Next generation Aircraft - A challenge for Interior Acoustics Developments

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ABSTRACT

Beside several comfort factors and economic value improvement the aircraft interior noise is of high interest and appears as a differentiating factor of attractiveness for airliners. Since the past decades the focus on noise metrics was set on quantified levels such as A-weighted sound pressure level and speech interference level, today consideration of the pleasantness of interior noise becomes essential to achieve an optimal acoustic design. In parallel there is a strong technology evolution of the propulsion systems, the structure, system and the interior trim designs, which raise new challenges. Several studies have been conducted to understand the perception of aircraft interior noise characteristics and significant difference in the perception has been obtained with no impact on conventional metrics. Accordingly it is essential to understand the excitation, its coupling into the fuselage and the transmission in detail in order to derive efficient noise control measures! To come to this deep understanding only by flight test is impractical therefore it is necessary to reproduce the inflight situation in the laboratory under controlled conditions.

Keywords: Passenger Aircraft, Cabin Noise Comfort, Perception, Acceptance, Preference, Noise Reduction Means, Cabin Noise Prediction

1. Evolution of Cabin Noise in Passenger Aircraft

Cabin noise in passenger aircraft is a one of the comfort parameter, which creates straightaway discomfort when exceeding personal thresholds. In the begin when long distance air travel became affordable with larger propeller aircraft, such as Lockheed Super Constellation, Tupolew TU-114 or Boeing 377 Stratocruiser, passengers were exposed to very high noise levels around 90dB(A) to 105 dB(A). Sometimes thousands of kilograms of noise control measures were installed to lower the sound pressure levels especially from the low frequent propeller tones. With entering into the jet-age by mid of the 1950 years with the first generation of turbo jet engines, the cabin noise was somewhat reduced by ~5dB and the spectrum changed from low frequency tones to low-to-mid frequency broadband noise. Aircraft like De Havilland Comet, Convair CV880, Boeing 367, McDonnell Douglas DC-8, Sud Aviation Caravelle and Tupolew Tu- 104 impressed the new cabin noise standard with levels around 85dB(A) to 90dB(A) depending on the location. Not until the second generation of fan jet aircraft like Boeing 707, 727 or DC-9 in the mid-1960s the cabin noise levels further dropped to 83 - 85dB(A). Since then engine and aircraft manufacturer were developing steady improvements on turbofan with higher bypass ratios and improved noise treatment concepts to significantly reduce fuel consumption while maintaining low weight. Now as we have reached a noise floor between 74dB(A) and 80dB(A) the question, whether the noise levels needs to be further reduced, is frequently occurring. The following chapters shall bring some new light to this question.

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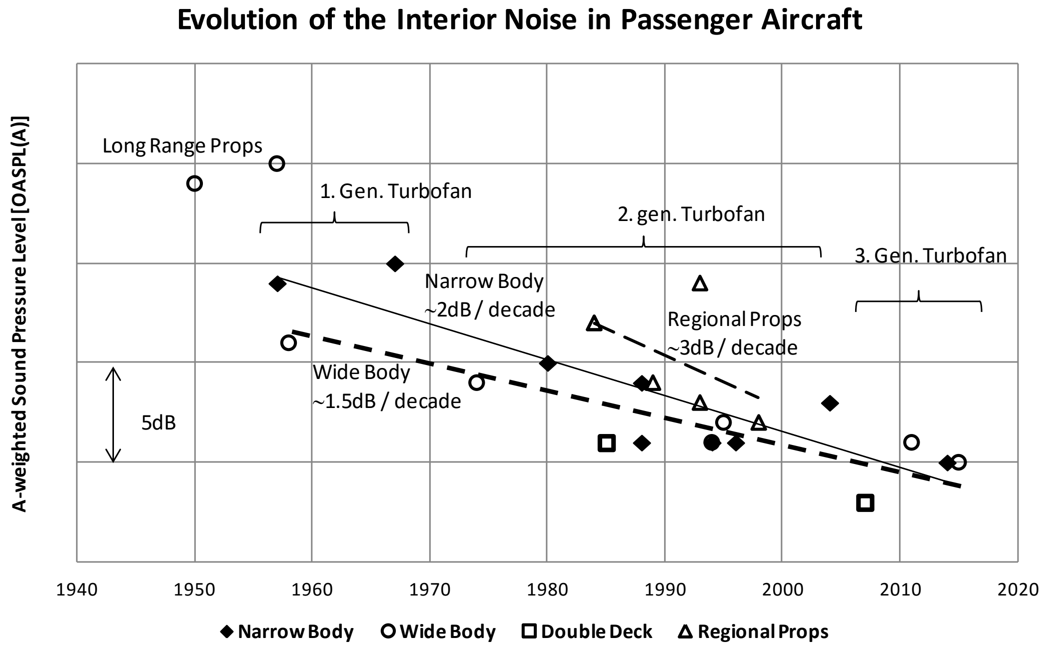

Figure 1: Evolution of cabin noise in passenger aircraft

In the first paragraph the general characteristics of cabin noise is introduced. Following a global outline of the overall cabin noise comfort in the second paragraph some aspects of noise acceptance are reviewed in detail and the certification aspect is touched with the speech intelligibility. Further a brief instruction on the perception of engine noise signatures is given. Chapter three is finally focusing on the challenges for interior noise development, first with a review on the design of a new speaker type for the passenger address system, and second on the need of new noise reduction technologies and prediction capabilities. Lastly in the conclusion an objective for research and technology developments for next generation aircraft is formulated.

1.1 GENERAL CHARACTERISTICS OF CABIN NOISE

In general the cabin noise varies by the seat position and changes with flight condition. It is driven by several source types, which are transmitted through different transfer paths into the cabin. In the forward area the noise is mainly dominated by the turbulent boundary layer described by pressure vortexes traveling along the fuselage surface. The higher the compression the smaller the vortexes are and the higher the frequency is. This source type is mainly described as structure-borne excitation. Further to the aft cabin the vortexes become larger resulting in lower frequencies. In addition the aftward cabin area is exposed to the engine noise, which mostly can be described as propagating wave sources. The main engine noise sources are known as combustion noise, fan noise, jet noise and shock cell noise. Some are directed forward, such as buzz saw noise, but the majority aftward. As the aircraft is traveling at high speed at cruise altitude the wavenumber is shorten in upstream and lengthen in downstream direction. And due to lower frequency at the aftward cabin the excitation either engine or turbulent boundary layer better matches with the structure trace wave length. In addition aircraft systems produce also a portion of noise in the cabin, which is typically characterized as flow noise from the air conditioning or tonal components from rotating machines like fans, compressors and pumps. One can imagine that each sound is perceived differently and might lead to different cabin comfort and noise acceptance.

In principle the cabin noise of modern turban aircraft is described through broadband noises and characterized by different spectral peaks and slope rates depending on along the cabin length. Three different characteristics are typical; low frequency driven with a peak around 300Hz to 500Hz, mid-frequency accentuated around 600Hz to 800Hz and high frequency pronounced with a plateau between 1kHz to 4kHz.

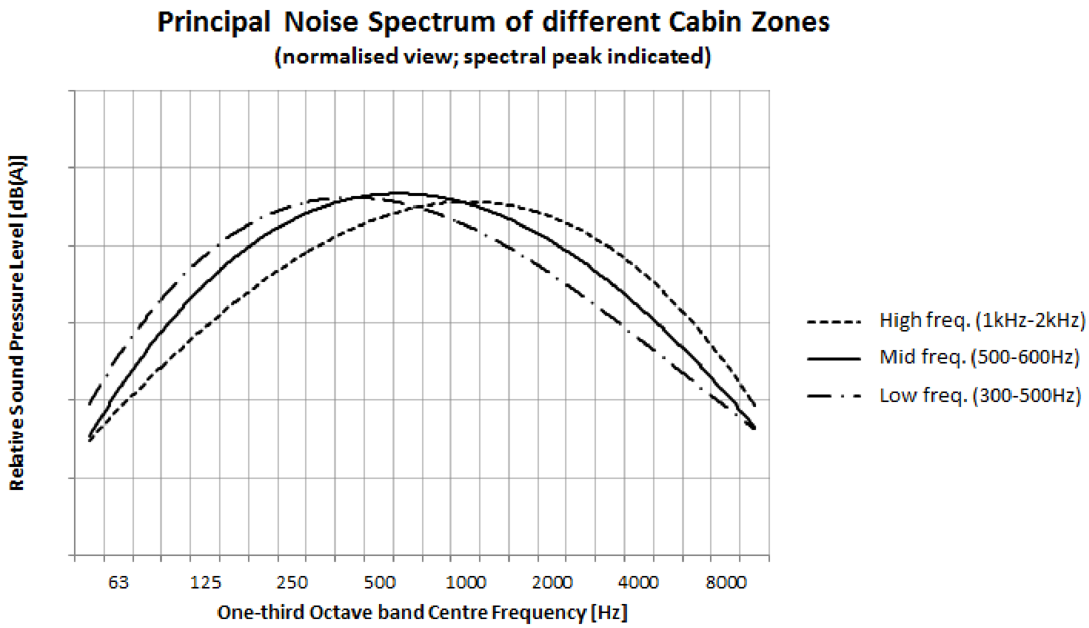

Figure 2: Principle noise spectra in different cabin zones a turbofan aircraft (wing mounted engines)

2. CABIN NOISE COMFORT

When speaking about cabin comfort, several parameters are contributing to the overall well-being. Past studies have shown a minor relevance of noise versus seat pitch, humidity, cabin pressure connectivity, and temperature. As the levels have dropped since the early days of air travel to a level similar than of the car interior or noisy urban residential, the noise is probably accepted because of daily experiences - as long as the exposure time is reasonably short or distracted by activities. In opposite to short haul flights the significantly longer exposure time during long distance flights let passengers rate the noise more relevant.

In preceding studies, conducted within the European joint research project “Friendly Aircraft Cabin Environment, FACE” the overall cabin comfort rating was investigated for different cabin noise levels but constant spectrum of a typical background noise. It pointed out, that the cabin noise is globally rated twelfth out of twenty-nine cabin parameters but does not strongly influence the overall comfort when levels ranging between 72dB(A) and 80dB(A).

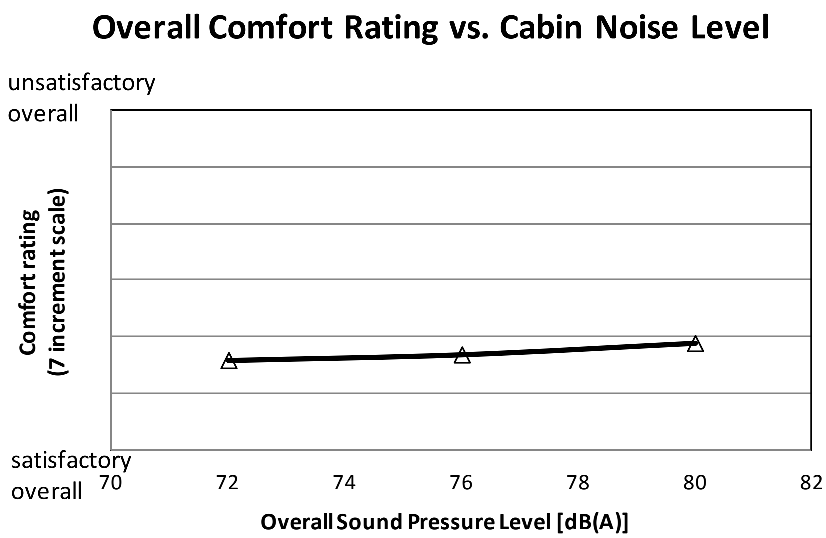

Figure 3: Cabin noise in relation to the overall comfort

When asking the test members about cabin comfort alone the loudness was rated between 4 and 5 on a 7-increment scale from very quiet to very loud and the noise satisfaction was rated slightly below 4.

2.1 ACCEPTANCE OF CABIN NOISE

Other simulator studies, conducted in the European joint research project “Ideal Cabin Environment, ICE” showed the percentage of dissatisfaction in relation to overall cabin noise. Here overall levels between 55dB(A) and 74dB(A) were adjusted having with spectrum taken from three different in-flight measurements. It was shown that the percentage of comfort satisfaction correlates with the background noise level. When increasing the background noise level by approximately 6dB the satisfaction decreases by roughly 10%. An 80% satisfaction was reached with levels around 60dB(A) and still 60% at levels around 67dB(A) to 70 dB(A).

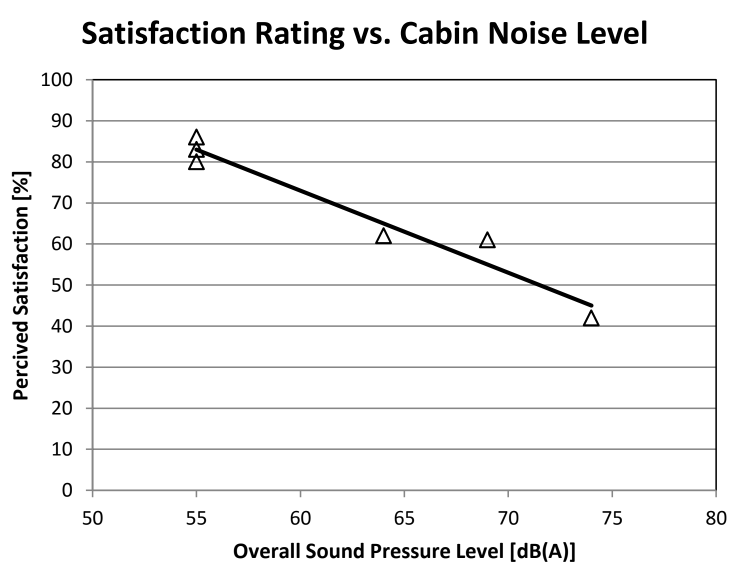

Figure 4: Perceived percentage of dissatisfaction in relation to the overall cabin noise level

These results were in principle agreement with noise acceptance determined from simulator test derived from studies in the German joint research project “Technologies for a comfortable and safe cabin, TeKos”. Here different test signals, derived from in-flight cabin noise measurements at location along the cabin, have been analyzed. The test results showed roughly 15% higher acceptance for cabin area with low frequency pronounced broadband noises than for noises composed mainly of mid to high frequencies. In reverse a 3dB to 4dB higher noise level was accepted for low frequency dominated cabin noise. These results suggest that the cabin noise comfort is to some extend driven by the higher frequency content which could possibly be described by psychoacoustic indicators like sharpness or simply the speech interference level.

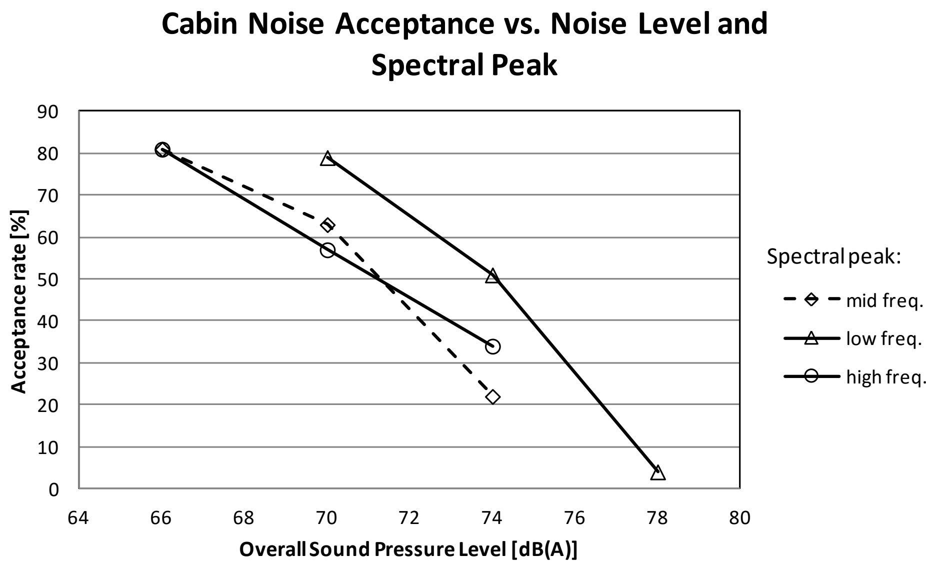

Figure 5: Acceptance of cabin noise in relation to overall sound pressure level and frequency content

2.2 SPEECH INTELLIGIBILITY IN AIRCRAFT CABIN

Beside the comfort, the more important aspect for the cabin noise design is given with the speech intelligibility. For aircraft certification it has to be ensured, that speech announcements from the flight deck and the cabin crew are intelligible during all normal and emergency conditions. Thus some emphasis must be put on the design of the communication systems with respect to the background noise – or wise versa.

In the frame of the German joint research project “Simplified Cabin, SIMKAB” studies have been conducted in a cabin simulator to analyze speech intelligibility with cabin noise signatures similar to a narrow body aircraft. Here the percentage of correct understood words was measured for low and high frequency pronounces typical background noises and signal to noise ratio ranging from -4dB to +11dB. For a signal to noise ratio of 0dB, and a typical background noise level as of today, the percentage of correct understood words is 70% to 90% depending on the background noise signature. While for high frequency contours, the percentage of correct understood words is around 17% lower than for signatures dominated by low frequency but at same overall sound pressure level. For an ~3dB reduced background noise level in the high frequency accentuated cabin area the percentage of correct understood words increases to 90%. The reasons are; one – the noise characteristics correlates with the typical frequency regime of normal speech and two - any speaker has a narrowing directivity with increasing frequency, which leads to good localization perpendicular to the speaker membrane but sidewise reduced levels.

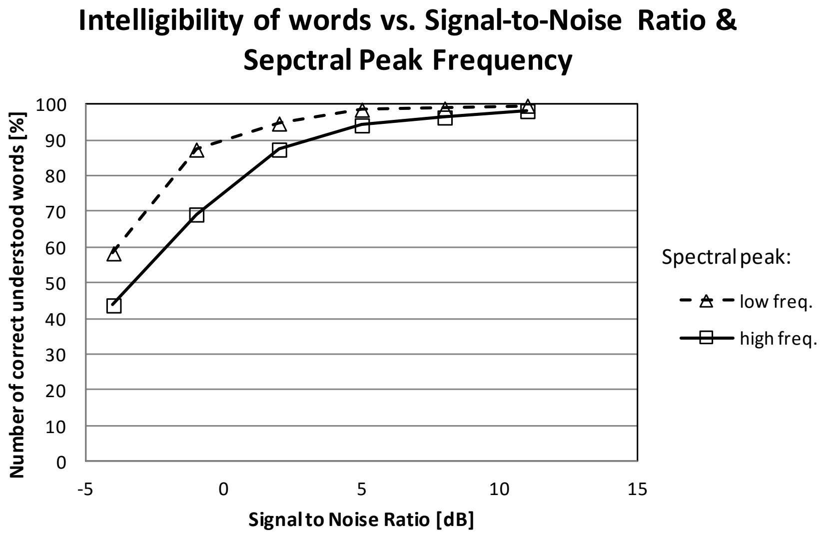

Figure 6: Percentage of correct understood words in ratio to signal to noise ratio for a typical cabin background noise

2.3 PERCEPTION OF ENGINE NOISE

As described in the previous chapters the cabin noise comfort does not necessarily correlate with the a-weighted sound pressure level. It changes significantly for different cabin areas. To know the relevant parameters improving the cabin noise comfort it requires throughout understanding the noise perception beforehand. With respect to engine noise there are two different propulsion systems widely used today to power a passenger aircraft - turbofans and propellers. But there are several other engine configurations and integration concepts rising (or recurring) on the horizon such as ultra-high bypass fans, counter rotating open rotors, improved single propellers, boundary layer ingestion engines and electrical or hybrid powered systems.

Of course it is impossible to investigate on all different types of engines in the same time and quality and thus preceding studies were focusing on the most critical ones. Consequently jury tests have been conducted on several multi-tone noise signatures, which can be used to principally describe the noise signatures of single or counter rotating propellers as well as turbofans with higher bypass ratio. Here the level penalty was measured for equal preference in comparison to a typical broadband background noise in flight. The level penalty is the level difference adjusted by a test member to obtain the same preference as of the reference signal. Two multi-tone signal characteristics, one simple harmonic signal similar to the buzz saw noise and one complex signal similar to counter rotating propeller noise, have been analyzed in comparison to the same reference sound.

The simple harmonic signals were artificially composed of one fundamental tone and its harmonics $f_i = i \cdot f_0$ embedded into a broad band noise. The complex signals were composed of two fundamental frequencies and its harmonics $f_{i0} = i \cdot f_{10}$ respectively $f_{0j} = j \cdot f_{01}$ and combinations of it $f_{ij} = i \cdot f_{10} + i \cdot f_{01}$ but without background noise. All sounds were changed in numerous temporal and spectral aspects such as slope decay rate, f_0, spectral peak / notch, tone structure and emergence.

For the simple harmonic sound, the emergence of the tonal components from the broadband background in terms of a shallower spectral slope (-12dB/octave and -9dB/octave) of the tonal components or an increase in tone-to-noise ratio raised the penalty from -8dB to -12dB. An even shallower slope (-6dB/octave) as well as the amplification of two, the sound characterizing, frequencies led to an increase in penalty to about -25dB. Removing the background noise the level penalty increased to -30dB.

For the complex sound, the amount of high frequency content had the biggest effect on the level penalty values. Removing all high frequency content to a single tone let the jury member adjust the level penalty highest (-30dB). Adding two simple harmonic signals (LP=-15dB) and higher tones the level penalty improved by 10dB. By introducing a steep spectral decay or attenuation of the higher tones, allowed much higher A-weighted levels while remaining equally preferred.

These results suggest that multi-tone signatures are not necessarily perceived similar even the temporal and spectral aspects are similar. Further if sounds composed only of low frequent fundamental tones, like propeller or counter rotating rotors with same blade count and shaft frequency, the level penalty for preference is rated highest. Future engines, integration concepts and associated noise control means must therefore be designed in a way to reduce mid-to-high frequency tones but should not necessarily suppress all harmonics.

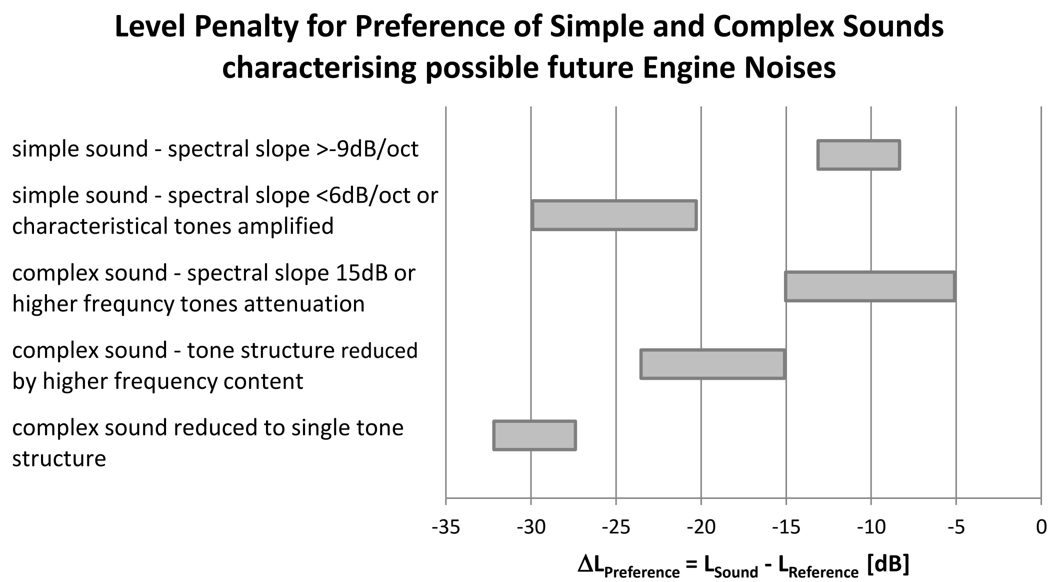

Figure 7: Level penalty for multi-tone propeller and turbofan noise signatures

3. CHALLENGES FOR INTERIOR NOISE DESIGN

3.1 ACOUSTIC DESIGN OF A PASSENGER ADDRESS SYSTEM

Following the challenges to ensure a good intelligibility of cabin announcements and the increasingly stated desire on an improved quality of music playback, a new speaker design was developed for the passenger address system. Therein the above mentioned effect of directivity was specifically addressed, through the development of a distributed mode loudspeaker. During jury tests, conducted in a cabin simulator, the conventional cone–loudspeaker was replaced by a distributed mode loudspeaker and tests have been conducted on syllable intelligibility, rapid speech transmission index and sound comfort. The results pointed out that the new speaker design was much more appreciated for music playback but less for speech reproduction. The test on syllable intelligibility supported the latter with a 20% lower percentage of correct understood syllables. One possible explanation for the lower syllable intelligibility is seen by the reduced locatability in noisy environment of a distributed mode loudspeaker in comparison to a focused cone loudspeaker.

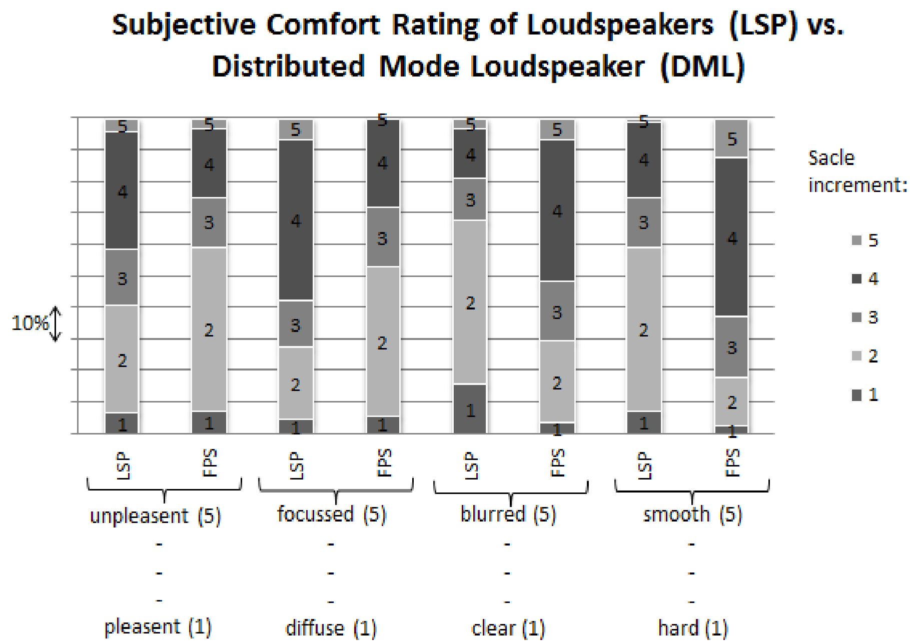

Figure 8: Comparison of the sound quality of a distributed mode (DML) and a conventional cone loudspeaker integrated (LSP) in the passenger supply chain

3.2 INTERIOR NOISE DESIGN FOR PASSENGER AIRCRAFT

Today the cabin noise is specified through quantified parameters such as a-weighted sound pressure level, L(A), and speech interference level, (SIL). As stated in the above mentioned paragraphs the cabin noise comfort does not necessarily correlates with the L(A) and sometimes even not with the SIL. Results from jury tests suggest that other indicators such as tonality, sharpness and roughness, but also temporal indicators like repetition rate better correlates with the perceived cabin noise comfort. However, these first studies do not account for completeness and further investigation are necessary to derive appropriate criteria for the evaluation of the cabin noise comfort. Nevertheless, some first demands for the interior noise design can be derived.

With future propulsion systems, arising in the next decades, the noise characteristic is assumed to change towards more tonal contribution and lower frequencies. Downstream the engine the higher frequency regime will reduce with reduction of shock cell noise due to higher bypass ratio which becomes relevant for the aftward cabin area. Upstream the noise may get higher tone emergence due to shorter inlets and larger fan diameter affecting the forward cabin. Thus the occurring tones may not only be audible during take-off and climb phases but also during cruise. Both aspects have to be taken into account for the development of noise control measures. In consequence passive but lightweight noise control principles are required for low to medium frequency range, which can be adapted to specific characteristics of the propulsion system and problem to be tackled.

3.3 DEMAND ON NEW NOISE REDUCTION TECHNOLOGIES

Today's noise control measures are acoustically designed for mid to higher frequency regime. In addition it has to fulfil requirements such as easy installation, light-weight, low cost and simple maintenance. Therefore the primary insulation made of glass wool is normally used twofold for acoustics and thermal isolation. But due to its lightweight the noise reduction performance of the glass wool has a drawback in the lower and mid frequency regime. Obviously there are other means available such as active controls, heavy layers or constrained layer damping but these are just applicable to distinct vibro-acoustics problems and not a general solution. Consequently specific noise control measures and integration concepts need to be designed for the upcoming challenges caused by the integration of new propulsion systems.

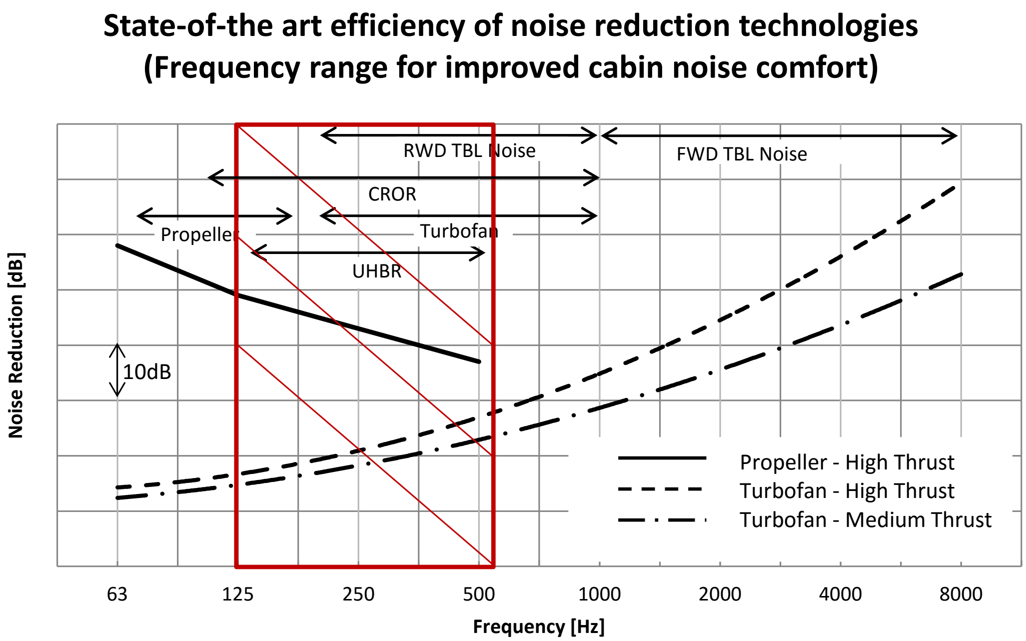

Figure 8: State-of-the-art efficiency of noise reduction technologies

3.4 DEMANDS ON INTERIOR NOISE PREDICTION AND DESIGN CAPABILITIES

In the previous chapters the challenges, which the interior acoustic development is facing in the coming future, were described. Consequently it must be asked whether the tools and competences are prepared to provide answers or solutions. When screening the market for available technologies and design tools it gets clear that there is still a long way to go. Not only that there is a strong demand to understand the perception of noise enabling proper definition of design targets but also in terms of prediction and design capabilities. Specifically is to mention; the demand on reliable models of the near field noise sources, its coupling into the structure and reliable numerical simulations tools for low to medium frequency range.

Moreover the increasing number of different propulsion systems, which are under investigation and the increasing competition abroad the world, require fast reaction and solution finding for the interior acoustics as flight test beds will come late in the development phase. As a consequence there is a need for experimental design capabilities enabling the evaluation of interior noise technologies and integration concepts at an early stage and under controlled conditions – at best with physical representations of the in-flight noise excitation.

4. CONCLUSION

An overview on the cabin noise comfort perception was given, saying that in principle the todays noise levels do not impair the overall cabin comfort but current quantifying parameter, e.g. L(A), may not be fully representative. Results from jury tests indicate that the acceptance of cabin noise can be increased by 10% with an overall noise level reduction of 6dB. To quantify the noise comfort one has to pay attention on the specific spectral aspects in the different cabin zones and dedicated psychoacoustics criteria have to be investigated and defined. In addition with the future propulsion systems such as ultra-high bypass fans or any type of rotors the noise preference may be impaired by 10dB or higher compared to typical background noise. Thus the interior acoustic developments need to focus on different aspects; new passive but tunable noise control technologies for low-to-mid frequency range, improved experimental design and validation platforms enabling a representative in-flight noise environment and reliable prediction and design tools.

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