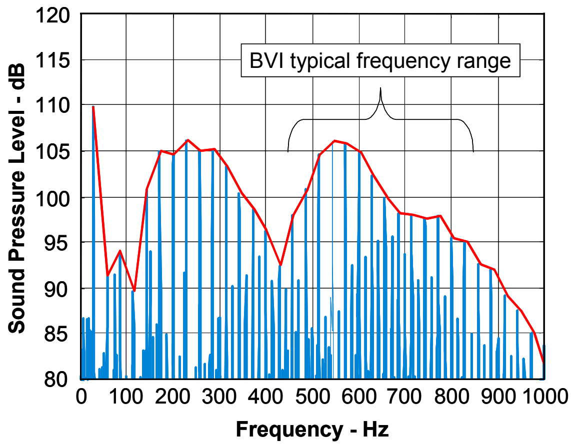

Figure 5 Typical BVI sound pressure spectrum at the skid microphones

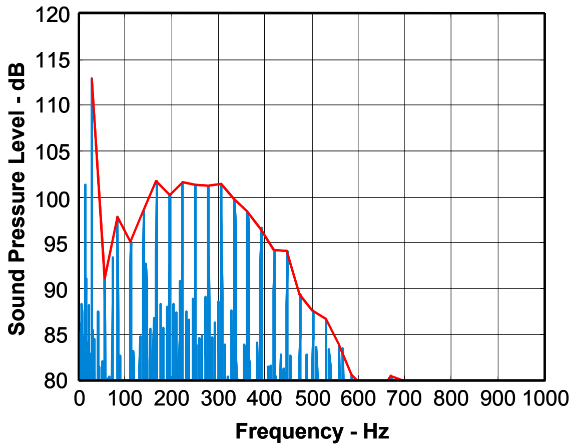

Figure 6 Typical sound pressure spectrum at the skid microphones with minimum BVI (1° amplitude @ 60° IBC phase)

The spectra (depicted in Figure 5 and Figure 6) were measured during a 6° descent flight of the BO 105 test helicopter, without and with an IBC input for minimum BVI noise. Due to this differences of the harmonic components between BVI and non BVI flights a spectrum distortion factor was chosen as control variable. This so called BVI index is defined as the quadratic pressure level of the typical BVI harmonics range normalised by the sum of all harmonics measured with the skid microphones.

Figure 7 visualises the correlation between the sound pressure at the microphones and the computed BVI index for a 8° descent flight with a temporarily IBC input. When the IBC is activated, the BVI noise reduction is indicated by both, the sound pressure and the resulting BVI index.

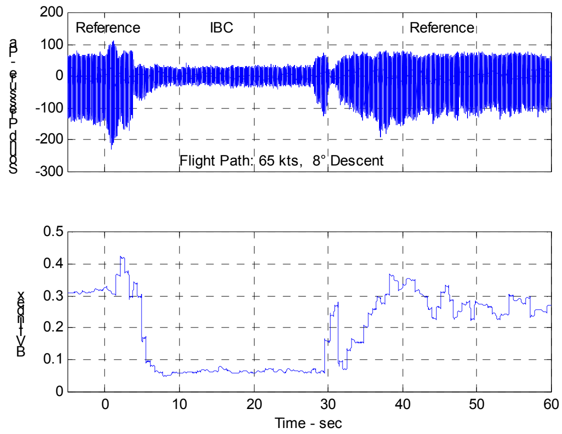

Figure 7 Sound pressure and BVI index for a 8° descent flight at 65 kts

The main advantage of this BVI detection method is the fact that the index is a non-dimensional scalar. Furthermore, the influence of other noise sources than BVI noise can be avoided by correlating the microphone signals with the rotor RPM.

3.2 BVI Noise Controller

The noise controller consists of two main parts: the threshold analysis and the BVI index minimisation (see block diagram in Figure 8).

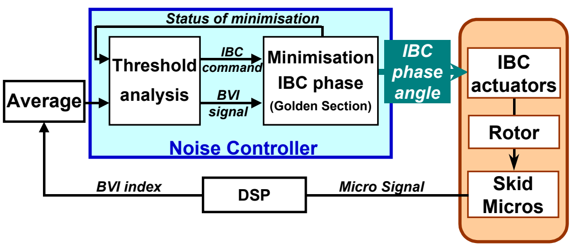

Figure 8 BVI noise control concept

The sound pressure measured at the onboard microphone is transferred to the digital signal processor (DSP) which performs the real-time calculation of the BVI index. The BVI index is time-averaged in order to assure the stability of the controller. Thus the fast fluctuations of the BVI index due to atmospheric factors or changes in the flight trajectory cannot perturb the noise control. The flight tests proved that approximately 4 rotor revolution are the ideal time-averaging period to identify the flight condition and the correlated BVI noise emission of the aircraft. The average BVI index is assessed in the threshold analysis and forwarded to the minimisation unit if a BVI state is identified. A “Golden Section” algorithm is applied for optimising the 2/rev IBC phase angle towards the minimum of the BVI index. The Golden Section rule (see Ref. /11/ for more details) is a strait and effective procedure for the one-dimensional minimisation of an arbitrary non-linear function.

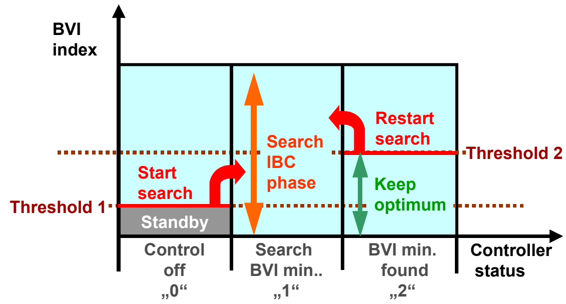

Figure 9 Logic of "threshold unit" of BVI noise controller

The logic of the threshold analysis illustrated in Figure 9. This part of the controller is mainly based on two thresholds and three controller states. The first threshold ("Threshold 1") is to activate the controller when BVI noise is identified for the first time, e.g. when the flight condition changes from a "non BVI" horizontal flyover to a BVI descent flight. In such a case, the controller switches from "standby - control off" to "search BVI minimum" (see Figure 9), whereby the IBC phase is optimised till a BVI minimum is determined. Once a minimum is found, the controller state changes to "BVI minimum found" and the optimal IBC phase angle is kept constant. This phase angle is maintained as long as the BVI index remains below the second threshold. In case the BVI index exceeds the "Threshold 2" the "search BVI minimum" is employed again in order to determine a new optimal phase angle. Thus every change of BVI relevant parameter can be considered and the IBC input is optimised to the flight condition of the helicopter.

4 Closed loop Flight Tests

The closed loop flight test were divided in two phases. The first phase comprised flight tests which were necessary to test and adjust the noise control system to real flight conditions. In the second phase the closed loop IBC flight tests were combined with BVI noise measurements on ground.

4.1 Test Equipment and Flight Procedures

The BO105 IBC demonstrator (Figure 10) uses proven electro-hydraulic blade pitch actuators with adequate authority for noise reduction (± 1° blade pitch angel). This actuation system is controlled by an embedded digital computer in combination with a high performance signal processing equipment for the data transfer between the rotating and non-rotating system (A more detailed description of the IBC demonstrator set-up is given in Ref. /10/). For the noise control a complex sensor system was installed consisting of blade pressure transducers and a landing gear mounted microphone array (see Figure 4 and Figure 10).

Figure 10 IBC demonstrator aircraft BO105 S1

The test side "Kleinkarolinenfeld" and the equipment which were chosen for the BVI noise measurements on ground is depicted in Figure 10. Three microphones at height of 1.2m in –100m, 0m, +100m lateral distance to the flight path of the helicopter were used to monitor the noise emission.

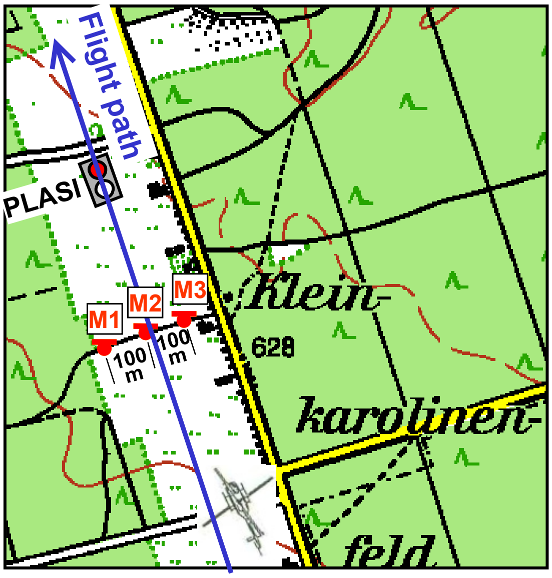

Figure 11 Test site and arrangement of test equipment noise measurements on ground

An optical indicator (Pulse Light Approach Slope Indicator, PLASI) was used to enlighten the orientation of the pilot during the descent flights with varying slope angles. The distance between the PLASI and the central microphone (M2) was nearly 1000 m resulting in flyover heights of 80m, 120m and 160m for the 4,° 6° and 8° landing approaches.

The flight tests with noise measurement on ground comprised procedures listed in the following table:

Slope angle	Flight speed	Flight Procedures
4°	65 kts	2 Reference flights 3 IBC flight
6°	65 kts	6 Reference flights 4 IBC flight IBC switched on during flight IBC switched off during flight
6°	65 kts	2 Reference flights 4 IBC flight

Table 2 Flight procedures for noise measurements on ground.

4.2 Test results and analysis

The first flight tests (without noise measurements on ground) were dedicated to the proof-of-concept of the noise control system. The main objectives of these tests were:

- to validate that the skid mounted microphones and the related BVI index is suitable for BVI noise control,
- to verify the control algorithms under real flight conditions,
- to adjust the control parameter (e.g. threshold values and average time of the BVI index, ideal position of the onboard sensor microphone) for a stable and effective function of the noise controller.

These preparatory flight tests on the BO 105 have been performed with a flight speed of 65 kts and a slope angle of 6° (corresponding to a descent rate of 600 ft/min), which are typical maximum BVI flight conditions for this type of aircraft.

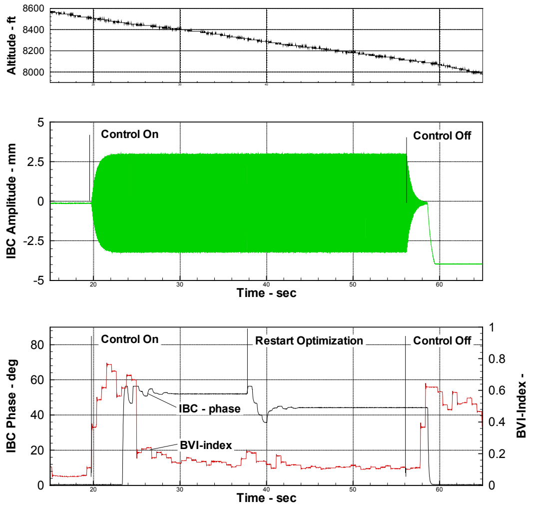

Figure 12 Closed loop BVI noise reduction at the descent flight with 600 ft/min

Figure 12 shows the time-histories of the flight path, the IBC actuator displacement, the computed BVI index and the IBC phase determined by the controller. The first seconds of the plot mark the transition phase of the helicopter from horizontal to descent flight. As a result, the BVI index increases rapidly and the noise control is switched on. Due to safety reasons the actuator amplitude is increased slowly to the constant value of 1°. Once the IBC amplitude is reached and the IBC phase optimisation starts the BVI index is drastically reduced. After approximately 4 sec the optimal phase angle of 52° and the minimum of the BVI index is found. At test time of 37 sec the BVI index is slowly increasing due to changes of flight parameters causing the controller to restart the optimisation and to find a new optimum at 45° IBC phase angle. After 57 sec the noise control is switched off and the BVI index is rising again to the high values related to this flight condition.

This very encouraging functional evaluation of the noise controller in flight was completed by noise measurements on ground.

The noise reduction results in terms of sound exposure levels (SEL) are presented in Figure 13 for all representative flight tests. The noise levels are adjusted to the reference heights related to each slope angle. It is obvious that 2/rev IBC feedback control clearly minimises the noise emission of the test helicopter. The highest reductions are achieved for the noisiest 6° and 8° descent flights.

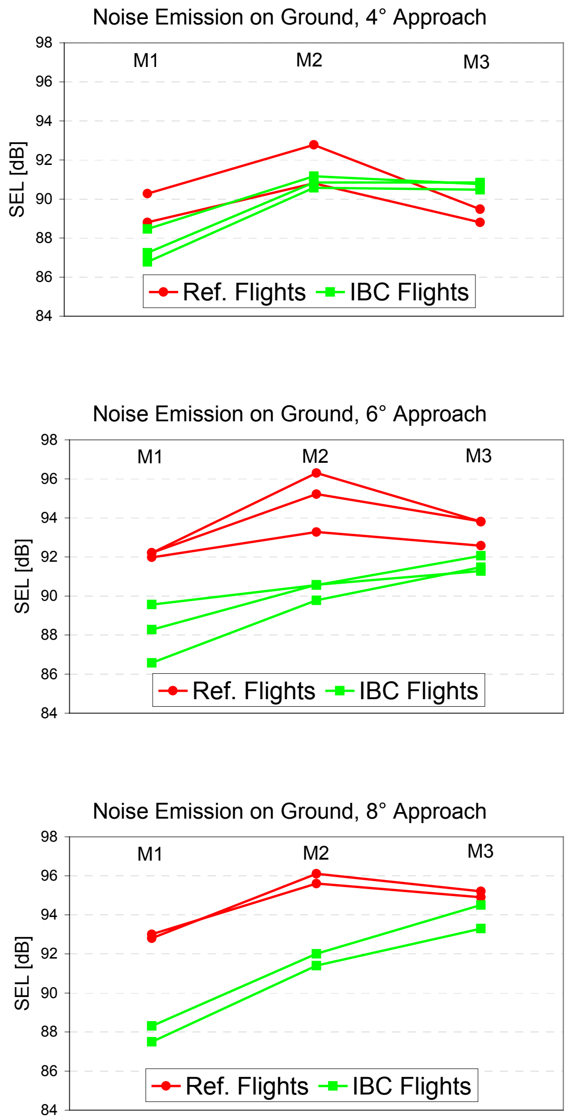

Figure 13 BVI noise reduction measured on ground reduction for the 2/rev closed loop IBC flights

As it can be seen in Table 3, the average difference in the noise emissions rises up to 5 dB. Moderate reductions are achieved for the 4° descent flight only. In this case the noise levels for the IBC flights can be decreased on the retreating side of the rotor (microphone "M1") but are even higher on the advancing side (microphone "M3"). One possible reason is the fact that the 4° approach at 65 kts is not a noisy flight regime and the influence of BVI is rather minor (the noise levels are approximately. 4 - 5 dB lower compared to the 6° and 8° glide slopes). Obviously, the directivity of the noise emission is changing with the slope angle of the flight path. In particular, the BVI noise radiated on the advancing side of the rotor is increasing with the slope angle (see "Reference Flights" in

Figure 13). This directivity characteristic might alter the BVI detection for the 4° approach, which was provided by the microphone mounted on the top of the right skid of the heli-copter.

Slope angle	**Noise Reduction** (ΔSEL, [dB]) Microphone Position on Ground M1	M2	M3
4°	-2.0	-0.9	+1.6
6°	-4.0	-4.7	-1.8
8°	-5.0	-4.2	-1.2

Table 3 Average noise reduction for the 2/rev closed loop IBC flights

In order to have a better understanding of the results, the BVI noise was filtered out of the overall noise signals recorded on ground. This was done by considering only the higher harmonics related to BVI for the computation of the sound exposure levels.

Slope angle	**Noise Reduction** (ΔSEL, [dB]) Microphone Position on Ground M1	M2	M3
4°	-4.0	-3.6	-2.0
6°	-5.7	-4.9	-3.2
8°	-4.3	-4.5	-3.0

Table 4 Average noise reduction for the 2/rev closed loop IBC flights "BVI filtered" microphone signals!

The results are summarised in Table 4. It can be seen that the reduction of the BVI noise components on ground due to IBC are clearly higher compared to the "unfiltered" noise reduction (Table 3). Even for the 4° descent the noise levels are significantly reduced, indicating that other effects or noise sources than BVI may contribute to the slight increase of the unfiltered noise levels discussed before.

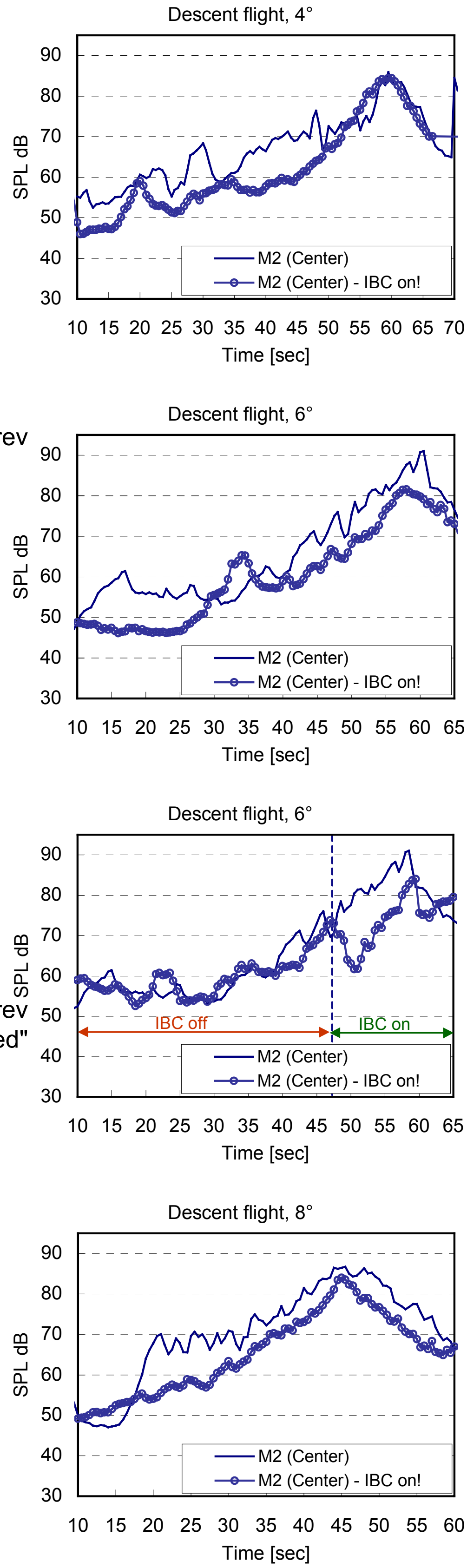

Figure 14 Time histories of noise levels measured by the central microphone (M2)

Figure 14 compares the time histories of the sound pressure levels measured by the central microphone (M2) for both reference and IBC

flights. For each slope angle, the noise levels are reduced nearly during the complete flyover time. The maximum noise levels appearing in the time histories are also minimised by the BVI control and the periods of high noise annoyance for the population on ground are shortened.
The effect IBC input can be seen for the second 6° descent flight in Figure 14. The BVI control is switched on after 47 sec and noise emission is rapidly decreased.

5 Conclusions and Outcast

The active rotor technology has been developed continuously at ECD. The recent closed-loop flight tests on the BO105 IBC demonstrator are a further step towards the commercial application of the rotor active control in future helicopters.

The evaluation of the flight test results presented in this paper led to the following conclusions:

- The proof-of-concept of the newly developed BVI noise controller has been performed successfully. This control concept consisted in minimising an adequate BVI index (using either blade pressure or onboard microphone signals) by applying a 2/rev IBC input. The minimisation of the index was achieved by optimising the IBC phase angle only and keeping the IBC amplitude at a constant value.
- The presented BVI detection method combined with onboard microphones proved to be an appropriate approach to reduce the noise emission of the helicopter. This strategy is therefore a possible alternative for the use of the more demanding blade pressure sensors.
- Significant BVI noise reduction on ground up to 5 dB were demonstrated for all descent flights performed with different slope angles.

These promising results represent an important milestone in the progress of the active rotor technology program, wich will continue with the following short and medium term activities:

- Optimisation of the current BVI noise controller
- Flight testing of the IBC vibration controller
- Adaptation and implementation of these technologies on a new BK117 test helicopter equipped with active trailing edge flaps for individual blade control

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