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SOUND QUALITY ANALYSIS AND SYNTHESIS OF ROTORCRAFT FLYOVER NOISE USING A SOURCE-TRANSFER-RECEIVER APPROACH

Danilo Sabbatini[1,2], Karl Janssens[1], Herman Van der Auweraer[1], Fausto Cenedese[3]

[1]*LMS International, Leuven, Belgium;* [2]*IMP PAN, Gdansk, Poland*

[3]*AgustaWestland, Cascina Costa, Italy*

danilo.sabbatini@lmsintl.com

Noise pollution from air traffic is one of the major environmental problems affecting many citizens. Aircraft noise in general and rotorcraft noise in particular represents an extremely complex auditory scenario. Several acoustic and psychoacoustic factors such as spectral content, loudness, sharpness, tonality, modulations, etc. play a role and affect the human perception. That brings the need for a complex analysis of the sound, which takes into account all these factors and not just the total loudness.

This paper presents a source-transfer-receiver approach that allows a sound quality accurate synthesis of rotorcraft flyover noise in heliport communities, based on source component data and atmospheric noise propagation models. The approach was developed in the framework of the JTI Clean Sky Green Rotorcraft ITD where one of the objectives concerns the optimization of flight paths in order to minimize the perceived noise annoyance. The sound synthesis is based on a so-called Sound Quality Equivalent (SQE) model describing the noise source components in terms of harmonics, including the Doppler shift, and one-third octave noise bands, that may be modulated in amplitude. The SQE model approach allows the storage of information in a relatively compact database and permits a flexible and easy editing of the sound as required for sound quality analyses. The noise produced by the rotor blades, engine and transmission gears is propagated to the receiver location(s) on the ground by taking into account the directivity of the noise sources, the Doppler shift, the atmospheric noise propagation phenomena and ground impedance characteristics. The impedance characteristics of the ground and the delay between the direct incident and reflected sound are taken into account to describe the interference phenomena in the sounds.

The proposed synthesis approach is interesting for several reasons. It allows studying and assessing noise annoyance in relation to the acoustic and psychoacoustic characteristics of the sound, hence introducing the ”human-in-the-loop paradigm” as one of the criteria to optimize flight paths. Another interesting aspect of the sound synthesis approach is its capability to investigate which noise source components are important and should be targeted in the acoustic design and development process of rotorcraft. The method also helps to better understand sound quality differences among various type of rotorcrafts,

new rotor blade designs and flying conditions and forms a good basis for designing target sounds with lower noise annoyance. Various flying conditions can be simulated including multiple events, which is important for investigating long term annoyance.

The method is discussed and illustrated for an A109 helicopter of AgustaWestland. The synthesized audio signals are compared with measured noise recordings and the potential to use this technology approach to target sound design is briefly discussed.

1. Introduction

The growth of the air traffic, driven by the increasing request of the last years, and the positive trend predicted for the coming years introduce the noise pollution as one of the major environmental problems affecting many citizens.
In order to decrease the annoyance of the air traffic produced noise, an optimization of the flight path can be performed by mean of a source-transfer-receiver approach and a sound quality analysis. Aircraft in general and particularly helicopter flyover noise represent a challenging auditory scenario. Not just the trajectory of the maneuvers has to be considered, but also the balance among the noise sources components is important in order to obtain a more pleasant sound.
The need of a more pleasant sound is also expressed by medical studies that show the negative effects of the noise on population healthy.
Several acoustic and psychoacoustic factors play a role and affect human perception, role that can be quantified by mean of psychoacoustic metrics.
This paper presents a flyover noise synthesis approach which allows investigating the human perception and noise annoyance of rotorcraft operations. The sound synthesis is based on a Sound Quality Equivalent (SQE) model that is identified from noise recordings on the ground. Such a model is composed of Doppler shifted tonal components and modulated broadband noise and takes the ground impedance characteristics into account to reproduce the interference patterns in the sounds. This model, combined with directivity of the sources and atmospheric absorption, is the input for a source-transfer-receiver approach that propagates the noise source components towards the ground.
The method was developed in the frame of the JTI Clean Sky Green Rotorcraft ITD project.

2. Extraction of noise features.

In order to better understand the characteristics of helicopter flyover noise, ten measured noise recordings of a A109 helicopter of AugustaWestland (measured at 1.2m above the ground as required by the rules for noise certification) were analyzed in the time-frequency domain (Figure 1: Time-frequency spectrogram of A109 flyover noise recording.). Three major sound components can be recognized:

- A set of Doppler shifted tonal components;
- A broadband noise;
- An interference pattern.

The main rotor, tail rotor, engine and gearbox are responsible for the tonal noise generation. Since the noise sources are moving, a Doppler effect will be applied, causing a frequency shift of the tonal components during flyover.
The broadband noise consists of vortex noise produced by the rotors, engine broadband noise and airframe noise. The vortex noise in particular has a very typical sound character which can be clearly recognized and distinguished from aircraft noise. It is a strongly modulated noise that is generated as a result of the random fluctuations of the forces on the rotor blades [1] . The interference pattern in the time-frequency spectrogram is caused by a superposition of the direct sound and the reflections on the ground [2]. This is due to the fact that the sound waves, originating from the noise sources, reach the measuring station following two path-ways: one is the direct transmission path from source to receiver; the second one is the indirect path of sound waves that are reflected by the ground before they are captured by the microphone. The shape of the ground interference pattern is determined by the time-delay between both sound contributions. This time-delay changes in function of the helicopter position and reaches its highest value when the helicopter is right above the measurement microphone.

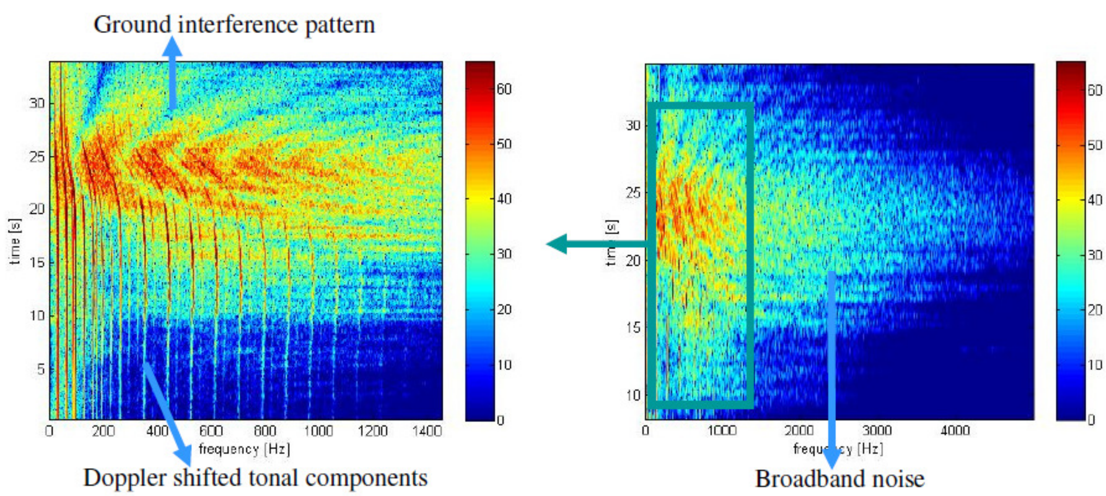

Figure 1: Time-frequency spectrogram of A109 flyover noise recording.

2.1 SQE Model

It is not the purpose of the technology approach under study to achieve high accuracy in reproducing the physics of all noise features, as a “pure” physical synthesis often results into a sound signal that is perceived as “artificial” or “synthetic”. In addition, such approach would require a far more intense computational load.
In order to have a light model that can be used to synthesize sounds perceived equivalent to the original sound, we make use of so-called Sound Quality Equivalent (SQE) model[3][4]. Such a model has the capability to reproduce the human perception of the noise under study.
For a helicopter flyover, the Doppler shifted harmonic components, the modulated broadband noise and the interference pattern are the model components that most affect the perception in psychoacoustic terms. These components, identified from a flyover

noise recording, are superposed into the SQE model using the approach described in the section below.

2.2 Extraction and synthesis of tonal components

In the first step of the approach, the tonal components are tracked from the recorded sound. The tonal components in the flyover noise spectra mainly originate from the main and tail rotor. All tonal components have in common the periodicity of their time structure. This is strongly dependant on the RPM regime of the rotating system they relate to. The number and the relative position of the tonal components in the noise spectra depend on the variations in the RPM and the relative speed between the source and measurement microphone (Doppler effect). The resulting frequency shifts affect the noise perception. Psychoacoustic phenomena such as tone masking effects, sharpness and modulations may arise, that can lead to strong variations in annoyance.
One of the basic requirements to model the noise is then the capability to extract the tonal components, with accurate identification of their amplitude and phase relations all along the duration of the noise recording. To this purpose, a two steps method was developed:

- Step1: identify the frequency shift of the various tonal components.
- Step 2: track their complex envelope as a function of time.

There are various ways to extract the frequency trend of the Doppler shifted harmonics from the time-frequency spectrogram. First of all, this can be done by selecting manually multiple points of a certain tonal component on the spectrogram and then run a spline interpolation algorithm to extract its frequency evolution and derive the Doppler shift ratio. A more elegant way is to select only the first point of the tonal component and then utilize a linear prediction algorithm that automatically follows the harmonic in the spectrogram. Finally, a fully automatic cross-correlation algorithm can also be applied to the subsequent FFT spectra (with a frequency log scale) of the noise recording, which is very interesting as it allows identifying the Doppler shift ratio from all spectral information and without any user input.
Once the frequency evolution of all tonal components is known, their complex envelope can be estimated as a function of time using the Discrete Fourier Transform (DFT). The DFT is applied to short time-segments in order to track the fast variations of the harmonics caused by atmospheric turbulences.
Finally, when all harmonic components are characterized, they can be easily resynthesized as time-domain signals.

2.3 Broadband noise modelling and synthesis

The second step of the method involves the broadband noise synthesis. To characterize the broadband noise, the tonal components are first filtered from the original sound recording by using a Vold-Kalman harmonic tracking filter. Subsequently, the remaining broadband noise is decomposed into one-third octave bands and resynthesized.
However, this synthesis procedure does not give the correct feeling of the background noise.
The broadband noise consists of vortex noise produced by the rotors, engine broadband noise and airframe noise. The vortex noise in particular has a very typical sound character

which can be clearly recognized and distinguished from aircraft noise. It is a strongly modulated noise that is generated as a result of the random fluctuations of the forces on the rotor blades [1].

In order to better understand the structure of the modulation is possible to perform an analysis of the time evolution of the sound envelope (Figure 2: envelope frequency in function of time and carrier frequency) (Figure 3: envelope frequency in function of time).

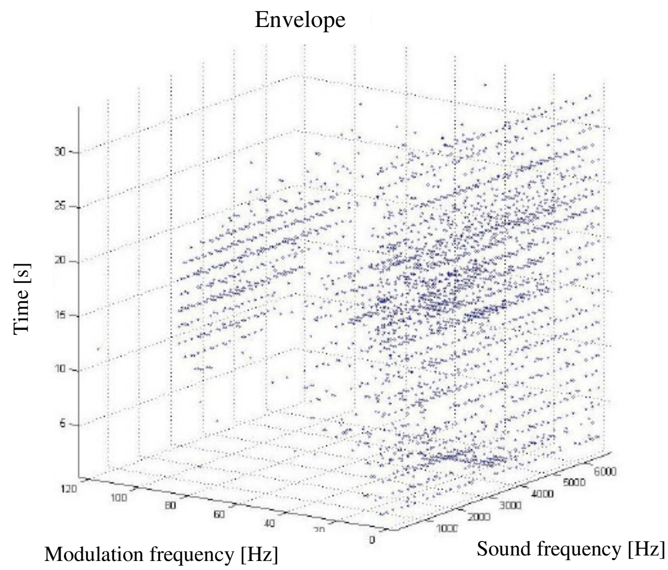

Figure 2: envelope frequency in function of time and carrier frequency

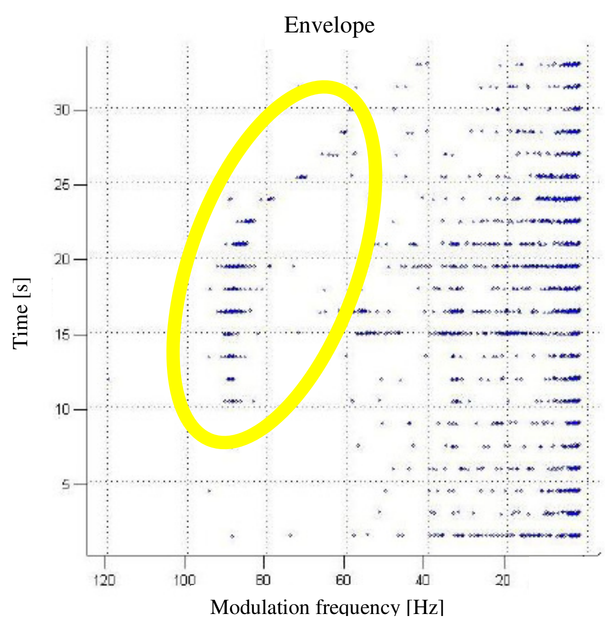

Figure 3: envelope frequency in function of time (modulation frequency remarked in yellow)

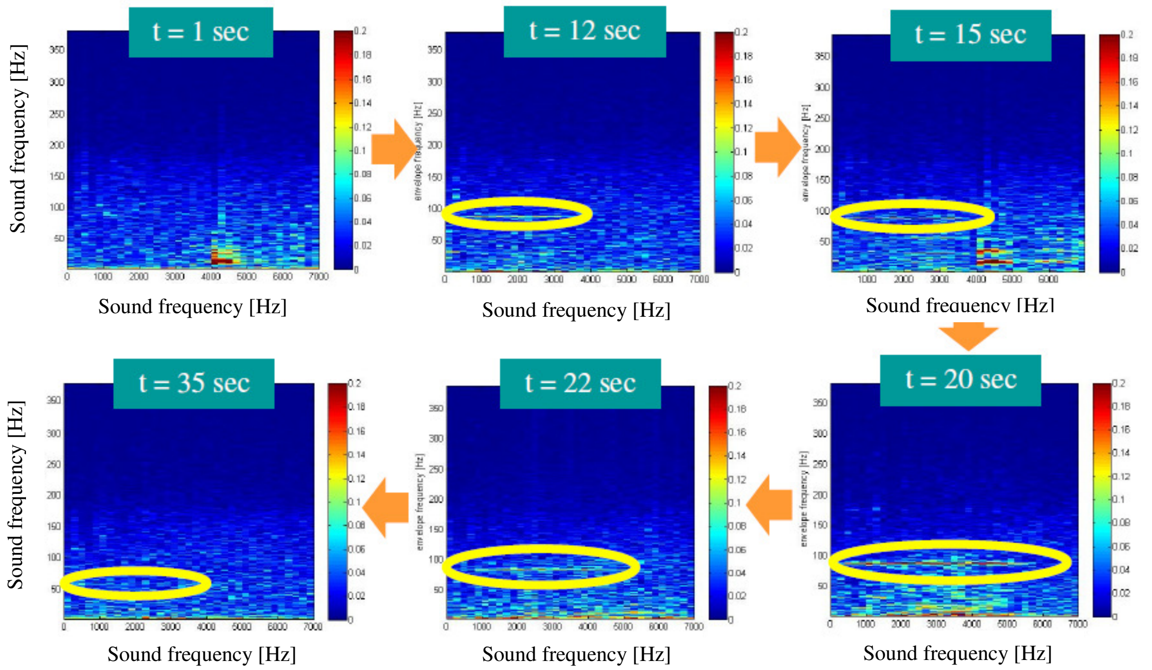

Figure 4: broadband noise at various time steps of the flyover (x-axis: carrier frequency; y-axis: modulation frequency; color scale: modulation strength; modulation frequency remarked in yellow)

To reproduce this feeling, the one-third octave noise is modulated in amplitude at the main modulation frequency and some additional random fluctuations are included as well to avoid "artificial" or "synthetic" sounds.
The amplitude modulations are not visible from this time-frequency spectrogram, but can be clearly heard when listening test are performed.

2.4 Superposition and ground reflection filter

The synthesized harmonic components and amplitude modulated third octave noise are then added up, representing the helicopter sound in free field conditions. Still missing is the ground interference pattern which should be added to the model as it strongly affects the overall sound character and its perception. The interference pattern in the time-frequency spectrogram is caused by a superposition of the direct sound and the reflections on the ground [2]. This is because the sound waves originating from the noise sources reach the measuring station following two path-ways: one is the direct transmission path from source to receiver; the second is the indirect path of sound waves that are reflected by the ground before they are captured by the microphone. The shape of the ground interference pattern is determined by the time-delay between both sound contributions. This time-delay changes in function of time with the flight path and reaches its highest value when the helicopter is right above the measurement microphone.
In order to characterize the ground interference pattern, a cepstrum analysis is performed at several time steps of the noise recording. This analysis provides an estimate of the time delay between the direct and reflected sound (from the time shift of the peak in the cepstrum) and the ground reflection coefficient (from the ratio of the peak amplitude to

the DC). From both parameters, a ground reflection filter is then generated and finally applied, delivering the final synthesized sound.

3. Source-transfer-receiver synthesis approach

Once obtained a reliable SQE capable to reproduce the sound at measurement point, it is possible to predict a stationary sound back propagating the sound at observer location to the aircraft stationary sound. The input data for the sound-transfer-receiver synthesis can be obtained in several other ways, as database of wind tunnel tests and numerical simulations.

Furthermore, the flight path, directivity curves of each SQE component, atmospheric conditions (temperature, humidity, wind speed and turbulence information) and ground impedance characteristics are required as input data to propagate the sound from the source to the receiver locations of interest. This data can be obtained from measurements.

The flyover noise synthesis is performed in four consecutive steps:

- A stationary sound is first generated for each of the different source components. The synthesized audio signals are then shaped, to include the directivity effects, and added together. The resulting sound is the noise that would be captured by a microphone that is moving around the helicopter.
- In the second step of the approach, the Doppler effect is introduced to represent the relative motion of the helicopter with respect to the receiver. The Doppler frequency shift is included by applying a non-linear transformation of the time axis from τ to $t = \tau + r/c$, where r is the time-changing distance between the source and receiver and c is the speed of sound. The flight path and observer location are required as input data to perform the resampling process.
- In the third phase, an atmospheric propagation filter is applied to the Doppler shifted audio signal. Two effects are taken into account: the reduction of the sound pressure level with the distance (1/R) and the atmospheric absorption [5]. The atmospheric absorption mainly attenuates the higher frequencies, in particular for large distances between source and receiver as shown in figure 2a. Other atmospheric phenomena such as wind effects and turbulences are considered as well by generating time fluctuations in the sound. These are important to avoid synthetic or artificial sounds.
- Finally, the ground reflections are taken into account as they significantly affect the overall characteristics of the sound. The superposition of the direct incident and reflected waves leads to a typical interference pattern in the sound. This ground 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. From both parameters, a ground reflection filter is generated. By applying this filter, we finally obtain the flyover noise for the observer location.

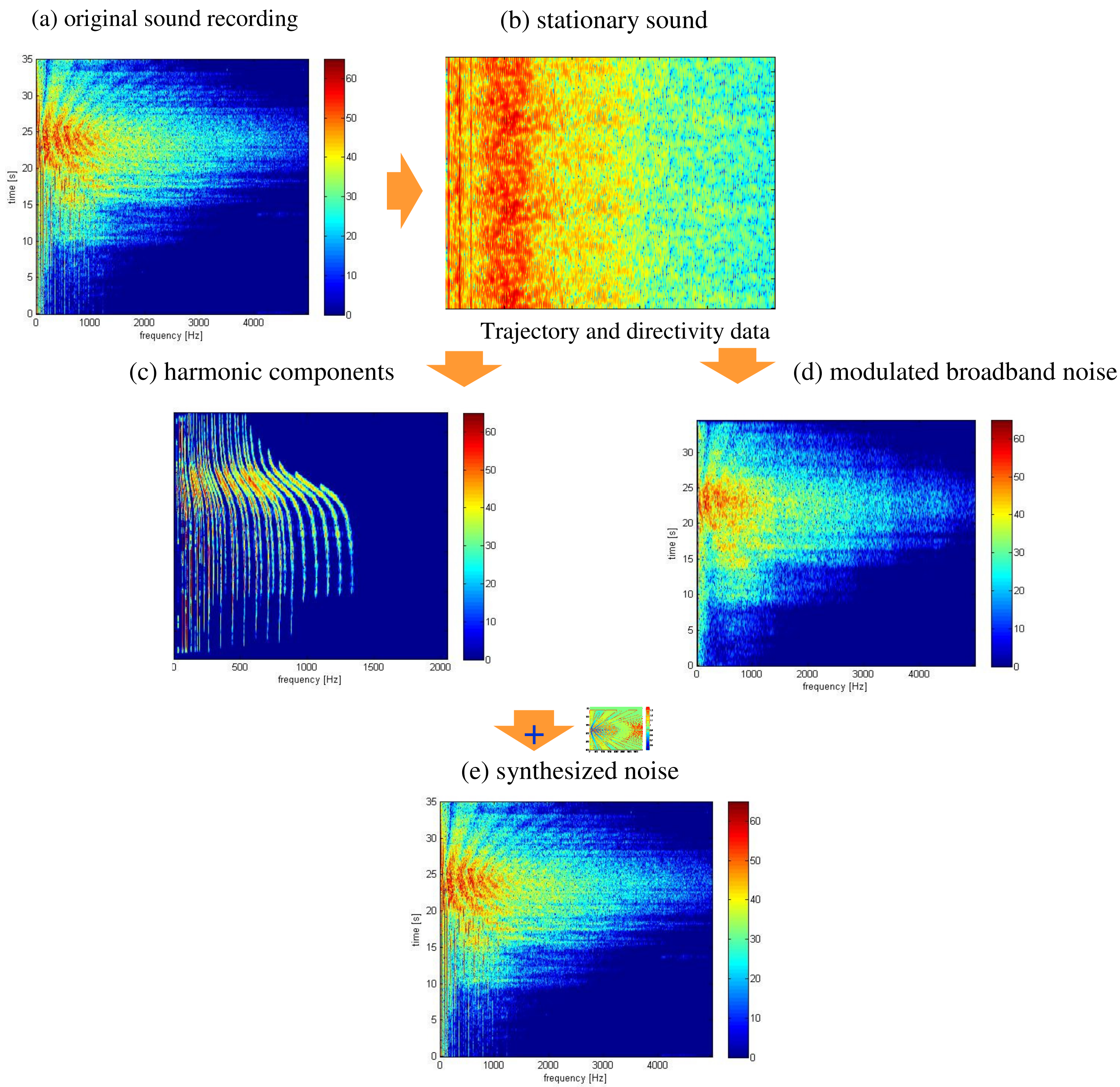

Figure 5: Sound decomposition and resynthesis

4. Validation

The main idea of the above presented technology approach was to develop synthesis models and propagation tools that allow investigating the human perception and noise annoyance of rotorcraft operations. High accuracy in simulating the detailed physics of all noise features is not the goal of this paper; the target is to obtain simplified SQE models that are capable of reproducing the human perception of the noise under study. Listening tests were hence organized where the synthesized sound signals were compared to the original noise recordings for the ten flyover noise of A109 helicopter from

AgustaWestland. The tests were performed on a small scale by three experienced listeners. To each of them was given the opportunity to replay the sounds several times and concentrate on shorter time segments and specific frequency bands. The results of the jury tests were very satisfying. For most of the sound samples, none of the listeners heard a difference between the original and synthesized sounds. Only the broadband noise modulations were sometimes slightly different at some time steps, but never perceived as "synthetic" or "artificial".
In addition to these tests, psychoacoustic metrics were computed for both the measured and resynthesized sounds. The following four metrics were calculated: Zwicker loudness, Aures tonality, sharpness and roughness. The strong modulations of the vortex broadband noise with extremely high roughness values up to 2 asper at flyover point are clearly very well reproduced.

5. Target sound design

When an accurate approach has been achieved, it can be used for target sound design. A SQE model allows to easily introduce modifications in the sound components and evaluate the impact of such modifications on the sound quality and perception. Due to the simplicity of the model, this sound editing and resynthesis process can be done on-line while listening to the sound.
A large variety of sound modifications can be applied. One can, for example, modify the fundamental frequency, amplitude and inter-phase relations of the harmonic components and evaluate the effect on tonality or pitch. Another interesting example is to apply changes to the frequency profile and modulation strength of the broadband noise and assess these in terms of sharpness and roughness. Also the influence of the ground reflections and interference pattern on the sound perception can be studied which is an interesting study as well. Interesting is also the study of the path influence and the sequence of events in a defined time interval. By playing such sound modification scenarios, acoustic engineers can obtain a much better understanding of the influence and importance of the different sound components. This is a valuable source of information helping them to design target sounds with improved sound quality and suggests engineering guidelines for future rotorcraft design improvements, nevertheless to improve the daily sequence of maneuvers for the heliport.

6. Conclusions

A sound synthesis approach was developed allowing a sound quality accurate synthesis and analysis of rotorcraft flyover operations based on a compact Sound Quality Equivalent (SQE) model that is identified from measured noise recordings on the ground, directivity data and noise propagation models.
For the few helicopter sounds studied so far, very good synthesis results were achieved. For most of these, no differences are audible between the synthesized and measured sounds.
The method allows investigating the impact of noise source components, flight paths and sequencing of maneuvers on the noise environment in heliport communities.

Psychoacoustic evaluations of the noise synthesis results allow setting targets for future rotorcraft designs and optimizing flight paths and heliport operations.
The flyover case discussed in this paper is only the first step of our research work within the JTI Clean Sky Green Rotorcraft ITD project. In a later phase, the presented approach will be tested on more complex flight conditions like approach and take-off which are considered for the trajectory optimization for noise in the Clean Sky project. In particular, the approach condition will be interesting as this is a flight condition where blade vortex interactions (BVI) are generally a major source and causing annoyance for the people on the ground.

7. Acknowledgement

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8. References

[1] J.Gordon Leishman, *Principles of helicopter aerodynamics*, 2002.
[2] M.J.T. Snith, *Aircraft noise Cambridge University Press*, pp. 359, 1989.
[3] K.Jannsens, A.Vecchio, H.Van der Auweraer,*Synthesis and sound quality avaluation of exterior and interior aircraft noise*, Aerospace Science and Technology, Vol.12/1 pp 114-124, DOI :10.1016/j.ast.2007.10.002, 2007.
[4] K.Janssens, H.Coomans, I.Belghit, A.Vecchio, P.Van de Ponseele, H.Van der Auweraer, *a virtual sound synthesis approach for on-line assessment of interior car and aircraft noise*, ICSV Conf., St.Petersburg, Russia, 2004.
[5] Acoustics – attenuation of sound during propagation outdoors – Part1, ISO9613-1, 1993.
[6] D. Berckmans, K. Janssens, H.Van der Auweraer, P.Sas, W. Desmet (2008), *Model-based synthesis of aircraft noise to quantify human perception of sound quality and annoyance,* Journal of Sound and Vibration 311 (2008) 1175-1195.