Sound Synthesis Approach for Noise Annoyance Assessment of Rotorcraft Operations

Sabbatini, D; Janssens, K; Hartjes, Sander; Visser, H.G.; Gennaretti, M; Bernardini, Giovanni

Publication date
2013

Document Version
Accepted author manuscript

Published in
NOISE-CON 2013

Citation (APA)
Sabbatini, D., Janssens, K., Hartjes, S., Visser, H. G., Gennaretti, M., & Bernardini, G. (2013). Sound Synthesis Approach for Noise Annoyance Assessment of Rotorcraft Operations. In *NOISE-CON 2013: 2013 August 26-28, Denver, Colorado*

Denver, Colorado
NOISE-CON 2013
2013 August 26-28

Sound Synthesis Approach for Noise Annoyance Assessment of Rotorcraft Operations

D. Sabbatini
K. Janssens
LMS International
Interleuvenlaan 68
3001 Leuven
Belgium
Karl.janssens@lmsintl.com

S. Hartjes
H.G. Visser
Delft University of Technology

M. Gennaretti
G. Bernardini
Roma Tre University

ABSTRACT

This paper presents a sound synthesis approach that allows investigating the noise annoyance of rotorcraft in relation to the source components and flight path. The sound synthesis is based on a source-transfer-receiver model, describing the noise emission and directivity of the sources and their propagation towards the receiver point on the ground. Several noise propagation effects are considered such as the Doppler shift, distance effect, atmospheric absorption, ground reflections and the effects of head and body. A case study is presented, showing the complete modeling and synthesis procedure for a four-bladed twin-engine helicopter. The source data was obtained from numerical simulations. Flyover sounds were synthesized for a baseline trajectory and a noise-optimized flight path.

1. INTRODUCTION

Noise pollution from rotorcraft affects many residents in heliport communities. In this work, a sound synthesis approach was developed to investigate the impact of rotorcraft noise sources and flight path on the perception of annoyance. The synthesis technology adopts a source-transfer-receiver approach, characterizing the noise spectrum and directivity of the different sources and their propagation towards the receiver on the ground. The main concept is shown in Figure 1.

The capability to synthesize sounds and analyze the human perception of annoyance is the key novelty of the approach with regard to many of the existing technology products which only address noise levels. With the present technology, complex heliport scenarios can be reproduced and psycho-acoustically assessed. Footprints of psycho-acoustic metrics (e.g. loudness, tonality, modulations etc) can be calculated, allowing the analysis of critical residence areas for various flight path scenarios.

The paper consists of two parts. The first part describes the main steps of the noise synthesis approach. The second part presents a case study on a Bo-105 helicopter.

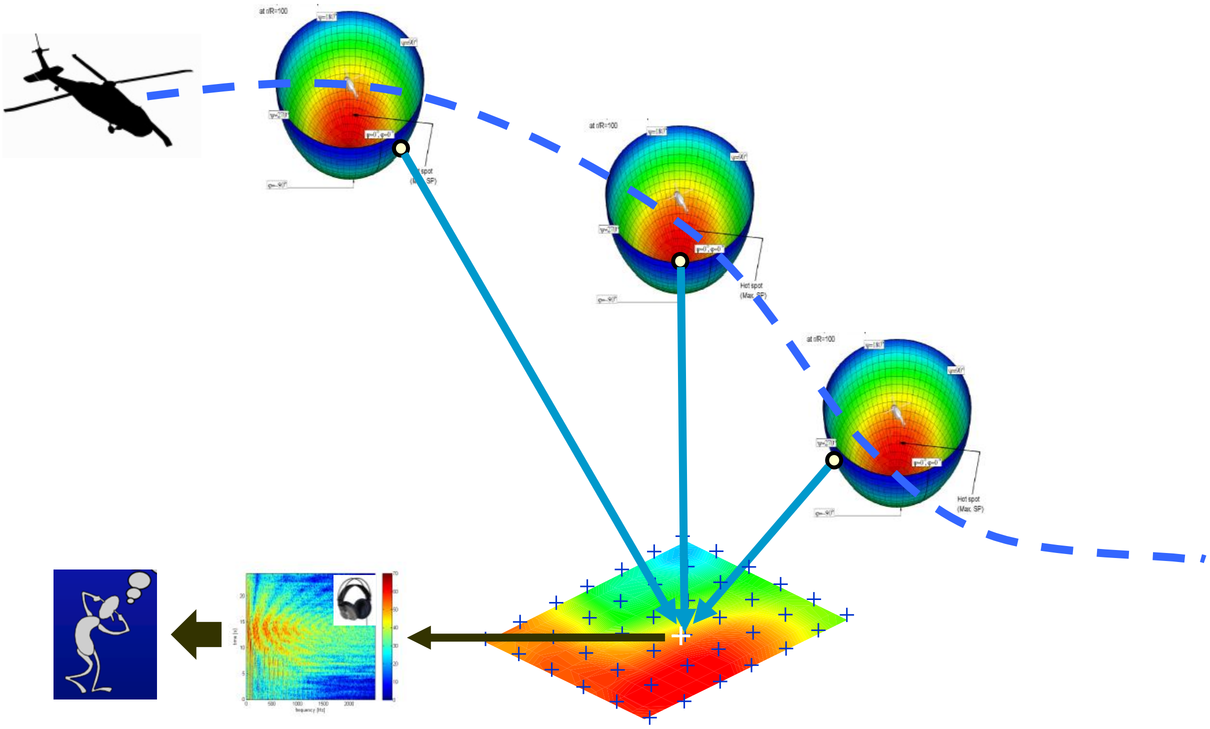

Figure 1: Flyover noise synthesis using a source-transfer-receiver approach

2. SOURCE-TRANSFER-RECEIVER APPROACH

Source component spectra and flight path data

In order to achieve a realistic flyover noise synthesis, the frequency spectrum and directivity of the different noise source components should be known. The noise source spectra are composed of harmonic components and broadband noise. The main and tail rotor, engine and gearbox are responsible for the tonal noise generation. The broadband noise is composed of vortex noise produced by the rotor blades, engine and airframe noise. Vortex noise has a typical unique sound character that can be clearly distinguished from aircraft noise. It is strongly modulated noise generated as a result of the random fluctuations of the forces on the blades[1]. The noise spectrum and directivity can be obtained from array measurements, numerical simulations, wind tunnel tests, etc. The data is commonly represented on a hemisphere surrounding the vehicle.

Next to that, flight path data, atmospheric conditions (e.g temperature, humidity, wind speed) and ground impedance information are required to propagate the noise from the sources to the receiver location of interest.

Sound synthesis methodology

The sound synthesis is performed in three consecutive steps. In the first step, a stationary sound is synthesized for every source component. The harmonics are synthesized as sinusoidal signals with RPM dependent frequency. The inter-harmonic amplitude and phase relationships have to be reproduced accurately. Broadband noise is synthesized in third octave bands. The source components are shaped to include the effects of directivity. The resulting sound represents the noise that would be captured by a microphone that moves along the hemisphere during the flight and points towards the observer on the ground.

In the second phase, the Doppler effect is included to represent the relative motion of the helicopter with respect to the receiver. The Doppler shift is introduced by applying a non-linear transformation of the time axis. The flight path and observer location are required as inputs for the resampling process. Spline interpolation is used to resample the data.

Finally, in the third step, time-varying noise propagation filters are applied to generate the sounds at the ear canal entrances of the receiver. The filters are constructed from a set of binaural Noise Transfer Functions (NTF's) computed for consecutive points on the trajectory. Three main phenomena are taken into account:

- Atmospheric noise propagation: this involves the reduction of sound pressure level with distance and the air absorption. The air absorption mainly attenuates the higher frequency components, in particular for large distances between the source and receiver[2]. Other atmospheric phenomena such as wind effects and turbulences can be reproduced by applying time fluctuations and spectral broadening to the signals.
- Ground reflections: these are taken into account by considering a direct and ground reflected path. The superposition of these waves allows reconstructing the interference pattern in the sound. The interference pattern is governed by two parameters: the ground impedance and the time delay between the direct and reflected sound. The impedance is frequency and angle dependant while the time delay changes as a function of time with the flight path.
- Effect of human head and body: this effect is incorporated through a set Head Related Transfer Functions (HRTF's). The HRTF's describe how a given sound wave is filtered by diffraction and reflection properties of the head, pinna and torso before reaching the eardrum and inner ear.

The noise propagation filters are implemented using a Fast FFT convolution approach[3]. A proper filter pre-processing is required to make sure that the filters are causal and do not generate artefacts. Special care is taken to cope with the time-varying filter characteristics and ensure a smooth transition between consecutive filter steps. The block size used for the convolution is a trade-off between computation time and accuracy.

3. CASE STUDY ON BO-105 HELICOPTER

Noise source predictions

A case study was performed on a four-bladed twin-engine Bo-105 vehicle. A hemisphere noise database was generated with a dedicated noise prediction tool. The noise prediction tool is based upon the three-steps procedure shown in Figure 2. First, helicopter attitude and control settings are evaluated through the flight mechanics solver of the Delft University of Technology[4], for given advance ratio, rotor speed and flight path angle. Then, the control settings are used in the aeroelastic solver of the Roma Tre University to evaluate both steady periodic blade deformations and blade pressure time history. Finally, the pressure field on the blades is used in the aeroacoustic solver for the evaluation of the emitted noise.

The aeroelastic tool is the result of the research work presented and validated by some of the authors during the last ten years[5-8]. It couples a blade structural dynamics model with a potential-flow, boundary integral formulation for the prediction of unsteady aerodynamic loads acting on the blades.

Blade structural dynamics is described through a flap-lag-torsion beam-like model valid for slender, homogeneous, isotropic, non-uniform, twisted, curved blades, undergoing moderate displacement[9]. It consists of a set of three coupled, nonlinear, integro-differential equations, governing the in-plane (lead-lag) and the out-of-plane (flap) displacements of the elastic axis, along with the blade cross-section rotation (torsion). These equations are spatially integrated through the Galerkin method, whereas the periodic blade response is determined by a harmonic balance approach[8].

The aerodynamic solver consists of a potential-flow, three-dimensional, free-wake, boundary element method solver suited for the prediction of Blade Vortex Interaction (BVI) effects[6], which is applicable to a wide range of rotor steady flight configurations, including approach trajectories. It assumes the wake divided into a near (potential) wake close to the trailing edge (that cannot come in contact with lifting bodies), and a far (vortex) wake that may experience collision with rotor blades. For a realistic modeling of the far wake, a non-zero thickness wake is used, expressing the wake vortices as thick Rankine vortices. Once the potential field is known, the Bernoulli theorem yields the pressure distribution on the body[7] that, in turn, is used both to determine the generalized forces for the aeroelastic prediction tool and as an input to the aeroacoustic solver to predict the noise field.

The aeroacoustic analysis is performed by a prediction tool based on the Ffowcs Williams and Hawkings equation[10], that is solved through the boundary integral representation, known as the Farassat Formulation 1A[11-12].

In the present case study, noise predictions were carried out for 12 flight configurations with different flight path angle (0, 5, 7.5, 10 deg) and vehicle speed (30, 65, 100 knots). A hemisphere noise database was generated, containing the noise spectra for 145 microphone locations with different azimuth and elevation angle.

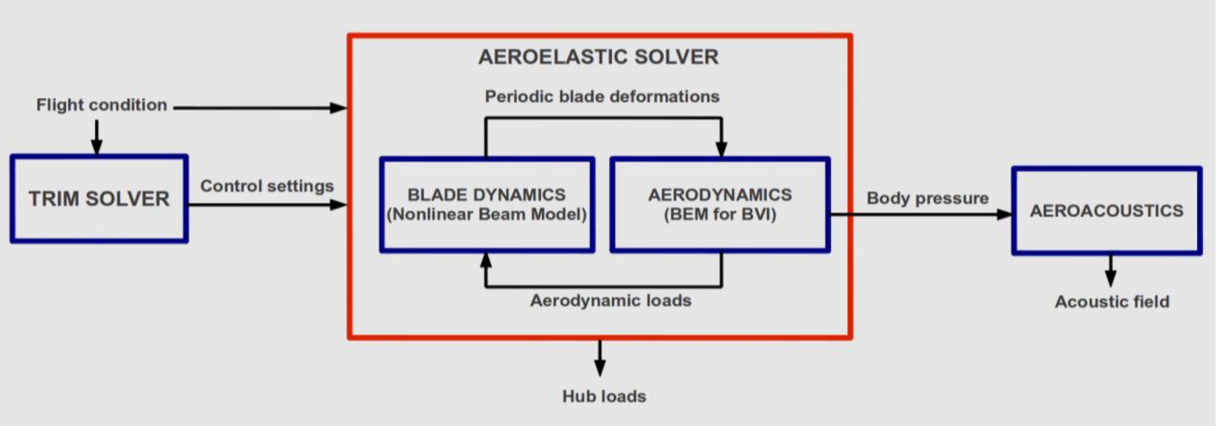

Figure 2: Noise source predictions based on a three-steps procedure

Trajectory specification

A baseline trajectory and noise-optimized flight path were specified for a densely populated area near Rotterdam (the Netherlands). The optimized trajectory was generated with the European Clean Helicopter Optimization (ECHO) suite, an optimization framework under development at the Delft University of Technology[13-14]. At the core of ECHO lies a fast pseudo-spectral theory based trajectory optimization algorithm, coupled with a high-fidelity rigid-body rotorcraft dynamic model[4]. The ECHO framework facilitates the development of advanced rotorcraft approach procedures that maximize environmental benefits based on an integrated assessment of multiple relevant factors, including noise impact, fuel burn, emissions and transit time. To enable the optimization of environmental criteria, a helicopter emissions model[15] and a noise model were integrated in the ECHO computation chain too. The latter model combines the hemisphere noise database with a noise propagation model based on a fast ray-tracing algorithm and a community noise impact model. The architecture of the ECHO software is shown in Figure 3.

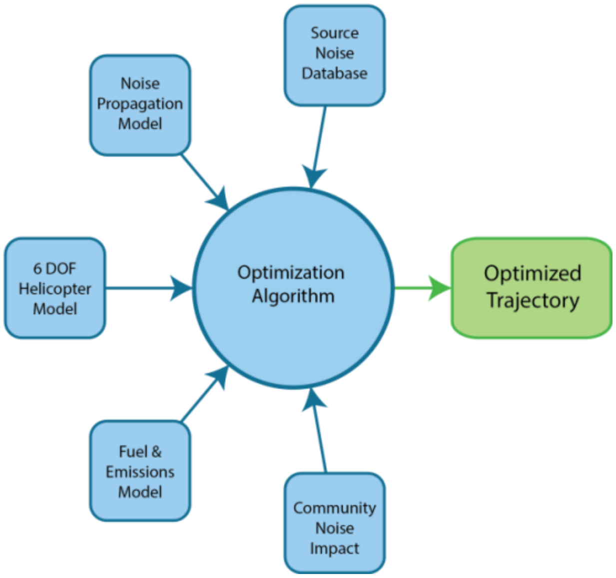

Figure 3: ECHO software architecture

The noise modeling in the ECHO suite consists of four steps. With the helicopter position in time defined by the flight mechanics model and a fixed grid of observer locations, first the ray path between the source and a receiver is constructed. With the ray path known, the spreading loss, absorption, ground reflection and hence the total propagation loss can be determined, yielding the A-weighted Sound Pressure Level (SPL) on the ground. In order to quantify the noise impact in local communities, a dose-response relationship is applied which, in the present case study, defines the percentage of expected awakenings due to a single night time flyover as a function of the Sound Exposure Level (SEL)[16]. This requires the additional step of integrating the A-weighted SPL's along the trajectory to find the SEL at each observer point. With the SEL known, the dose-response relationship can be used to determine the percentage of expected awakenings at each observer location. In the final step, the results from the dose-response relationship are combined with a Geographic Information System (GIS) containing population density data, to determine the total number of expected awakenings.

The weighted sum of the total flight time and total number of expected awakenings was used as composite objective function in the present case study. Figure 4 shows the noise-optimized flight path in comparison to the baseline trajectory on a geographic map of the area under study. The baseline trajectory is a straight linear path while the optimized one follows a river that crosses the area.

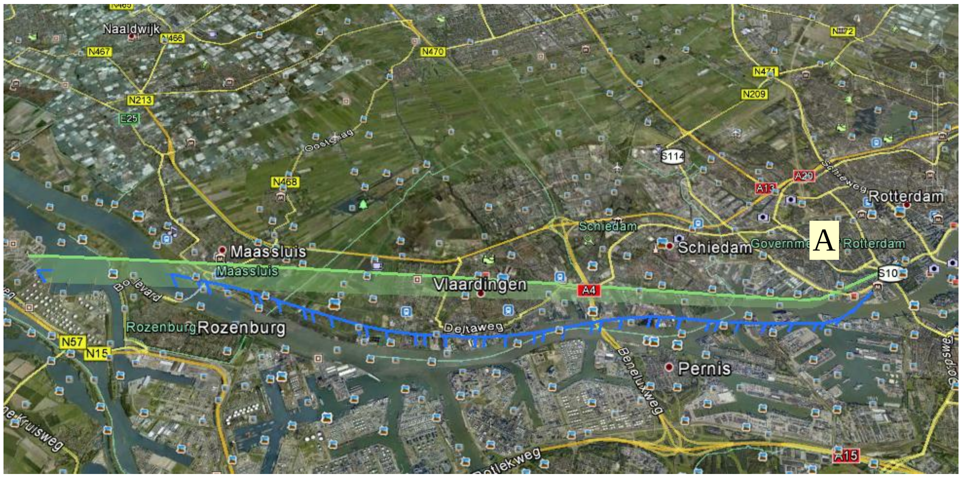

Figure 4: Baseline trajectory (green) and optimized flight path (blue)

Computation of binaural NTF's

By means of Virtual.Lab Ray Tracing, a computer-aided software technology of LMS, a set of binaural Noise Transfer Functions (NTF's) was calculated for consecutive points on the baseline and optimized trajectory. The binaural NTF's were calculated towards several observer locations in the area under analysis. The transfer functions incorporate the effects of atmospheric noise propagation, ground reflections, torso and head. The temperature of the air was assumed 20 degrees Celsius and the relative humidity 70%. The surrounding environment was modeled as a flat ground surface made of concrete.

The binaural NTF's were calculated for 167 positions along the two trajectories. The number of points used to discretize the trajectory is a critical factor. When the number of points is taken too low, the rapidly changing ground reflections are not sufficiently characterized by the set of transfer functions. Figure 5 shows the trajectory discretization in Virtual.Lab Ray Tracing.

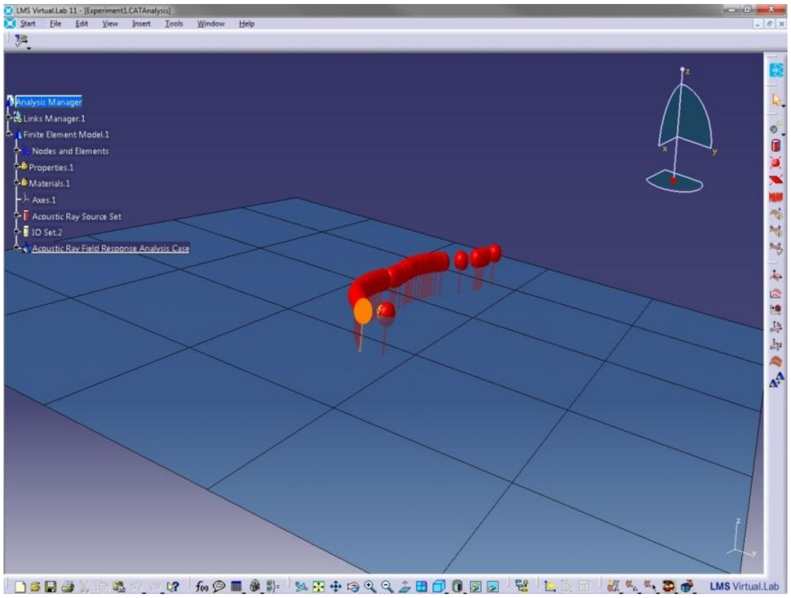

Figure 5: Calculation of binaural NTF's for consecutive points on the trajectory using Virtual.Lab Ray Tracing

Flyover noise synthesis

By using the afore-discussed sound synthesis approach, flyover sounds were finally synthesized for several residence areas. As an example, Figure 6 shows the sound synthesis results for location A, close to Schiedam. See geographic map in Figure 4. Time-frequency maps are shown for the baseline and optimized trajectory. Only the tonal noise, produced by the rotor blades, was synthesized. The trajectory clearly has an impact on the sound at the receiver point. The Doppler frequency shift and ground interference pattern are obviously different. Also the directivity is different in the two flight cases, influencing the tonal spectrum that is emitted in the direction of the receiver.

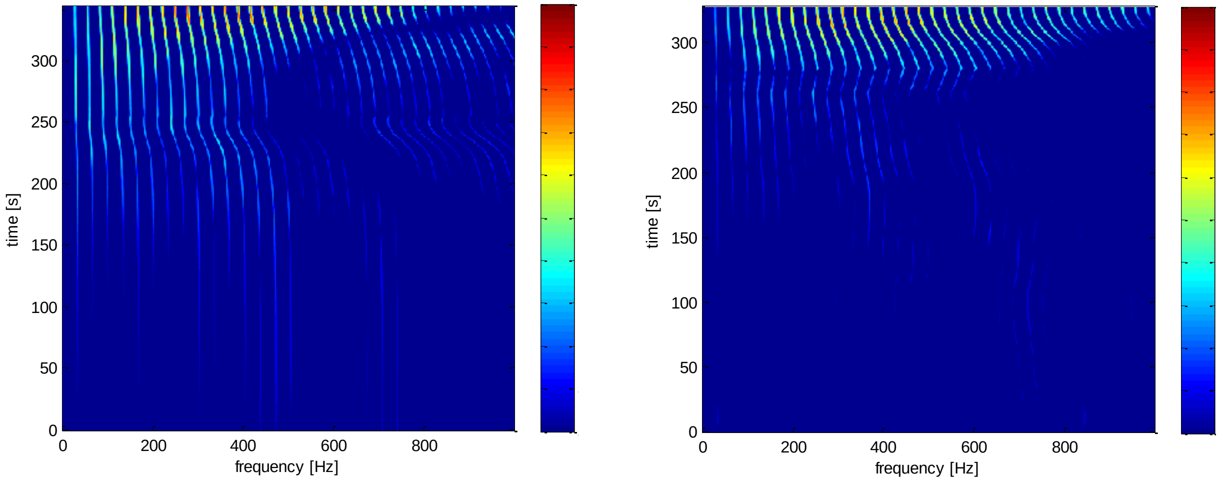

Figure 6: Flyover noise synthesis results: (left) baseline trajectory, (right) optimized flight path. The time-frequency maps have the same color scale (50 dB dynamic range)

4. CONCLUSION

The combined influence of several parameters on the noise emission and propagation and the lack of measurement data make it difficult to assess whether the synthesis correctly reproduces the noise environment on the ground. Nevertheless, the absence of artifacts in the audio signals, the correct shape of the Doppler shift and ground interference pattern and the realistic spatial perception created by the binaural synthesis are convincing parameters justifying the correctness of the synthesis approach.

The tool’s capability to investigate the impact of the noise sources and flight path on the annoyance perception is unique and potentially interesting for helicopter design and trajectory optimization purposes.

ACKNOWLEDGEMENTS

This research work was carried out in the frame of the JTI Clean Sky Green Rotorcraft ITD. The support of the European Commission is gratefully acknowledged.

REFERENCES

1. J.G. Leishman, "Principles of helicopter aerodynamics", 2002.
2. Acoustics - attenuation of sound during propagation outdoors - Part 1, ISO9613-1, 1993.
3. S. Smith, "Digital signal processing: a practical guide for engineers and scientists", Elsevier Science, 2003, ISBN 0-750674-44-X.
4. M. D. Pavel, "On the necessary degrees of freedom for helicopter and windturbine low-frequency mode modeling", PhD Thesis, Delft University of Technology, 2001.
5. M. Gennaretti, G. Bernardini, "Aeroelastic response of helicopter rotors using a 3-D unsteady aerodynamic solver", The Aeronautical Journal 110 (1114), 2006, 793-801.
6. M. Gennaretti, G. Bernardini, "Novel boundary integral formulation for blade-vortex interaction aerodynamics of helicopter rotors", AIAA Journal 45 (6), 2007, 1169-1176.
7. M. Gennaretti, G. Bernardini, "Aeroacousto-elastic modeling for response analysis of helicopter rotors", in G. Buttazzo, A. Frediani (Eds.), Variational Analysis and Aerospace Engineering: Mathematical Challenges for Aerospace Design, Springer Optimization and Its Applications 66, Springer Science+Business Media, LLC 2012, 27-50.
8. G. Bernardini, J. Serafini, S. Ianniello, M. Gennaretti, "Assessment of computational models for the effect of aeroelasticity on BVI noise prediction", International Journal of Aeroacoustics 6 (3), 2007, 199-222.
9. E. Piccione, G. Bernardini, M. Molica Colella, M. Gennaretti, "Structural and aeroelastic modeling of curved rotor blades using a Galerkin approach", 3rd CEAS Air&Space Conference - XXI AIDAA Congress, Venezia, Italy, 24-28 October 2011.
10. J.E. Ffowcs Williams, D.L. Hawkings, "Sound generation by turbulence and surfaces in arbitrary motion", Philosophical Transactions of the Royal Society A264 (1151), 1969, 321-542.
11. F. Farassat, "Linear acoustic formulas for calculation of rotating blade noise", AIAA Journal 19 (9), 1981, 1122-1130.
12. F. Farassat, K.S. Brentner, "The uses and abuses of the acoustic analogy in helicopter rotor noise prediction", Journal of the American Helicopter Society 33 (1), 1988, 29-36.
13. S. Hartjes, H.G. Visser, M.D. Pavel, "Environmental optimization of rotorcraft approach trajectories", Conference proceedings, 37th European Rotorcraft Forum, Gallarate, Italy, 2011.
14. S. Hartjes, Y. Buys, H.G. Visser, M.D. Pavel, M. Gennaretti, G. Bernardini, M. Arntzen, "Optimization of rotorcraft noise abatement trajectories", Conference Proceedings, Inter-Noise 2012, New York, NY, USA, 2012.
15. FOCA, " Guidance on the determination of helicopter emissions", Edition 1, 2009.
16. Federal Interagency Committee on Aviation Noise (FICAN), "Sleep disturbance caused by aviation noise", USA, 1997.