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MAIN AND TAIL ROTOR INTERACTION NOISE DURING HOVER AND LOW SPEED CONDITIONS

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SUMMARY

Interaction noise - the most dominating source in the wide spectrum of helicopter noise - is for most rotorcrafts a by-product of certain flight conditions. This paper deals with flight conditions, such as hover flight under the influence of light wind and partial power descent, at which impulsive noise signals were recorded. Major emphasis in this paper, however, is on impulsive noise during hover flight under light wind. It was observed during experimental investigation with the BO 105, that wind speeds of less than 10 knots can already initiate extreme interaction noise. Noise signatures indicate, that the interaction sound originates not only at the main rotor, but also at the tail rotor.

The analysis of the recorded noise signals clearly identified up to about 20 tail rotor harmonics for tail rotor interaction noise, and more than 50 harmonics for main rotor impulsive noise. The weighted noise level was, according to the high harmonic content of this interaction noise, equally effected. Differences of up to 17 dBA and 14 PNdB were recorded in hover.

The paper presents further a measured spectrum of a BO 105 in partial power descent and shows that this interaction noise, resulting from a main rotor blade intersecting the tip vortex of a preceding blade, is of much lower frequency content, than that for the hover case.

1. INTRODUCTION

The helicopter rotor operates, as a result of the immense performance versatility of today's modern rotorcraft, in a very complex aerodynamic environment. The nonuniform inflow - as experienced by the main and tail rotor blade in forward flight and especially during the various maneuvers - is responsible for the broad frequency content of a helicopters noise spectrum. These spectra range from the low fundamental main rotor blade passage frequency to the very pronounced discrete frequency peaks of interaction noise and up to the high frequency broad band or vortex noise. The most dominating sound source is - when it occurs - the impulsive interaction noise, which is often referred to as blade slap or rotor bang. This slapping sound is, however, for most helicopters only an undesired by-product of certain flight conditions. Partial power descent, extreme banked turns, high speed trimmed level flights as well as hover conditions influenced by light wind are expecially susceptible to blade slap.

Recent investigations on impulsive noise at MBB, sponsored by the Ministry of Defence of the Federal Republic of Germany, were almost intirely restricted to experimental work. Some of these results concerned with the above mentioned flight conditions are presented in this paper. However, since blade slap in general has been treated frequently in the literature, major emphasis will be on main/tail rotor interaction noise in hover flight under light wind. The experimental investigations have shown, that wind speeds of less than 10 knots can initiate extreme interaction noise. Other flight conditions where impulsive noise was recorded, find just brief attention in this paper and are only employed for comparison.

The frequency range in which amplifications of the discrete tones for various interaction conditions occurred are of primary interest, since this is especially for the evaluation of weighted sound levels of importance. Existing noise rating units, such as PNL and dBA, quantify the subjective effect of impulsive noise more appropriately if it dominates a relative high frequency region.

2. BACKGROUND INFORMATION

Impulsive sound gained in recent years due to its very annoying effect special interest and attention in the literature. Many of these investigations were based on experimental work [1][2] with model rotors. These tests under laboratory conditions are extremely useful for the basic understanding of rotor noise generation, since individual sound sources at full scale helicopters are often masked by other noise components.

Other investigations are based on the analytical modeling of blade-vortex interactions, which is, besides compressibility effects, in most cases the cause for the slapping sound. The non-uniform inflow produced by this interaction generates high blade loading harmonics. The harmonic drop-off becomes extremely slow. Wright [3] indicated first, that these higher loading harmonics are very efficient sound radiators which may completely mask the noise due to steady loads. Unfortunately, up to this date it is impossible to predict accurately enough the higher harmonics. The lack of theoretical methods to determine the load fluctuations is a major obstacle in predicting the radiated sound pressure. The phenomenon of blade and tip vortex interaction is still to difficult to describe mathematically. However, the basic mechanism of this interaction is well known and should at this point be briefly recapitulated.

A lifting surface, such as a rotor blade generates a distinct vortex at its tip. Before this trailing vortex can dissipate due to viscous action the following blade will cut through or pass by the vortex, depending on its path. The resulting momentary changes in the velocity are responsible for impulsive unsteady loadings on the intersecting blade section which gives rise to higher frequency blade stresses, to blade fatigue life, to structural vibrations, and to the sharp cracking sound known as blade slap. The intensity of this annoying noise depends on the magnitude of the fluctuating load, as well as the time duration of the intersection. The time-rate-of-change of the blade loading is the deciding factor for the frequency range dominated by interaction noise. The time-rate-of-change depends on the vortex core diameter, intensity, position, and distance of the vortex relative to the blade as well as on the angle of intersection. It can be seen from

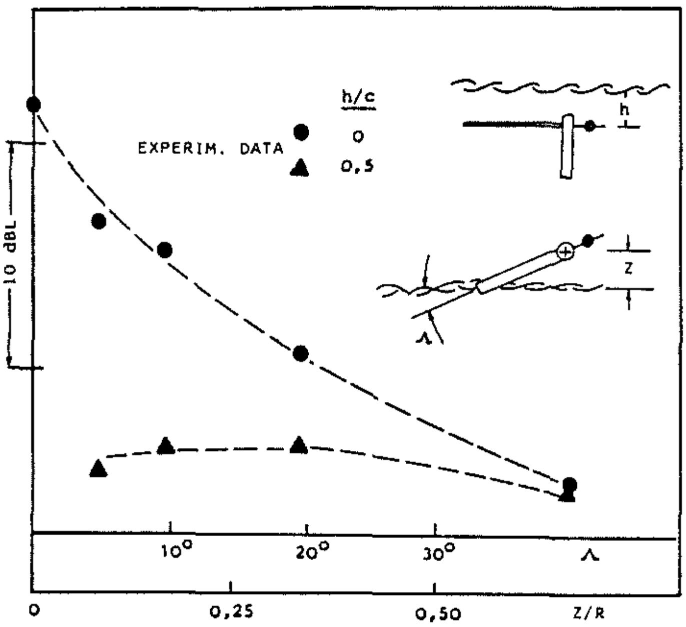

Figure 1 Isolated Blade-Vortex Intersection and its Effect on the Sound Pressure Level

Figure 1 that due to the skewness of blade vortex interaction (Λ > O), every section of the blade intersects the vortex at a *different time*. As a result of this 'time-lapse' a non-uniform pulse is produced in the radial direction of the blade, meaning, that every small radial blade increment generates noise at a different increment of time. Consequently, the impulsiveness and therefore intensity reaches a maximum when the intersecting angle is equal to zero (Λ = O), a situation which might occur with tandem helicopters, but also at main/tail rotor interactions. A major segment of the blade intersects in this case the vortex simultaneously and as these model tests [4] with an isolated tip vortex demonstrate (Figure 1), increase the sound level tremendously.

3. MAIN/TAIL ROTOR INTERACTION IN HOVER

It is often observed that the sound emission of a hovering helicopter varies enormously when the rotorcraft changes its relative position with respect to the observer. Of course, the directivity pattern of the tail rotor and maybe some pilot control adjustments in order to stabilize the hover position will contribute their part. However, recent investigations with the hovering helicopter BO 105 have shown, that a sufficient wind speed can initiate already severe main/tail rotor interactions. Figure 2 shows three time histories of a hovering BO 105 recorded at a fixed position but with different helicopter positions relative to observer and wind direction. Since blade slap occurs at the rotor blade passage frequency, the origin of the noise signals reproduced in Figure 2a can clearly be identified as tail rotor impulsive noise and the signals in Figure 2c as main rotor slap. The third trace (Figure 2b) represents the pressure amplitude/time trace of the non-banging helicopter. As mentioned before, all three traces are recorded at the same observer position and for the same helicopter, only the rotorcraft did rotate counter-clockwise in steps of 90°.

These time histories do propose that the wind was sufficient to blow the tip vortices of the main rotor into the tail rotor, or vice versa, depending on the relative wind direction. Bausch et al [3] encountered also impulsive noise in hover for certain aircraft headings with respect to the wind. They did simultaneous blade loading and noise measurements in order to localize the azimuthal interaction position. Continuous main rotor slapping was experienced only in one helicopter position and only here they observed in a small azimuthal region rapid blade load fluctuations which were caused by the interaction with the tail rotor's shed wake. However, they did not mention whether tail rotor impulsive noise signals were also recorded.

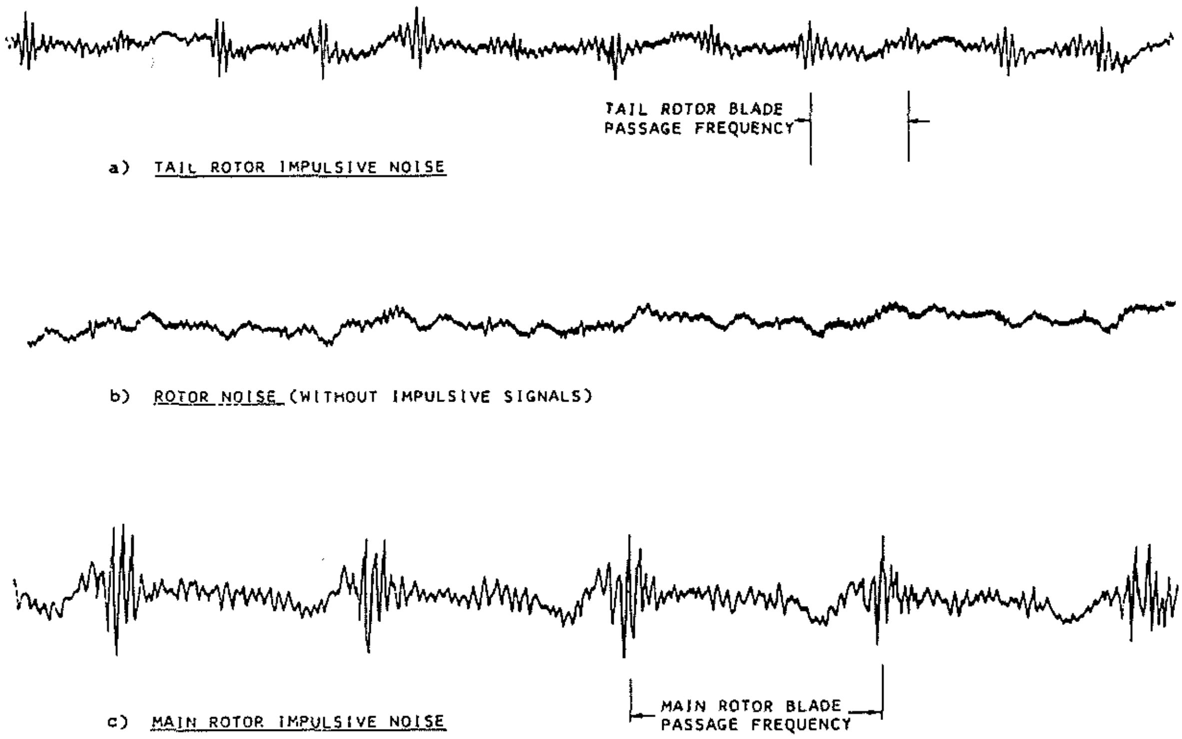

Figure 2 Time Histories - Measured During Hover Under Light Wind

Impulsive tail rotor noise, as illustrated by the time history in Figure 2a differs subjectively when compared with the slapping sound of the main rotor. It seems that the 74 pulses per second aren't perceived by the human ear anymore to such a degree as the 28 pulses of the main rotor. The different pulse sequence distinguishes the 'banging' main rotor clearly from the more 'buzzing' or 'burbling' sound of the tail rotor.

Blade-vortex interactions between two rotors of different rotational frequencies and with different number of blades do experience certain phase shifts from interaction to interaction. If we would focus on the position where main and tail rotor blade tips are closest to each other, we would notice that always 2 or 3 tail rotor blades would pass this point before the next main rotor blade tip appears. Identical main/tail rotor blade positions relative to each other for the BO 105 are repeated at a ratio of ≃ 3R/8T. This means, that under ideal test conditions every 8th tail rotor impulse should be identical. This was not the case and it wasn't expected either, since these measurements were not performed under laboratory conditions.

Nevertheless, a certain consistancy was noticable, groups of sometimes two or three pulses were observed, alternated by a complete omission. This is explainable by the previously mentioned ratio; every time a main rotor blade tip vortex passes through the tail rotor disc there will be a group of intersections followed by a time delay before the next vortex reaches the tail rotor disc. It also should be kept in mind, that every intersection takes place at a different radial and azimuthal position producing varying pulse amplitudes (see Figure 1).

A complete summary of the BO 105 sound pressure measurements in hover are shown in Figure 3. The distance between helicopter and microphone as well as the wind direction are indicated. The helicopter rotated during these tests in steps of 45^{O} relative to the observer, as pointed out by the small helicopters in Figure 3. A small portion of the corresponding pressure amplitude/time trace is also shown. This illustration pictures once more very clearly the rotorcraft positions were impulsive noise was recorded. The included noise levels prevail the immense influence of the interaction phenomenon on unweighted and especially on weighted sound pressure levels. This effect will be discussed in detail in the following sections.

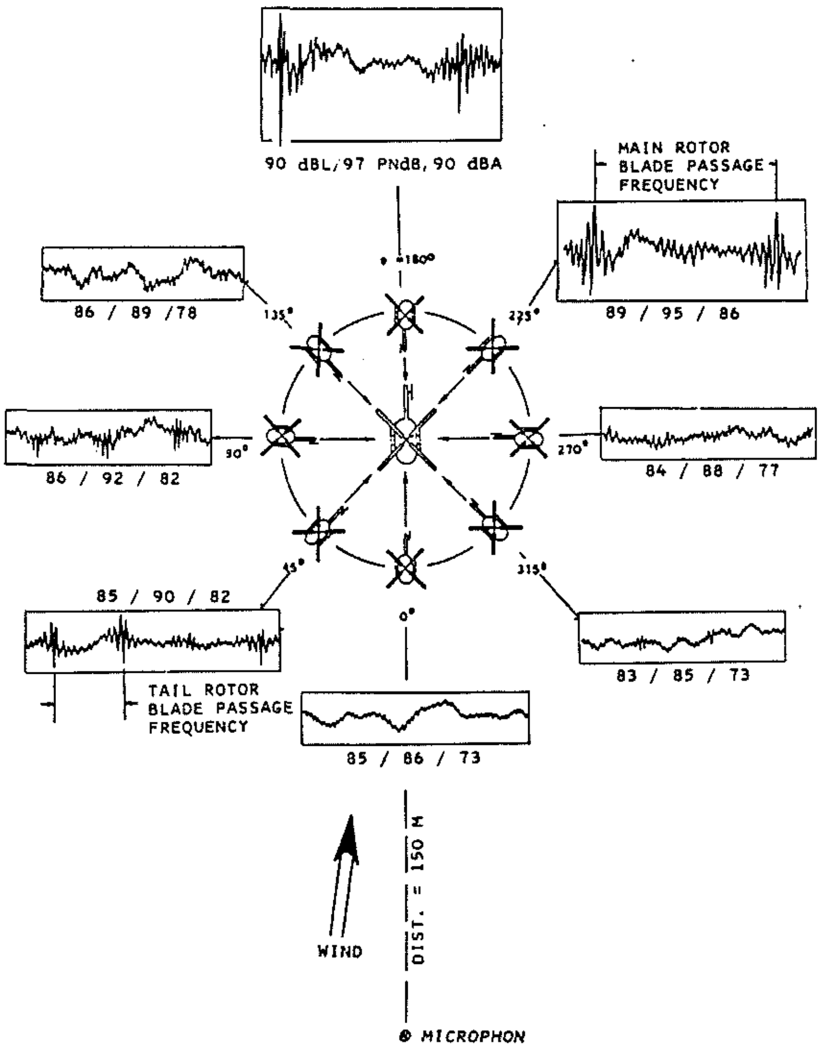

Figure 3 Time Histories for Various Helicopter Positions Relative to Observer and Wind Direction - Hover Under Light Wind

4. DATA ANALYSES

For the tests described in this paper a portable Nagra Tape Recorder Type IV with a built-in amplifier was used. Connected to it was a precision sound level meter Type 2203 of Bruel and Kjaer with an attached 1" condenser microphone.

The recorded sound pressure time histories were digitised and then analysed with the MBB digital analysing program "Harma". The program enables the calculation of narrow band, octave band, and 1/3 octave band spectra. The overall levels are given in dBLin and PNdB. A band width of 2.5 and 5 Hz, respectively, was chosen for the narrow-band analysis, which in this paper were all performed with some spectral smoothening.

5. EXPERIMENTAL RESULTS

5.1 Tail Rotor Impulsive Noise

As we have seen, tail rotor impulsive noise in hover can be initiated when the wind is sufficient to blow the main rotor wake into the tail rotor disc area. The analysis of a corresponding time history, shown in the upper trace of Figure 2, is illustrated in Figure 4 as a narrow band frequency spectrum. A logarithmic frequency scale has been chosen here - as very often done with helicopter spectra - because it not only compresses the whole rotor spectrum but it also reveals certain acoustic trends. Very pronounced is the frequency range between 800 and 1200 Hz, a range which is usually dominated by lower level broad band noise, however, the individual spikes indicated in this spectrum contain high harmonic discrete frequencies.

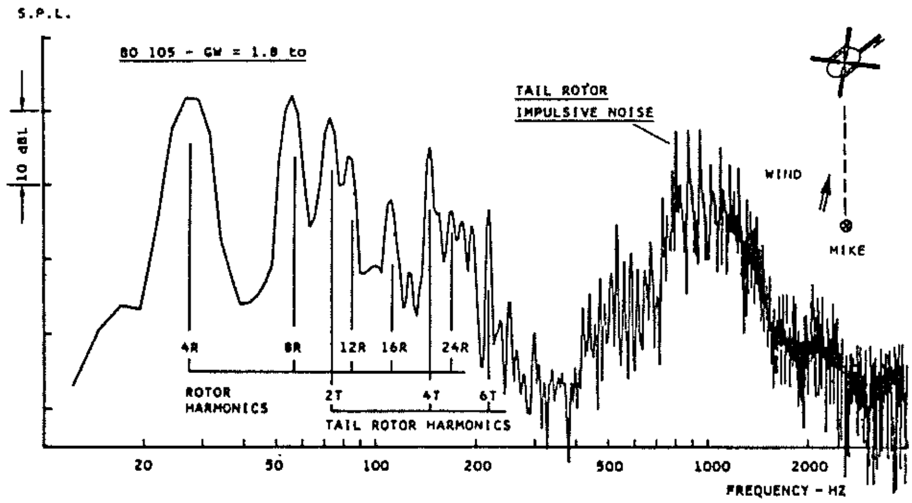

Figure 4 Narrowband Analysis: Tail Rotor Impulsive Noise - Hover Under Light Wind

The spectrum of Figure 4 is once more shown in Figure 5, but now with a linear frequency scale. This picture reveals very distinct tail rotor harmonics which up to about the 20th are clearly identifiable. The magnitude of the most pronounced spikes is almost comparable to that of the tail rotor fundamental. Interesting is also a comparison of the overall noise level with those of non-impulsive sound pressure time histories (Figure 3). The difference in dBLin overall noise level is almost neglectably small, whereas the dBA level is almost 10 dBA increased due to the tail rotor impulsive sound.

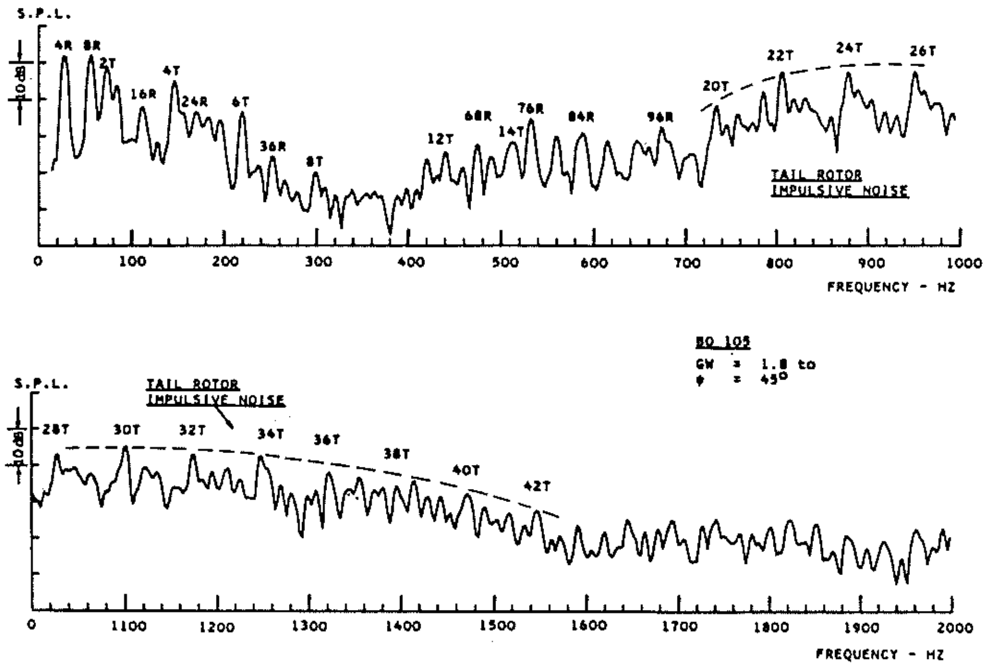

Figure 5 Narrowband Analysis: Tail Rotor Impulsive Noise - Hover Under Light Wind

5.2 Main Rotor Impulsive Noise

After rotating the rotorcraft by about 180 degrees relative to the wind direction, main rotor impulsive noise - as seen in Figure 3 - was recorded, proposing, that the tip vortices of the tail rotor blades intersected now with the main rotor blades. Corresponding narrow band spectra are shown in Figure 6a and b. The character of the spectra differs in the region which is dominated by the rotor impulsive noise (RIN) tremendously. The spectrum in Figure 6a is very peaky around 700 Hz, whereas in Figure 6b amplification of discrete frequencies are noticable in a broad band between 700 and 1200 Hz. Up to 40 high amplitude harmonics were recognized in this picture.

Further measurements were performed with a second helicopter at the same day under similar wind conditions. The gross weight was 2.3 tons instead of the 1.8 tons and the tail rotor was furnished with a cambered airfoil instead of the standard NACA 0012 profile. Again, extreme rotor impulsive noise signals were recorded. It seems interesting here, that the frequency region dominated by the impulsive sound was still considerably higher than in previous spectra. Up to about 60 main rotor harmonics are clearly identifiable on the linear frequency scale in Figure 7. There are several reasons which could have led to this high harmonic order. The increased gross weight of the rotorcraft requires, especially in hover condition, a higher tail rotor thrust which again leads to an increased tip vortex intensity. Of influence could also have been the cambered tail rotor profile. A further explanation would be, that the wind direction and intensity between the individual tests changed slightly, thus influencing the angle of intersection between tail rotor tip vortices and main rotor blades (see Figure 1). However, all these are assumptions and only controlled test under laboratory conditions could answer the question why the frequency region, dominated by the interaction phenomenon, varies to such a degree. This variation is illustrated once more in Figure 8, where all three spectra are shown as 1/3 octave band spectrum. The influence on the dBLin and the perceived noise level is also indicated.

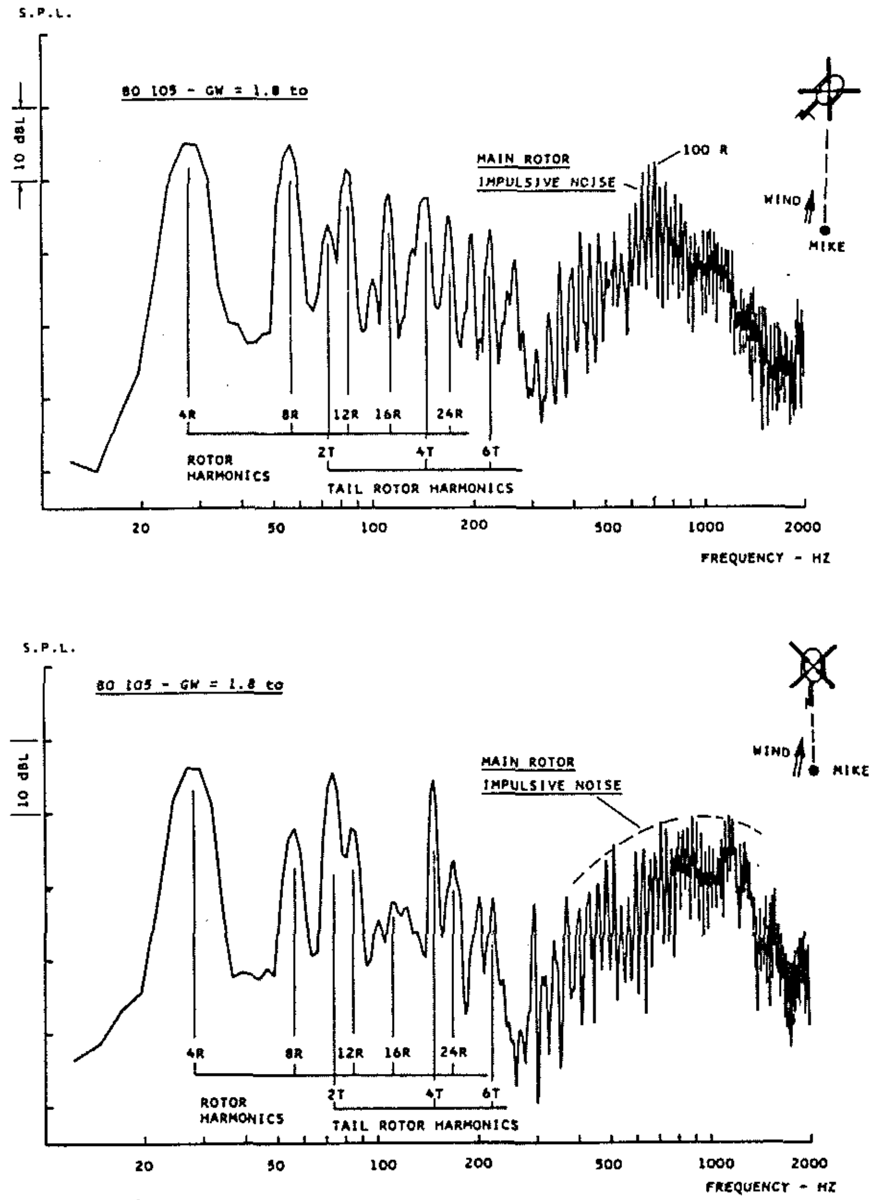

Figure 6 Narrowband Analysis: Main Rotor Impulsive Noise - Hover Under Light Wind

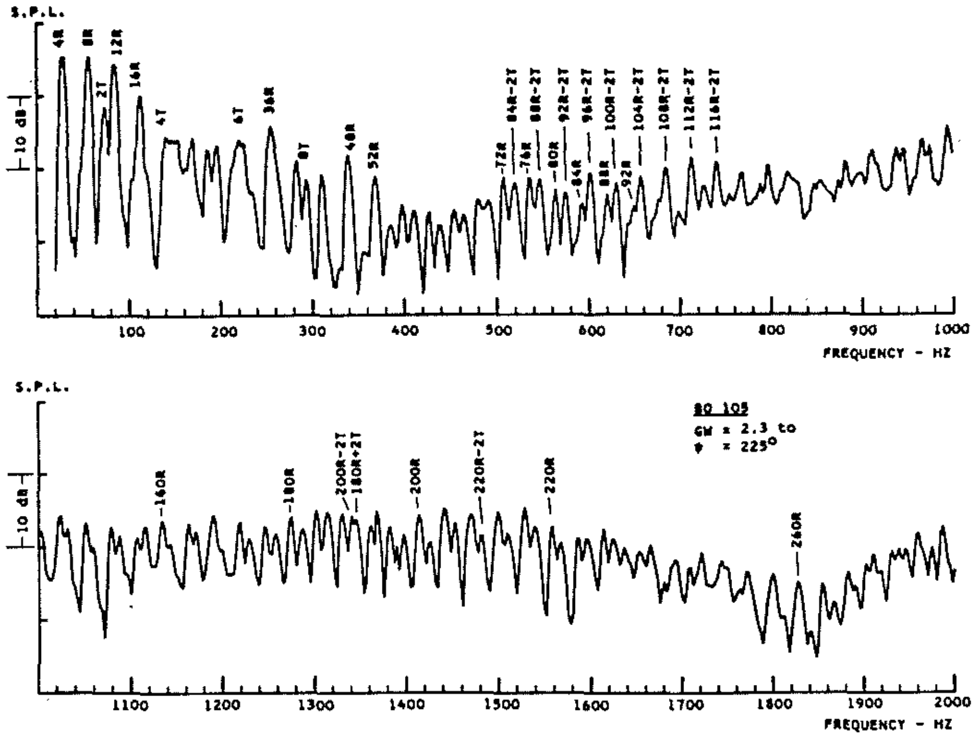

Figure 7 Main Rotor Impulsive Noise - Hover Under Light Wind

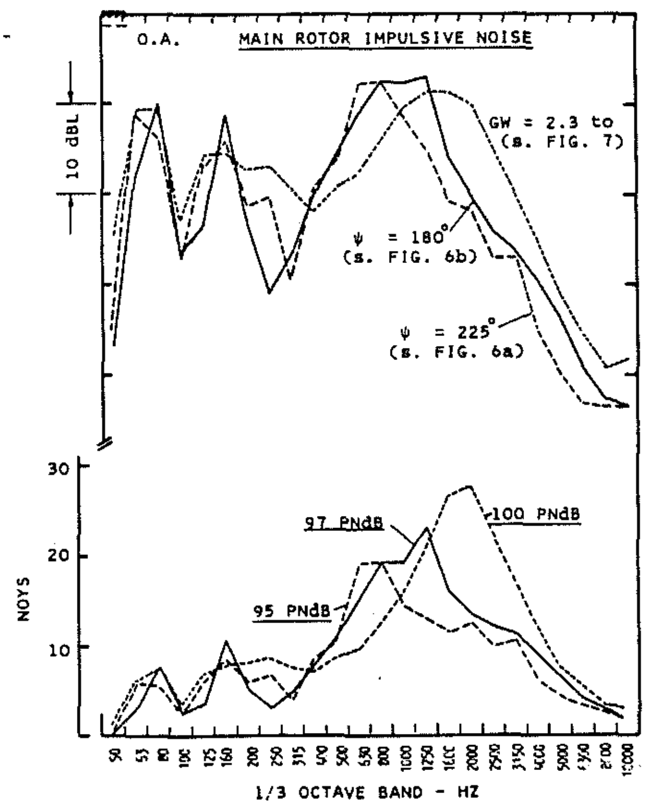

Figure 8 Various Frequency Regions Dominated by Main Rotor Impulsive Noise

Typical for main/tail rotor interactions are the very distinct discrete but non-harmonic peaks. These peaks are modulation frequencies which are combinations of main and tail rotor harmonics. High amplitude non-harmonic discretes, with an almost constant repetition frequency, can also be seen in Figure 7. Interesting is that they repeat almost solely at 4nR - 2T and only a few spikes are at 4 nR + 2T noticable. About non-harmonic discrete frequencies was also in a recent paper by Leverton [6] reported, which dealt with main/tail rotor interaction during high speed forward flight.

5.3 Acoustic Waveform

It was not the objective of this paper to present any detailed analysis about the origin of the rotor impulsive noise signals, merely a presentation of experimental interaction data for various flight condition was intended. However, a brief look at some acoustic waveforms should give at least speculative information.

Since the frequency region dominated by rotor impulsive noise differed in Figure 6 and 7 to such a degree, the respective acoustic pressure traces are presented in Figure 9. Comparing the individual pulses, it becomes obvious, that trace 9c contains the highest frequency sound since it exhibits by far the sharpest spikes. The pulse duration is about 0.5 ms when measured from peak to peak and it is this time-rate-of-change in acoustic pressure (dP/dt), which is the determining factor regarding the frequency range dominated by rotor impulsive noise.

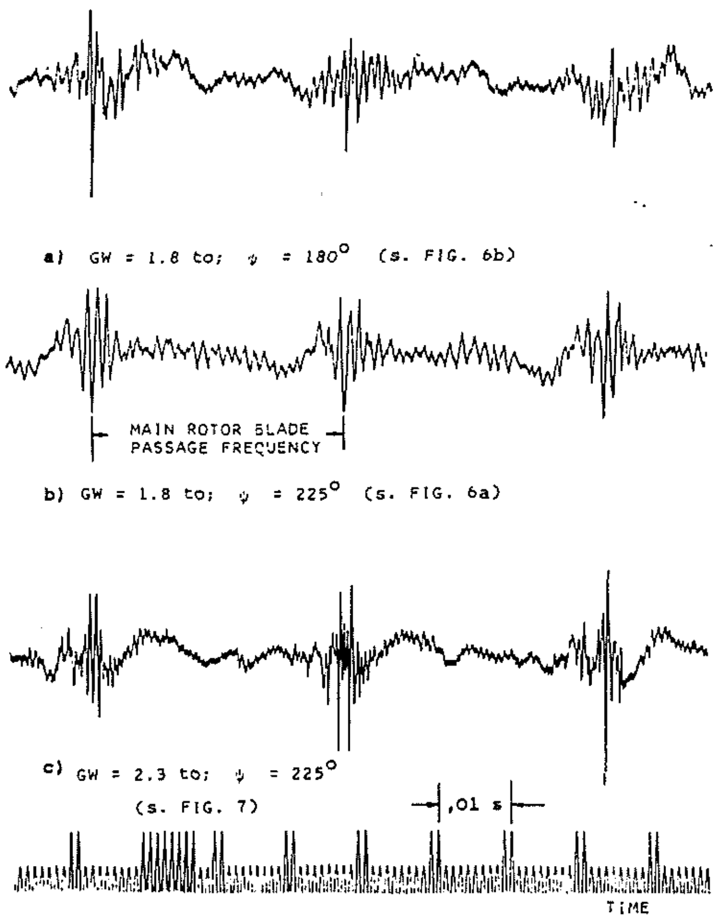

Figure 9 Acoustic Waveforms - Main Rotor Impulsive Noise

The pulses, as seen in Figure 9, are made up of groups of major spikes; any statement regarding their origin is again purely speculative. Measurements of isolated blade-vortex interactions under laboratory conditions did exhibit always one impulse, and only when the core itself was intersected two spikes became visible [7]. One assumption regarding these spikes would be, that the main rotor blade intersects at different radial stations with more than one tail rotor blade vortex. Local shocks initiated by blade vortex interactions can cause pressure fluctuations at the blade, however, the shock itself should not be able at $M_{tip} = 0.65$ to radiate into the far acoustic field. The hypothesis of Boxwell et al [8] that the negative pressure pulse is related to compressibility is regarding these conditions questionable.

5.4 Low Speed Descending Flight

Impulsive rotor noise can often be heard when helicopters are in a low speed descending flight path. The sound emitted at certain flight path angles is attributed to the interaction of the main rotor blade with the tip vortex of the preceding blade. Several investigations have been performed in order to determine the severity of this impulsive noise with respect to the flight path angle. Measurements of this kind were also conducted with the helicopter BO 105. One of these analysed narrow band spectra is presented in Figure 10. Comparing this spectrum with those of the main/tail rotor interactions, one can see, that the frequency range dominated by the impulsive noise is here considerably lower.

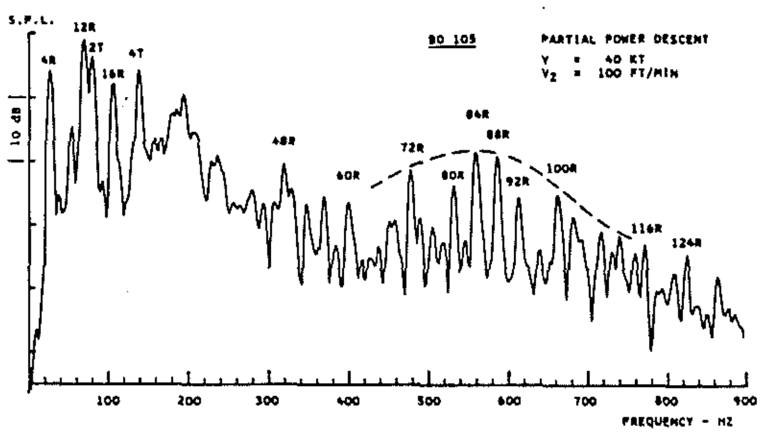

Figure 10   Narrowband Analysis - Impulsive Noise During Partial Power Descent

The frequency range is of major importance in regard to the rating of aircraft noise. Current methods do not distinguish between broad band jet noise and impulsive rotorcraft noise, so that the slapping sound of a helicopter is thus only rated to an adequate extend, when it dominates the spectrum in a high frequency range.

6. SOME THOUGHTS ABOUT HELICOPTER NOISE RATING

It is well known that conventional methods of weighting aircraft noise are inadequate to account for subjective annoyance when the sound is dominated by impulsive noise. Experimental studies were conducted by several investigators [9][10] in order to determine a correction factor with respect to the subjective annoyance. These attempts have shown that impulsive helicopter noise could be quantified by the use of a so-called 'Crest Factor'. The crest factor is measured as difference between the peak of the impulse and the general level of normal helicopter noise.

Investigation by Leverton [11] have shown, that typical bang durations are in the order of 4 ms. This observation justified the statement in Ref.11 that the bang energy could be isolated in a relative narrow band between 100 - 400 Hz, and that this frequency region would be sufficient to determine the crest factor. However, returning to the previously discussed main/ tail rotor interactions during hover condition, bang duration of around 1 ms were observed which subsequently shifted the impulse energy into higher frequency regions. This effect is illustrated in Figure 11, where the unfiltered time history (trace a) is compared with the 100 - 400 Hz band limited signal

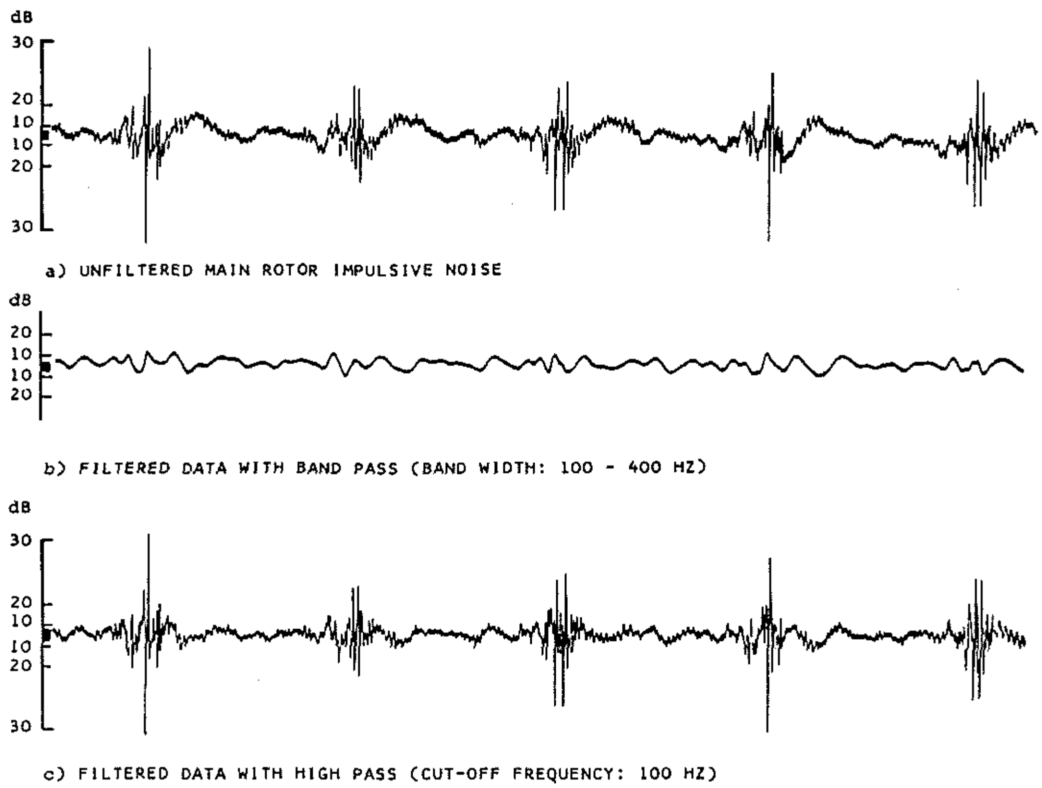

Figure 11 Unfiltered and Filtered Time Histories - Main Rotor Impulsive Noise in Hover

(trace b). The interaction pulses are almost completely filtered out in trace b, which suggests, that the determination of the crest factor can in general not be limited to this frequency band. Instead, an acoustic pressure amplitude/time trace has to be chosen which doesn't alter the peak amplitude. Filtering only the signal below 100 Hz - the low frequency main rotor noise - should therefore give a more appropriate measure of the crest factor in regard to Leverton's proposal.

It should be kept in mind, that these attempts to correct impulsive noise arose out of a situation where blade slap dominated a relative low frequency range. The influence on weighted sound levels was for these cases, despite a very noticable subjective effect, only in the order of about 1 to 3 PNdB. However, the situation changes significantly when the energy of the impulsive signal, due to a shorter pulse duration, is concentrated in a higher frequency region. This is illustrated in Figure 12 where 1/3 octave band spectra with and without impulsive main/tail rotor interaction noise are compared. Portions of the respective time histories, which are identical to those in Figure 3, $\psi = 180^{o}$ and $\psi = 315^{o}$, are also shown. These spectra reveal a measured difference of 17 dBA. This immense difference is due to the fact that the pulse energy is concentrated around 1000 Hz. If we now assume that the crest factor remains constant but the time duration of the impulse changes, than a subsequent shift of the bang energy into a lower frequency range will follow (see dotted line in Figure 12). The result would be an increase of only 5 dBA in comparison to the non-banging noise spectrum. This raises the question, whether a correction of impulsive

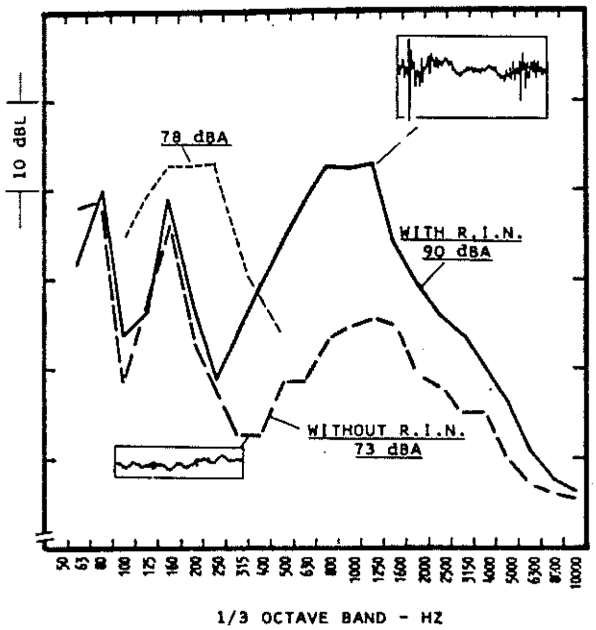

Figure 12 Frequency Range Dominated by Rotor Impulsive Noise and its Effect on dBA

noise is still necessary when it dominates a frequency range, which is already very sensitive to dBA and PNL weighted noise levels. Perhaps a correction factor with frequency dependence would be a more correct approach. This, however, can only be determined through further subjective annoyance tests.

In order to show the full scale of fluctuating sound levels measured during these impulsive noise tests in hover, all dBLin, dBA and PNdB results are compiled in Figure 13a and 13b. As already indicated in Figure 3 the helicopter was rotating in steps of 45° relative to a fixed microphone position and of course relative to the wind. Both pictures indicate a max. difference of 17 dBA between the banging and non-banging rotor, whereas only a fluctuation of about 7 dBLin were recorded.

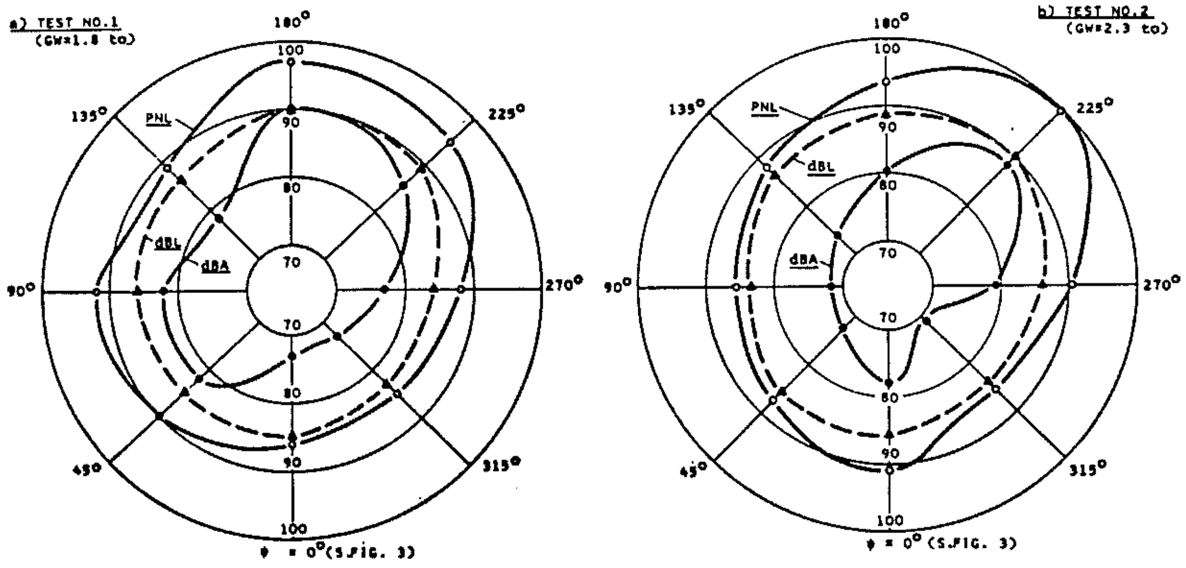

Figure 13 Sound Pressure Levels of a Hovering Helicopter Under the Influence of Wind - Fixed Microphone Position, Helicopter Rotated in Steps of 45°

The following maximal differences in sound pressure levels were measured:

a)	GW	=	1.8 to		b)	GW	=	2.3 to	
	ΔdBL	=	7	dB		ΔdBL	=	7.5	dB
	ΔdBA	=	17	dB		ΔdBA	=	17	dB
	ΔPNL	=	12	PNdB		ΔPNL	=	14	PNdB

Interesting is, that the dBA and PNL curves (Figure 13) are of similar shape, this however, was already noticed by Ollerhead [12], who found very little differences among various rating units including PNL and dBA.

The above mentioned differences of up to 17 dBA in hover illustrate the importance of reducing interaction noise. Interactions between main and tail rotor are also very common in forward flight, where the wake of the main rotor is blown,due to the translational speed of the helicopter,into the tail rotor disc area.

Two possible ways of reducing these interactions could be mentioned:

- first by passive means, such as shielding off the tail rotor in order to prevent the main rotor wake from interfering with the tail rotor

- second by active means, like the noise attenuation at the source itself - the blade tip. Special advanced tip configurations can influence the intensity and geometry of the tip vortices and thus reduce the impulsiveness of the interaction itself. Reduced impulsiveness has also its effect on structural vibrations.

7. CONCLUSION

The following conclusions can be drawn from these experimental investigations:

- Wind speeds of less than 10 knots can lead to severe impulsive noise during hover. Recorded time histories indicate that the acoustic pressure signals originate at the main rotor as well as at the tail rotor, depending on the helicopters position relative to the wind.

- Typical pulse durations in hover are in the order of 1 ms. Subsequent frequency ranges dominated by impulsive noise are considerably higher than for a comparable slapping helicopter in a low speed descending flight.

- The weighted noise level is according to the high harmonic content of these main/tail rotor interactions equally affected. Differences of up to 17 dBA and 14 PNdB are recorded in hover.

- The high sensitivity on weighted noise units raises the question, whether a correction of impulsive noise is still necessary when the pulse energy is concentrated in a relative high frequency range. A correction factor with frequency dependence would be a more appropriate approach.

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