Noise Reduction by Blade Root Actuation - Analysis of Flight and Wind Tunnel Tests

Référence : TE06

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As a step towards the application of rotor active control technology in production helicopters, open-loop IBC flight tests with higher harmonic blade root pitch inputs were performed on a BO105 test helicopter equipped with an advanced IBC system having significantly increased control authority. The test setup featured a highly complex data acquisition system for simultaneous measurements of noise emission, vibrations, rotor operational parameters and rotor blade pressures. After a brief summary on previous HHC and IBC wind tunnel tests, the results of the first flight test data analysis are presented and compared to the wind tunnel observations. The BVI noise test results from all relevant sensors both on the helicopter and on ground will be shown and discussed, including an evaluation of the accompanied effects of the higher harmonic blade pitch inputs on vibrational levels.

Introduction

The flight comfort and public acceptance of todays helicopters strongly depend on the vibration and interior noise encountered by passengers and the exterior noise radiation annoying the population on ground. The levels of noise and vibration raise to exceptionally high values in flight conditions where Blade-Vortex-Interactions (BVI) occur. Despite numerous efforts to reduce the vibratory loads by isolation systems and the BVI noise emission by carefully designing the rotor blades, the levels remain far away from the standards set by commercial fixed wing aircrafts.

One of the most promising technique to significantly reduce BVI noise and vibrations is the application of active rotor blade pitch control like Higher Harmonic Control (HHC) and Individual Blade Control (IBC). HHC consists of a blade pitch control law depending on multiples of the main rotor rotational frequency, whereas IBC additionally allows for arbitrary pitch control inputs.

The first applications of HHC were obtained by actuators acting on the fixed part of the swashplate, and thus were restricted to n/rev and (n±1)/rev frequency inputs for a n-bladed rotor. IBC can be realized by various means such as rotor blade trailing edge flaps or rotor blade embedded smart structure elements. By now, however, only blade root actuators in the rotating pitch links were designed and tested as hardware.

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Several research programmes have been performed to develop, investigate and evaluate the techniques of active rotor control experimentally in wind tunnel and flight tests. The extensive and detailed analysis of the measured noise and vibration data reveals the great potential for tremendous reductions in main rotor BVI noise radiation and vibrational levels. Most of the active rotor control experiments were conducted by prescribing HHC or IBC control laws and an analysis of the data afterwards (open-loop control). For a future introduction of this technology in production helicopters, it is indispensable to develop closed-loop controlled systems with high efficiency, reliability and low costs.

As a step towards this aim, flight tests on a 4-bladed BO105 helicopter featuring an advanced IBC system with blade root actuation were and will be performed. Based on the experience of IBC wind tunnel tests, the first campaign in spring 1998 was restricted to open-loop IBC input schedules following the higher-harmonic pitch control law

$$\theta_{IBC} = A_n \cdot \cos(n \cdot \psi - \phi_n)$$

where A_n denotes the amplitude, n the multiple of the rotational frequency, ψ is the azimuth angle and ϕ the phase angle. The main goals were to validate the wind tunnel results and to prepare a data base for the development of a closed-loop controlled IBC system for BVI noise suppression. The present paper summarizes the conclusions of the analysis of the wind tunnel data base, describes the IBC flight test helicopter and the test set-up and presents the first results of the BVI noise measurements performed during the flight tests.

Although higher harmonic control (HHC) of rotor blades can be performed by using any IBC system, HHC is usually refered to as swashplate actuation in the fixed system with its restriction on frequency inputs. In the absence of a clear wording and to be consistent with other publications, the abbreviation HHC in the remainder of this paper denotes a higher harmonic input using fixed system swashplate actuators whereas IBC refers to a higher harmonic input at the blade root using the pitch link actuators.

Towards an Efficient Active Rotor Control Technology for BVI Noise Reduction

EUROCOPTER DEUTSCHLAND (ECD) devotes a substantial part of its research efforts to the development and improvement of active rotor control technology. In the following, a short summary will be given on some of the national and international experimental programmes with participation of ECD.

HHC Wind Tunnel Tests 1991

In 1991, a cooperative research effort on HHC was conducted by the Deutsches Zentrum für Luft- und Raumfahrttechnik (DLR), the NASA Langley Research Center, ECD (formerly MBB) and EUROCOPTER of France (formerly Aerospatiale). A dynamically scaled model of the 4-bladed BO105 main rotor was tested in the German Dutch Wind Tunnel (DNW) to examine the benefit of higher harmonic controlled blade pitch to reduce impulsive noise generated by Blade-Vortex-Interactions (BVI) (Ref. [1]). It was demonstrated by open-loop HHC inputs, that the BVI noise levels could be reduced significantly (locally more than 6 dB). At the most beneficial HHC schedules a negative effect was the increase in vibrational loads. The minimum BVI noise levels correlate with maximum values of the vibration quality criterion for a single-frequency 4/rev HHC input. This correlation can be somewhat relaxed, if multi-frequency HHC modes are used.

First IBC Flight Tests 1990 / 1991

In contrast to HHC, which is limited to 3/rev, 4/rev and 5/rev modes on a 4-bladed rotor, IBC offers the highly desirable capability to decouple the pitch control of one blade from the other and thus to allow for arbitrary single- and multi-frequency pitch schedules.

In 1990 and 1991, first flight tests on a BO105 helicopter equipped with a prototype open-loop IBC system developed by Zahnradfabrik Friedrichshafen Luftfahrttechnik (ZFL) were conducted. For safety reasons, the pitch control authority (< 0.5 deg), the flight speed and the load factors were limited. Therefore, it was not possible to fully explore the potential of the IBC technology. Nevertheless, some promising results were obtained and a BVI noise reduction of about 4 dB(A) was measured during flyover (Ref.[2]).

IBC Wind Tunnel Tests 1993 / 1994

In order to explore the full potential of IBC, the full-scale BO105 main rotor equipped with an improved open-loop IBC system having greater control authority and increased frequency response was tested in the 40-by 80-Foot NASA Ames wind tunnel in 1993 and 1994 (Ref.[2,3,4,5]). Partners involved in this research project were NASA Ames Research Center, US Army Aeroflightdynamics Directorate, ZFL, ECD and DLR. It could be shown that IBC has a higher BVI noise supression potential as the HHC system tested in the DNW. Extensive variations of the IBC input parameters in single-frequency mode (amplitude, frequency and phase angle) revealed the suitability of the 2/rev and 3/rev inputs for an efficient BVI noise reduction. Furthermore, in contrast to a HHC system, the 2/rev IBC input mode showed the potential for simultaneously decreasing noise and vibration levels. As an efficient 2/rev IBC amplitude a value of about 1° was found.

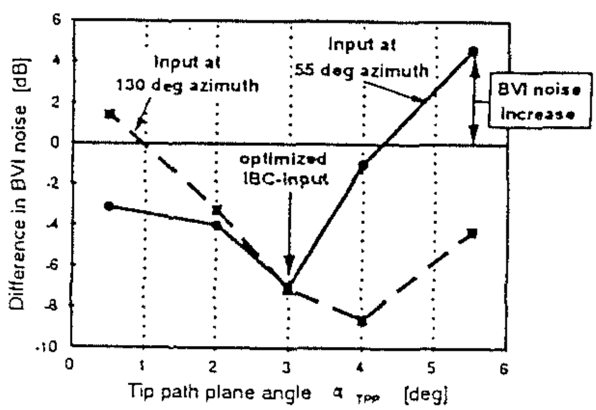

Figure 1: Noise Radiation versus Tip Path Plane Angle for two different IBC settings (from Ref. [2])

The phase angle which has to be chosen for BVI noise suppression depends on the actual flight condition. An optimized IBC input for a specific flight condition will induce noise level increases in other flight regimes (Figure 1). This behaviour clearly argues for the implementation of a closed-loop controller, if the installation of an IBC system on production helicopters is envisaged.

Closed-Loop HHC Wind Tunnel Tests 1992

One of the first attempts to develop a closed-loop controlled blade pitch actuation was done on a HHC system and tested in the DNW wind tunnel in a cooperation of DLR, ECD and EUROCOPTER FRANCE (Ref. [6]). The tests were aimed at investiging the suitability of different controller designs, assessing the potential of a closed-loop HHC for BVI noise suppression and evaluating, whether or not the closed-loop controller is able to handle the negative correlation between noise reduction and vibration level increase. It turned out that noise suppression by using closed-loop actuation is shifted to another single-frequency mode and is not as efficient as the noise reduction found in open-loop HHC tests. Furthermore, only a controller with optimized amplitude and phase angle produced a satisfying noise level reduction. On the other hand, however, the closed-loop system proved to be able to simultaneously reduce noise and vibrational level and to adapt efficiently to the actual flight condition.

State-of-the-Art in Active Rotor Control for BVI Noise Suppression

Summarizing the lessons learned in all experimental wind tunnel tests, the following conclusions can be drawn:

- Open-loop HHC can reduce the BVI noise emission significantly while keeping the vibration level approximately constant.
- IBC is a very promising technique to overcome the drawbacks of HHC in the fixed system. It is possible with IBC to create arbitrary input schedules and to restrict the active blade pitch control to a limited azimuth range.
- BVI noise level reduction is better with open-loop IBC than with HHC.
- In contrast to HHC, IBC shows a great potential of simultaneous BVI noise and vibration level reduction.
- For the whole flight regime IBC has to be governed by a closed-loop controller to adapt the active blade pitch control dynamically to the actual flight condition.
- The performance of a closed-loop system for adjusting the pitch input schedule to the actual flight condition was documented in HHC wind tunnel tests.

RACT – IBC Flight Tests

In the German Rotor Active Control Technology (RACT) research programme (Ref. [7,8]), ECD in cooperation with the DLR, the Daimler-Benz (DB) research laboratories and ZFL explores the potential of Individual Blade Control (IBC) technology under real flight conditions. An advanced IBC system developed by ZFL and an extensive measurement equipment provided by ECD, DLR and DB was installed on a BO105 helicopter (Figure 2). Compared to the first full scale IBC tests performed on the same aircraft in 1990/91, the blade pitch control authority was significantly increased.

With this IBC testbed, a first flight test campaign was conducted in March/April 1998. A highly complex data aquisition system was applied for simultaneous measurements of rotor operational parameters, vibrational loads, blade pressures, noise at the aircraft and on ground.

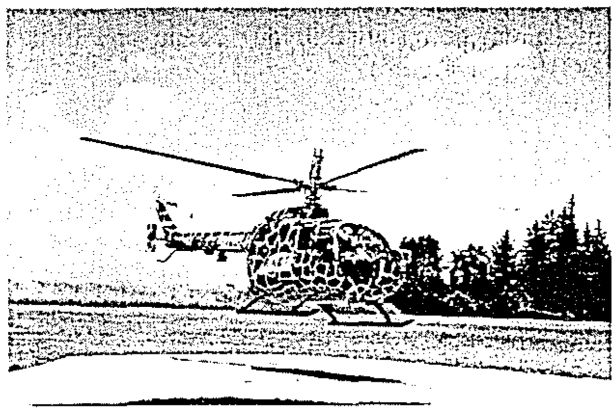

Figure 2: IBC demonstrator aircraft BO105 S1

Test Objectives

The main goals of the flight test programme were:

1. To confirm and validate the results of the IBC wind tunnel tests under real flight conditions. Unfortunately, this can only be achieved qualitatively because of the impossibility to ensure comparable test conditions:
   - In the wind tunnel the noise of the isolated main rotor was measured whereas during flight tests the measured noise data included tail rotor and engine noise as well.
   - In general, the wind tunnel trim to minimum hub moments does not correspond to the real flight trim.
   - During flight tests, weather conditions have a strong influence on noise radiation characteristics.

2. To test and evaluate a closed-loop controller concept for vibration reduction. The analysis of flight test data with respect to this goal is presented in Ref. [9].
3. To provide a high-quality data base for developing a closed-loop controlled IBC system for simultaneous BVI noise and vibration reduction in the whole flight regime.
4. To investigate different BVI identification algorithms under real flight conditions. The results of this part of the RACT flight tests are discussed in detail in Ref. [10].

With respect to BVI noise reduction, the test matrix was designed in a way to cover the strongest BVI flight conditions in combination with different IBC settings.

Test Equipment and Flight Test Procedure

The BVI noise emissions and the effects of IBC control input were evaluated by a large measurement installation on ground and on the BO105 test aircraft:

- One rotor blade was equipped with five pressure transducers at the leading edge to detect impulsive pressure changes due to blade vortex interaction. These signals were processed and analyzed online by BVI identification algorithms resulting in a single BVI index (Ref. [10]).
- Microphones were installed on the helicopter landing skids (Figure 3) for fast evaluation of noise reduction on IBC inputs.

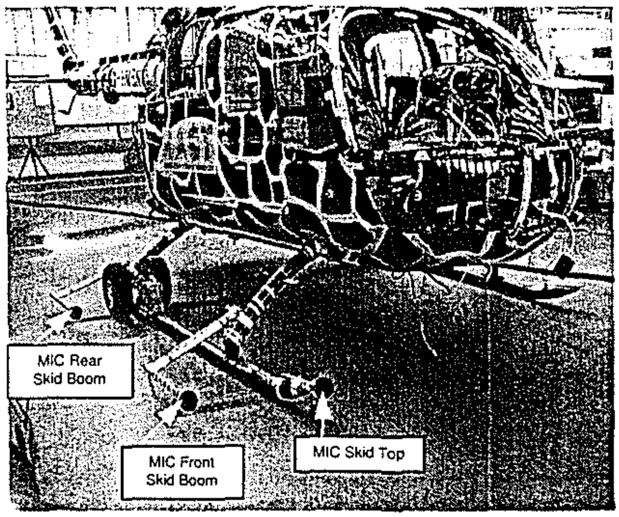

Figure 3: Microphones installed on Landing Skids

A ground-based microphone array (Figure 4) extending 300 m to both sides of the flight path showed the effects of IBC inputs on neighbourhood noise. The microphone array comprised of 11 ground microphones and of 3 microphones installed on 1.2 m tripods at the certification positions -150 m, 0 m and 150 m.

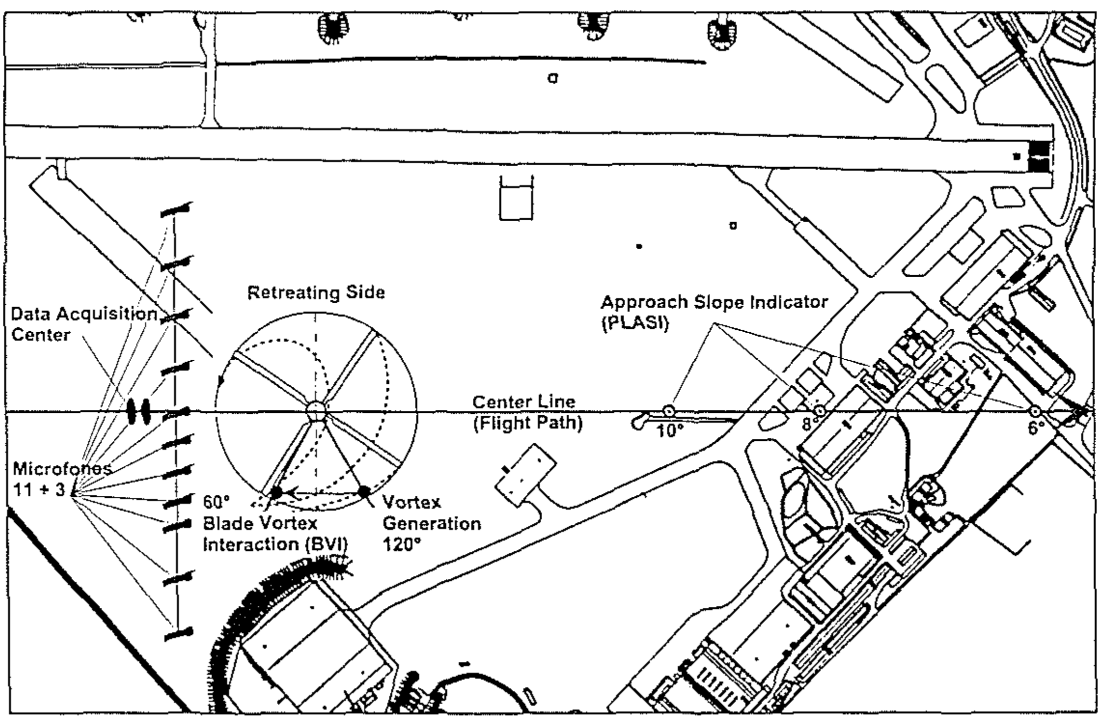

Figure 4: Arrangement of Test Equipment on Ground

The noise data measured by these tripod microphones should contribute to an analysis in accordance to the ICAO noise certification rules.

The more dense distribution of ground microphones on the advancing side area should resolve the BVI noise emission in a more accurate way.

- Weather conditions were measured on ground simultaneously with noise data aquisition to assess the validity of the test data.
- Flight path, flight speed and rate of descent were recorded and analyzed online by a differential GPS system. The aircraft altitude above centerline microphones was determined by photometric analysis.

In addition, all relevant operational data including helicopter performance and rotor condition parameters were recorded onboard of the BO105 test aircraft.

Due to the restricted flight test period, the number of valid flights per test point were limited and some of the test points were flown at non-optimal weather conditions. Therefore, the acquired test data had to be analyzed very carefully and the results shown are not reliable from a statistical point of view.

Test Results and Analysis

Although the IBC system installed on the test helicopter allows for arbitrary pitch schedules, there are little experimental experiences with others but higher harmonic inputs. Even the comprehensive data of the NASA wind tunnel test relate all, with some minor exceptions, to higher harmonic control. Therefore, the RACT flight test campaign in March/April 1998 was performed applying only higher harmonic pitch control laws using the IBC blade root actuation system.

As a first step, flight tests without IBC activation were performed to evaluate the descent flight condition for the following IBC tests. The noise measurement results of an approach slope angle sweep at 65 KIAS are shown in Figure 5. The BVI noise maximum correlates quite well with the result obtained in an aeroacoustic wind tunnel test using a dynamically scaled BO105 model rotor (Ref. [11]). The directivity of the noise radiation changes from the retreating side at smoother descent angles (4°) to the advancing side for steep approach flights (10°). For the maximum BVI flight conditions (6°, 8°), the maximum noise is measured at the centerline position.

Following the experienced test pilot's advice that the steeper 8° approach is not of operational importance, the 6° descent flight at 65 KIAS was chosen as the reference flight condition for evaluating the IBC system. Furthermore, the 6° approach is one of the ICAO certification flight conditions.

In IBC wind tunnel tests at NASA Ames, the 2/rev frequency input was identified to reduce the BVI noise most efficiently while vibrations were not increased. Hence, the first part of the IBC flight tests focussed on higher harmonic schedules following this frequency.

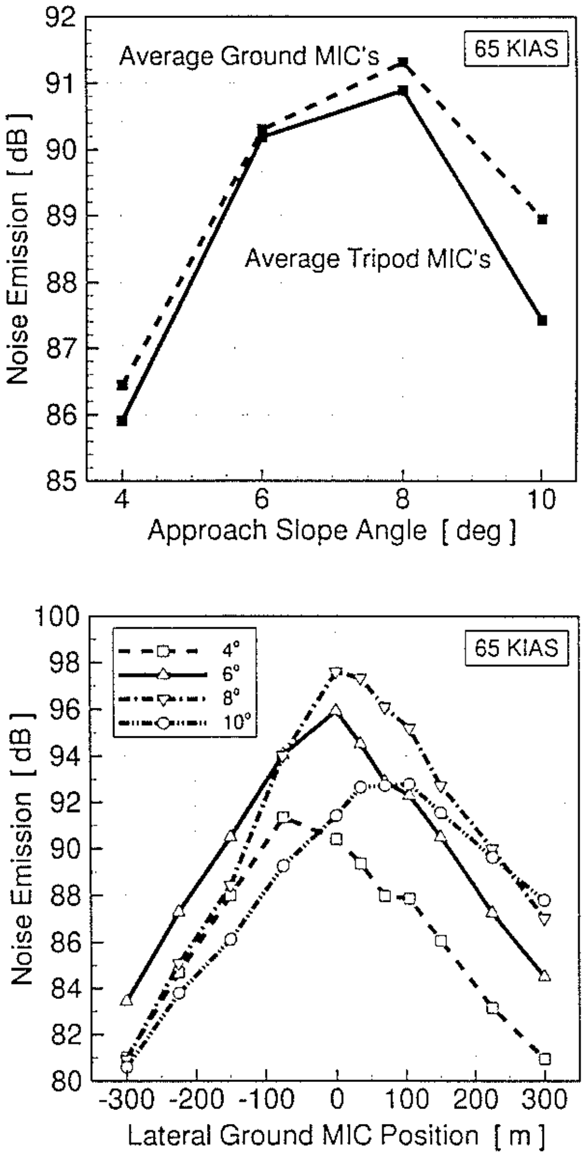

Figure 5: Noise emission for various approach slope angles at 65 KIAS, IBC not activated.

2/rev IBC

Figure 6 shows the correlation of noise emission and input phase angle for a 2/rev, 1° amplitude IBC setting for the reference descent flight condition (6° slope, 65 KIAS flight speed) as measured by the certification microphone. The corresponding results obtained in the NASA Ames IBC wind tunnel tests are presented in Figure 7.

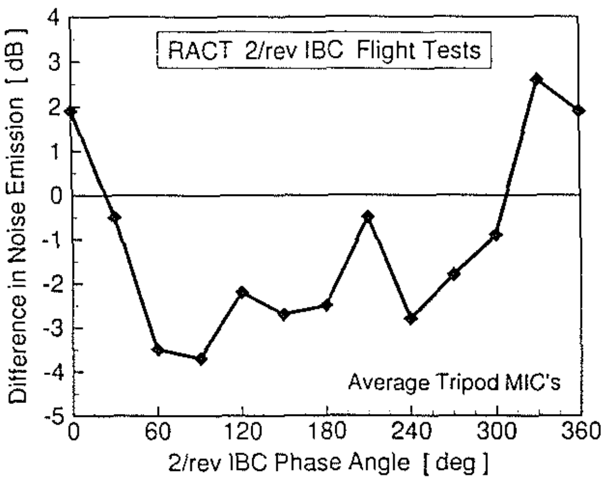

Figure 6: BVI noise reduction versus phase angle for a 2/rev, 1° amplitude IBC input as measured in the RACT flight tests.

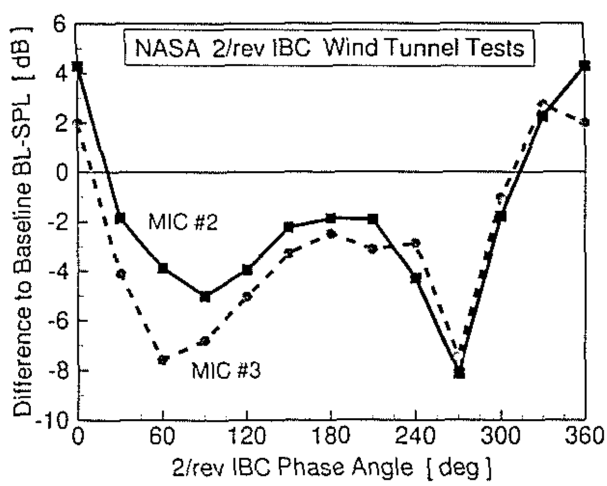

Figure 7: BVI noise reduction versus phase angle for a 2/rev, 1° amplitude IBC input as measured in the NASA wind tunnel.

Because of the aforementioned systematical differences between wind tunnel and flight tests, a quantitative comparison of both curves is diffcult. Moreover, there are additional restrictions due to different test setups and methods of analysis:

a) In contrary to the flight test, a band-limited (6^{th} to 40^{th} blade passage frequency) sound pressure level was used as noise measure in the wind tunnel tests.
b) The noise characteristics in the flight test were evaluated using the mean value of the certification microphones. The wind tunnel results were obtained by two single microphones located on the advancing side one rotor radius beneath the rotor rig.

Nevertheless, the noise reduction characteristics with varying 2/rev IBC phase angle as measured in the NASA wind tunnel tests can be confirmed qualitatively by the RACT flight test results. There are two beneficial ranges for the phase angle setting between 60°-90° and 240°-270°. Unfortunately, the flight test results for phase angles between 180° to 300° exhibit a high scatter and the second optimum cannot be confirmed with confidence. For the 60° phase angle, the highest number of test points was acquired and the scatter of flight test noise data is surprisingly low. The obtained noise reduction of 3.5 dB in average can be regarded as assured.

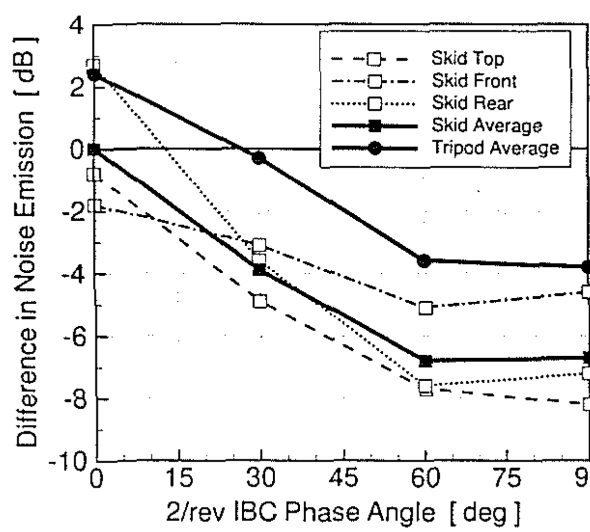

Figure 8: Noise reduction versus phase angle as measured by the landing skid microphones, 2/rev IBC input, 1° amplitude, 6° descent flight at 65 KIAS.

The optimum phase angle range of 60° to 90° could be confirmed by the skid microphone data. The measured noise reduction correlates very well with the results from the microphones on ground (Figure 8). The location of body microphone installation does not have a great influence on the measured noise reduction, although the microphone mounted on top of the skid seems to deliver the best reproduction of the ground noise characteristics. Therefore, this is recommended as position for a possible BVI noise sensor as part of a closed-loop controlled IBC system.

Now the question arises, whether the BVI noise suppression was a global effect, or was confined to local area or radiation directivity was changed due to IBC activation. In the following, the results of a more detailed analysis of the 2/rev, 1° amplitude, 60° phase angle IBC input will be presented to answer to this question.

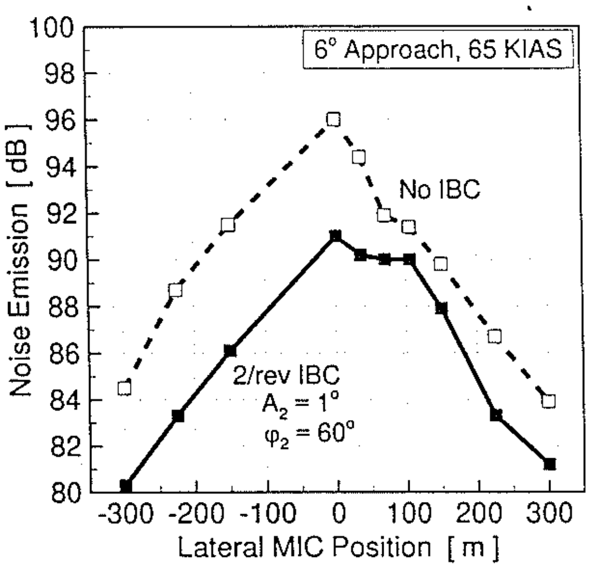

Figure 9: Noise emission as measured by the ground-based microphone array for a 6° descent flight at 65 KIAS.

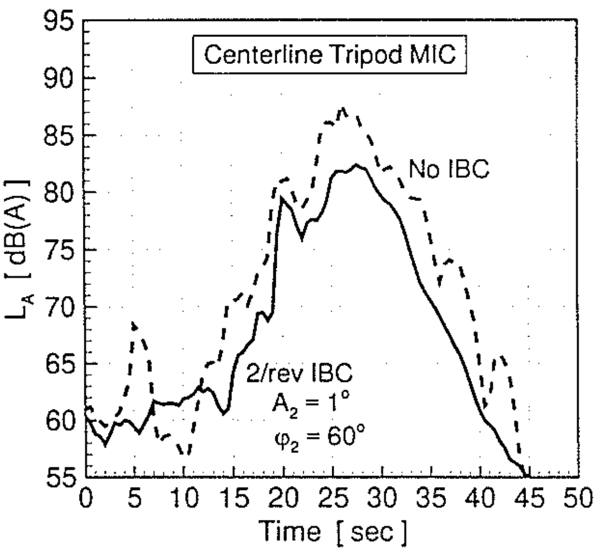

Figure 10: Noise emission as measured by the centerline tripod microphone for a 6° descent flight at 65 KIAS.

The results from the ground microphones depicted in Figure 9 show that with IBC activation the noise was reduced for all lateral positions. The most efficient noise reduction occured at the centerline, i.e. in the direction of the maximum noise radiation (compare to Figure 5) and on the side of the retreating blade of the helicopter.

Figure 10 compares the time histories of the A-weighted sound pressure levels measured by the centerline tripod microphone for a flight with and without IBC activation. Again, the noise level is reduced along the complete flight path and the highest reduction was obtained for the maximum noise level. Furthermore, the time period of high noise annoyance for the population on ground was shortened by using IBC.

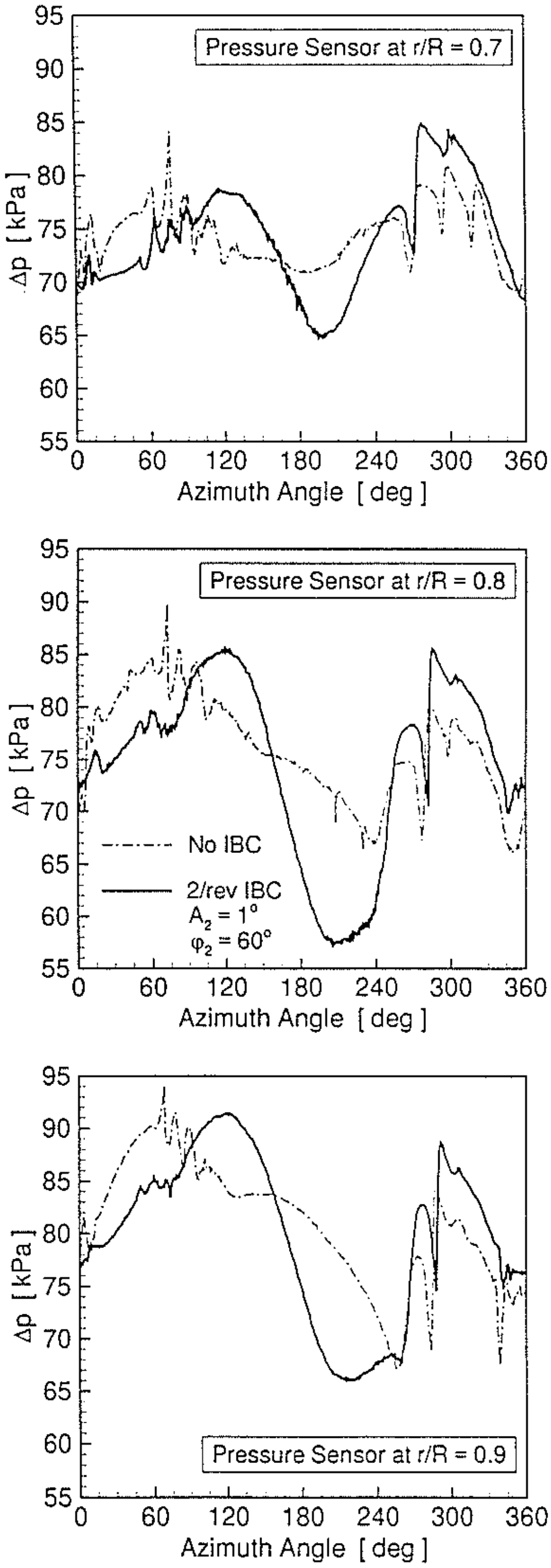

Figure 11: Leading edge blade pressure distribution versus azimuth angle for three radial stations (6° approach, 65 KIAS).

Hence, the RACT flight test results allow to extend the wind tunnel results of locally measured BVI noise reduction to the potential of IBC for a global reduction of BVI noise signature on ground.

The leading edge blade pressure transducers installed on one rotor blade of the test helicopter allow for detailed analysis of the source for BVI noise reductions. In Figure 11, the azimuthal distribution of the blade pressures measured at 3 % chord on three radial stations are presented. For IBC not activated, the impulsive pressure changes at all three radii clearly show the occurence of BVI. Since these pressure pulses are all located at the same azimuth range of 60° to 90°, the interacting vortex is positioned parallel to the rotor blade. This so-called 'parallel BVI' situation is supposed to be the one with the most annoying noise emission. On IBC activation, the pressure level in the parallel BVI region is reduced and the impulsive pressure peaks are smoothed out resulting in the noise level reductions shown in the figures before. On the retreating side, the characteristic of the leading edge blade pressure distribution does not change significantly on IBC input.

One of the motivations for applying IBC was the inverse correlation between noise reduction and vibrations found in HHC wind tunnel tests. The NASA Ames tests demonstrated that for an efficient BVI noise reducing IBC input a decrease in vibrational level can be achieved simultaneously.

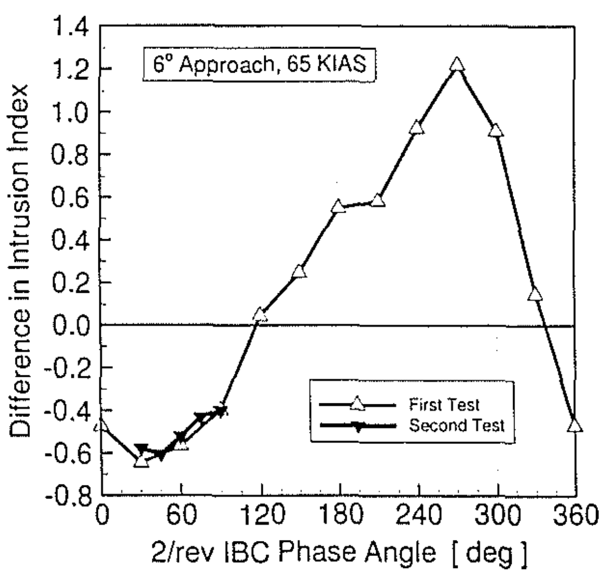

Figure 12: Reduction of intrusion index for varying 2/rev, 1° amplitude IBC phase angle (6° approach, 65 KIAS).

For the reference flight condition, Figure 12 depicts the differences in Intrusion Index obtained in the RACT flight tests for varying phase angles of the 2/rev, 1° amplitude IBC schedule. The Intrusion Index is a weighted average of the vibratory loads of all three spatial directions and takes into account the human vibrational sensibility. The phase angle sweep exhibits a remarkable vibration suppression for the 30° to 90° range which has to be compared to the BVI noise level reduction in the same region plotted in Figure 6. The encouraging correlation between efficient BVI noise reduction and vibration suppression for the 2/rev, 1° amplitude, 60° phase angle could also be confirmed by the subjective perception of the test pilot and test engineer during the test campaign.

All results presented up to now were obtained for a constant IBC amplitude of 1°. The next interesting question concerning the BVI noise reduction using 2/rev IBC deals with the amplitude influence. The investigation of different IBC amplitudes were performed for a fixed phase angle of 60°.

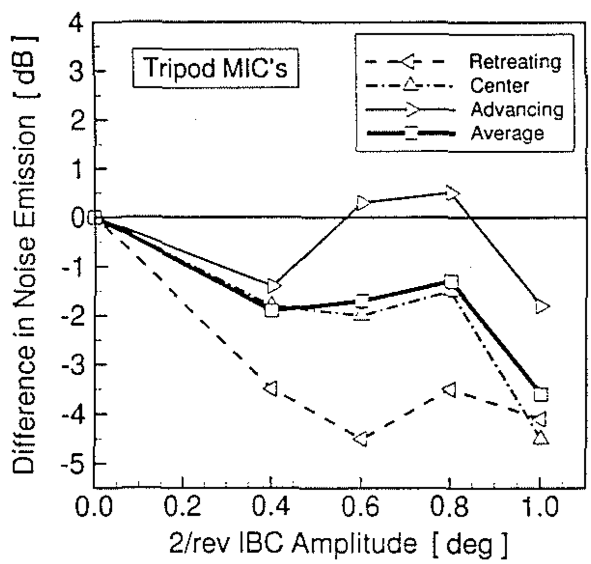

Figure 13: BVI noise suppression versus amplitude for a 2/rev IBC input, 60° phase angle (6° approach, 65 KIAS).

Figure 13 shows the measured difference in ground noise. For all amplitude values tested, a reduction of average BVI noise level was obtained. As expected, the most efficient reduction found was for an amplitude of 1°. But in contrast to the wind tunnel data, the correlation between increasing amplitude and decreasing noise level could not be confirmed. Unfortunately, only 4 microphones on the advancing side at fixed position were used in the NASA wind tunnel test for the amplitude sweep. Therefore, a direct comparison to the RACT flight test result is difficult. Surprisingly, noise suppression capability measured in the flight tests decreases for the 0.6°

and 0.8° amplitudes. This is due to a remarkable noise level increase on the advancing side.

The analysis of leading edge blade pressure distribution for all amplitudes in Figure 14 reveals that parallel BVI around 60° azimuth is effectively suppressed with increasing efficiency for increasing amplitudes. For azimuth ranges between 300° and 360° additional pressure peaks appear for 0.6° amplitude and more pronounced for 0.8° amplitude. A possible explanation for the appearance of these impulsive pressure changes might be the occurence of additional BVI events caused by a reduction of vortex misdistance due to an unfavourable amplitude setting. These additional BVI events radiate sound mainly in the direction perpendicular to the blade leading edge towards the ground area on the advancing side. Hence, the advancing side microphones will measure higher noise level explaining the results presented in Figure 13.

Finally, the influence of flight condition on the achieved BVI noise reduction for a fixed IBC setting was addressed by lowering the 6° approach flight speed to 42 KIAS. Table 1 compares average values measured by the certification microphones for both flight speeds tested. Obviously, noise suppression efficiency impairs for lower flight speeds and the need for adapting IBC inputs established in the wind tunnel tests can be confirmed.

Table 1: Influence of flight speed on noise emission using a constant 2/rev IBC setting with 1° amplitude and 60° phase angle.

Flight speed	42 KIAS	65 KIAS
Noise Reduction [dB] by IBC activation	-0.4	-3.1

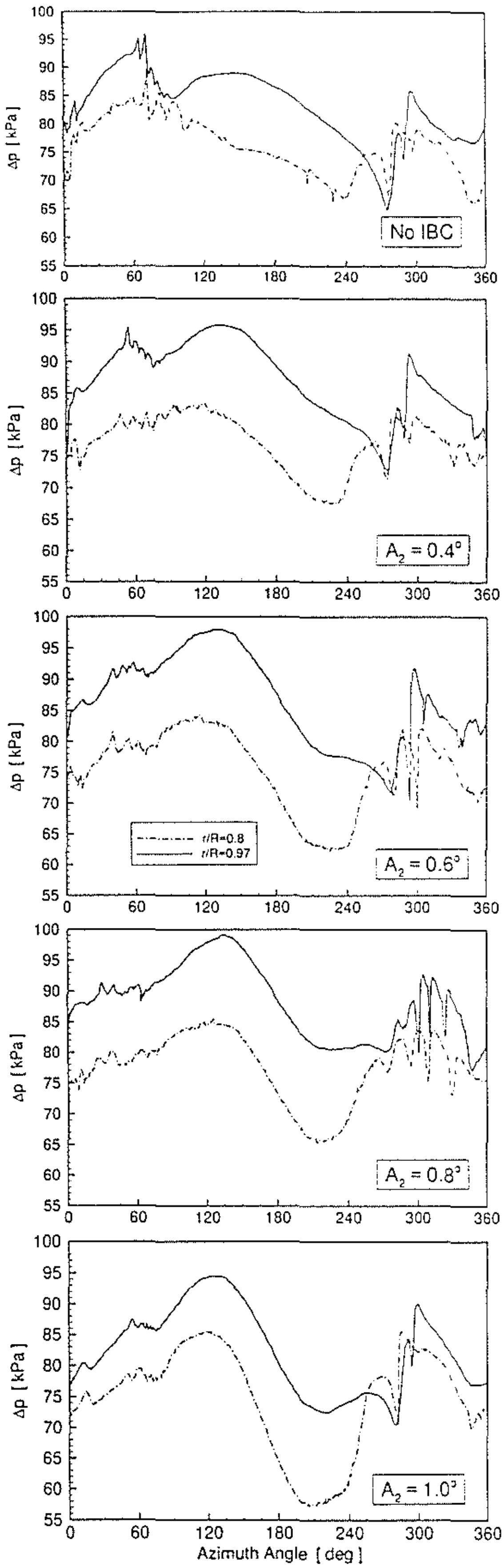

Figure 14: Leading edge blade pressure distribution for the 2/rev IBC amplitude sweep (6° approach, 65 KIAS).

3/rev and 3/rev+5/rev IBC

The second part of the flight tests was devoted to the 3/rev higher harmonic input schedule which was identified in the wind tunnel tests to reduce vibratory loads most efficiently. In the following, the influence of the 3/rev IBC on noise emission will be discussed shortly.

Figure 15 shows the noise reduction for a 3/rev IBC phase angle variation. Although the resolution of the phase angle sweep was rather coarse, a BVI noise optimum can de detected around 270°.

To check the wind tunnel observation of an increased noise reduction efficiency for multi-frequency inputs, a 3/rev+5/rev schedule was studied using 270° as fixed 3/rev phase angle and varying 5/rev phase angles.

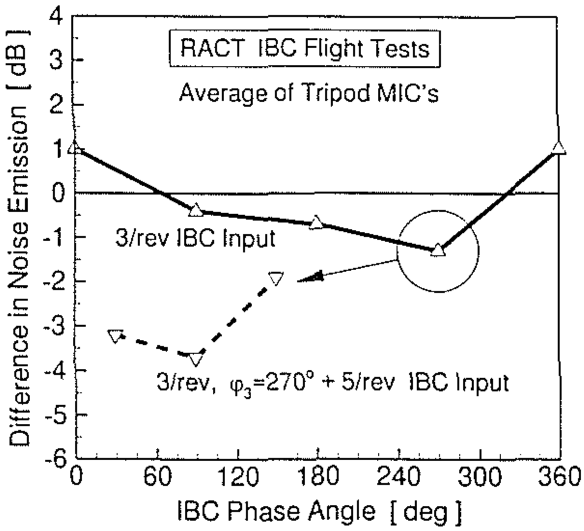

Figure 15: Influence on noise for a variation of 3/rev IBC phase angle and of 5/rev phase angle for 3/rev+5/rev IBC input.

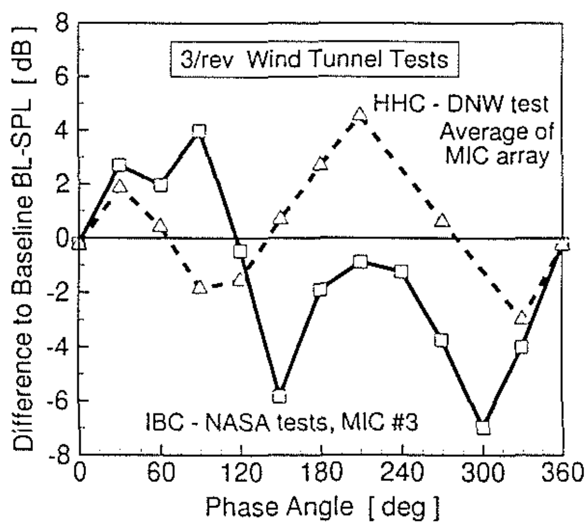

Figure 16: Results of wind tunnel tests for 3/rev HHC and IBC input for a trim condition corresponding to a 6° descent, 65 kts flight.

Figure 15 clearly shows the improvement in BVI noise reduction with a maximum for a 5/rev phase angle of 90°, thus validating the wind tunnel result. The noise reduction level achieved by a multi-frequency input is equal to the one using a 2/rev single-frequency pitch schedule (compare with Figure 6).

The 3/rev pitch schedule was extensively tested in wind tunnel experiments using fixed system swashplate HHC actuation in the DNW and IBC at NASA Ames. Figure 16 depicts the variation of band-limited sound pressure level differences with phase angle measured by one microphone in the IBC tests against the averaged results of the microphone array used in the HHC tests (Ref. [12]). Although quantitatively not comparable, both measurements show a qualitatively similar phase angle characteristic. In contrast, the flight test results do not follow the wind tunnel behaviour. Despite the low number of test points and the aforementioned restrictions for comparing wind tunnel and flight test, there is no indication for a noise increase for 90° phase angle as identified in the IBC wind tunnel test. For a final conclusion on the noise influence of 3/rev IBC schedules, however, further analysis is necessary.

Conclusions

As a step towards the application of rotor active control in production helicopters, open-loop IBC flight tests were performed featuring a highly complex data acquisition system for simultaneous measurement of noise emission, vibrations, rotor operational parameters and rotor blade pressures. The BO105 test aircraft was equipped with an advanced IBC system having significantly increased control authority.

The results of the first flight test data analysis were presented in this paper and were compared to the experiences from previous HHC and IBC wind tunnel tests. The measured values of all sensors on ground and onboard of the highly instrumented test helicopter were processed and evaluated to obtain the following conclusions.

2/rev IBC

1. The result of the IBC wind tunnel tests at NASA Ames could be confirmed qualitatively with respect to the influence of phase angle on noise reduction.
2. The phase angle optimum at 60° is statistically most assured and could be confirmed by simultaneous measurements using landing skid microphones.
3. The measured noise level time histories and the data from the ground microphone array prove that for optimized IBC inputs the obtained BVI noise reduction is not restricted to a local region but is achieved globally on all microphone position.
4. The blade pressure data show that the noise reductions achieved by IBC inputs

originated from the decreased pressure levels and suppressed impulsive pressure pulses at the azimuthal position where BVI events occur.

5. The phase angle of 60° not only turns out to be a noise reduction optimum, but also remarkably decreases the vibrational levels.
6. The noise reductions dependency on the IBC amplitude does not correlate with the results from the wind tunnel tests. For amplitudes between 0.6° and 0.8°, additional blade pressure pulses appear around 330° azimuth. It is assumed that these BVI events radiate sound to the advancing side of the helicopter, thus deteriorating or even increasing the noise levels on ground.
7. A first assessment of flight speed influence for a constant IBC schedule confirms the wind tunnel data, that an IBC input has to be adapted to the actual flight condition. This promotes the development of a closed-loop controlled IBC system with a highly efficient BVI identification algorithm. First results of evaluating different BVI identification methods performed within the RACT flight tests can be found in Ref. [10].

3/rev and 3/rev+5/rev IBC

1. The 3/rev IBC input schedule that was found appropriate for efficient vibration reduction in the wind tunnel revealed the potential of simultaneous BVI noise reduction in the RACT flight tests.
2. Using a multi-frequency IBC schedule, the same level of noise reduction as obtained by 2/rev inputs can be achieved.

A further analysis of the results from the ground microphone array measurements and a comparison with theoretical predictions can be found in Splettstößer et al. (Ref. [13]).

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References

[1] SPLETTSTÖßER W.R., SCHULTZ K.-J., KUBE R., BROOKS T.F., BOOTH E.R., NIESL G., STREBY O.
BVI Impulsive Noise Reduction by Higher Harmonic Pitch Control: Results of a Scaled Model Rotor Experiment in the DNW
17th European Rotorcraft Forum, September 1991

[2] NIESL G., SWANSON S.M., JACKLIN S.A., BLAAS A., KUBE R.
Effect of Individual Blade Control on Noise Radiation
AGARD Aeroacoustics Conference, Berlin, October 1994

[3] SWANSON S.M., JACKLIN S.A., BLAAS A., KUBE R., NIESL G.
Individual Blade Control Effects on Blade-Vortex Interaction Noise
50th Annual Forum of the American Helicopter Society, Washington DC, May 1994

[4] TEVES D., NIESL G., BLAAS A., JACKLIN S.
The Role of Active Control in Future Rotorcraft
21st European Rotorcraft Forum, St. Petersburg, Russia, August 30 - September 1, 1995

[5] SWANSON S.M., JACKLIN S.A., BLAAS A., NIESL G., KUBE R.
Acoustic Results From a Full-Scale Wind Tunnel Test Evaluating Individual Blade Control
51st Annual Forum of the American Helicopter Society, Fort Worth TX, May 1995

[6] KUBE R., ACHACHE M., NIESL G., SPLETTSTÖßER W.R.
A Closed Loop Controller for BVI Impulsive Noise Reduction by Higher Harmonic Control
48th Annual Forum of the American Helicopter Society, Washington DC, June 1992

[7] SCHIMKE D., JÄNKER P., BLAAS A., KUBE R., SCHEWE G., KEßLER C.
Individual Blade Control by Servo-Flap and Blade Root Control - A Collaborative Research and Development Programme
23rd European Rotorcraft Forum, Dresden, Germany, September 1997

[8] SCHIMKE D., ARNOLD U.T.P., KUBE R.
Individual Blade Root Control Demonstration - Evaluation of Recent Flight Tests

54th Annual Forum of the American Helicopter Society, Washington DC, May 20-22, 1998

[9] DIETERICH O.
Application of Modern Control Technology for Advanced IBC System
24th European Rotorcraft Forum, Marseille, France, September 1998

[10] HONERT H., VAN DER WALL B., FRITZSCHE M., NIESL G.
Realtime BVI Noise Identification from Blade Pressure Data
24th European Rotorcraft Forum, Marseille, France, September 1998

[11] SPLETTSTÖßER W.R., JUNKER B., SCHULTZ K.-J., WAGNER W., WEITEMEIER W., PROTOPSALTIS A., FERTIS D.
The HELINOISE Aeroacoustic Rotor Test in the DNW - Test Documentation and Representative Results -
Internal Report, DLR 93-09, December 1993

[12] KUBE R., VAN DER WALL B., SCHULTZ K.-J.
Mechanisms of Vibration and BVI Noise Reduction by Higher Harmonic Control
20th European Rotorcraft Forum, October 4-7, Amsterdam, 1994

[13] SPLETTSTÖßER W.R., SCHULTZ K.-J., VAN DER WALL B., BUCHHOLZ H., GEMBLER W., NIESL G.
The Effect of Individual Blade Pitch Control on BVI Noise - Comparison of Flight Test and Simulation Results
24th European Rotorcraft Forum, Marseille, France, September 1998