NEW ASPECTS OF MEASURING NOISE AND VIBRATION

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ABSTRACT

Measuring noise, sound quality or acoustical comfort presents a difficult task for the acoustic engineer. Sound and noise are ultimately jugded by human beings acting as analyzers. Regulations for determining noise levels are based on A-weighted SPL measurement perfomed with only one microphone. This method of measurement is usually specified when determining whether the ear can be physically damaged. Such a simple measurement procedure is not able to determine annoyance of sound events or sound quality in general. For some years investigations with binaural measurement analysis technique have shown new possibilities for the objective determination of sound quality. By using Artificial Head technology /1/, /2/ in conjunction with psychoacoustic evaluation algorithms - and taking into account binaural signal processing of human hearing, considerable progress regarding the analysis of sounds has been made. Because sound events often arise in a complex way, direct conclusions about components subjectively judged to be annoying with regard to their causes and transmission paths, can be drawn in a limited way only. A new procedure, complementing binaural measurement technology combined with multi-channel measurements of acceleration sensor signals has been developed. This involves correlating signals influencing sound quality, analyzed by means of human hearing, with signals from different acceleration sensors fixed at different positions of the sound source. Now it is possible to recognize the source and the transmission way of those signals which have an influence on the annoyance of sound.

1. INTRODUCTION

The current trend in the automobile industry is to build increasingly lighter models with engines of higher performance. This results in higher vibration levels from the engine and, at the same time, higher sensitivity to vibrational excitation on the body side. In addition, air excited by the radiating effect of the engine in the frequency range up to approx. 400 Hz, meets only slight resistance by the insulation or lack of insulation offered by body components such as the bulkhead. Low-frequency components up to an upper limit of approx. 400 Hz are not only acoustically experienced as unpleasant "humming" and "howling". They are also experienced as disturbing vibrations on the floor, in the seating, and in the steering and gear lever. The "sensitivity" threshold for the body as a whole is approx. 200 - 300 Hz. Individual parts of the body, such as the finger tips, act as fine sensors in a frequency range of up to approx. 600 Hz. In recent years, artificial head measurement engineering has proved effective in identifying actual sound conditions. Together with the corresponding analysis and visual representation possibilities, this new technology provides engineers with a tool for processing and modifying actual acoustic conditions aurally-equivalently. Technical evaluation becomes a reality. Measuring the SPL with a single microphone will not give sufficient information about the disturbing sound event. Even at low frequencies, measurement points in close proximity often show large differences in level. Subjectively-experienced annoyance is often due to the difference in level from one ear to the other, rather than the particular level value measured at any one point. These effects can only be pinned down to a particular cause if additional information about possible structural transmission paths can be obtained. This problem leads on to the desirability of simultaneous recording of Artificial Head data and vibration data through multi-channel measurement engineering. The basis of a new approach to measurement engineering for objective determination of subjectively experienced sound quality is created by two factors. Firstly, the inter-connection of airborne sound events with structure-borne signals at the engine. Secondly, the inclusion of the transmission characteristics of the engine mounts in the correlation process. The structure-borne sound measurement results can be visually represented not only as order analyses and spectrograms but also as running modes. The new measurement procedure makes it possible to display simultaneously vibrations from the sound source and airborne sound events recorded simultaneously with the artificial head.

2. Aurally-equivalent Measurement Technology

Evaluation of a sound event by the "communications receiver" human hearing is influenced by numerous parameters. Sound events cannot be evaluated on the strength of a single dimension (until now, the A-weighted sound pressure level). This measurement is only one of numerous parameters which play a part in the evaluation of a sound event. These parameters are basically of two kinds: subjective (psychological) and objective (physical and psychoacoustic) parameters. Subjective parameters can only be defined in terms of statistics. It is practically impossible to derive an objective parameter from them. This underlines precisely how necessary an objectively-based aurally-equivalent sound measurement technology is. Such a technology ensures, for example, that complaints about noise are not ascribed to any subjective components, but that the objectively existing annoyance factor in noise can be identified. Human hearing is a highly sensitive measuring system, but has only a limited long-time memory. This means that when human hearing has experienced a sound event as unpleasant and annoying, these parameters will continue to obtain, even when the noise is reduced by 2 or 3 dB or even more. When human hearing has been sensitized with respect to a given sound event pattern, it is no longer able to make an objective evaluation when the sound quality or noise component as a whole is modified. Aurally-equivalent sound measurement technology is therefore concerned with objectively definable parameters. In this connection, not only the A-weighted sound pressure level is of importance, but also the duration of exposure, the spectral composition, the time structure and also the number and spatial distribution of the sound sources. If a sound event originates not from a single but several sound sources, which may also be spatially distributed, a correct evaluation of the sound event can only be obtained through binaural signal processing.

Binaural technology comprises recording of sound by means of an artificial head measuring system and incorporating an evaluation algorithm analogous to human hearing. Aurally-equivalent sound measuring technology is not therefore an alternative to, but an important extension of, existing sound measurement techniques /3/. In complex sound situations, which cannot be defined in terms of A-weighted sound pressure level alone, it can be used for gathering additional data, necessary for an objective evaluation of the sound event. The following points must therefore be noted:

(a) simple physical measurement values such as A-weighted sound pressure level and third octave spectrum do not provide full information about sound events,

(b) the subjective sound impression is also determined by the psychoacoustic characteristics of human hearing,

(c) human hearing comprises two input channels, which together with selectivity, create spatial hearing and therefore, in the case of several spatially distributed sound sources, yield results different to those provided by monaural measuring procedures.

The outer ear is a strongly directional filter. These filtering properties of the human outer ear arise through diffractions and reflections, depending on direction, caused by the outer geometry, such as pinna, head, shoulder and torso, as well as by resonances, which are independent of direction. However, a standard measuring microphone has a linear, frequency-independent level characteristic for all directions of sound incidence. These filter properties of the outer ear are very important for further signal processing at the receiver end "human hearing". An obvious difference between human hearing and conventional acoustic measuring methods is the fact that man has two auditory channels. The second ear is not simply a spare, but allows binaural signal processing and pattern recognition in conjunction with directional hearing, selectivity and suppression of noise. In a complex sound situation with various spatially distributed sound sources radiating different signals with the same acoustic power, the elimination of a single sound source leads to a very insignificant reduction of the measured level. In contrast, human hearing is able to perceive considerable changes, depending on the temporal structures of the signals. This binaural signal processing is essential for everyday life: speech intelligibility in a noisy environment is only possible through binaural signal processing.

3. Multi-channel Measurements and Analysis

The procedure provides a basis for combining, in a mobile analysis system, signals from an Artificial Head measurement microphone with signals from acceleration sensors. This is particularly suitable for noise diagnosis of sounds inside cars. Auditory evaluation by test persons allows selection of individual signal components from the total sound which are judged to be annoying. The correlation with different signals from acceleration sensors makes it possible to discover the origins of these sound components and their transmission paths before they reach the interior of the car. Fig. 1 shows the basic idea. The sound situation in the interior of a car arises from several sound sources SC_a to SC_m arriving from various transmission paths $\underline{H}_{a,1}$ to $\underline{H}_{m,n}$. Moreover, the sound impression is determined by the radiation of airborne sound from the individual noise sources within the car. The engine noise reaches the interior of the car via the engine suspension in the form of structure-borne sound. This transmission can be registered in front and behind the engine mounts in terms of measurement technology by appropriate measurement usig acceleration sensors. The radiated sound is initially unknown. The Artificial Head Measurement System can be used to determine the resulting sound inside the car. In this way, conclusions as to the unknown airborne sound transmission path may be reached. Such a procedure would mean a very rapid and appropriate method of improving sound quality inside cars.

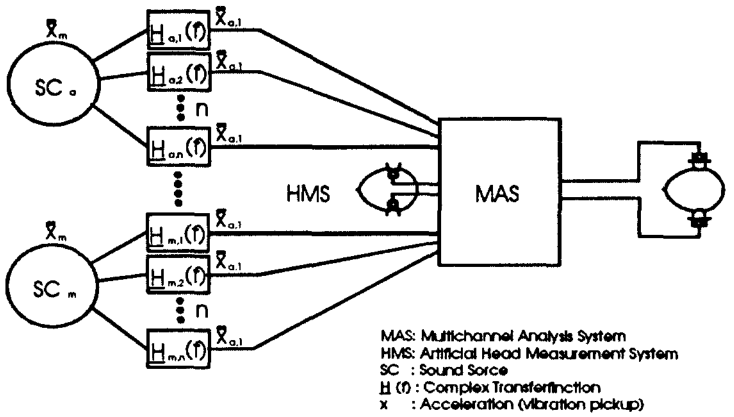

Fig. 1: Principal possibility of combining Artificial Head microphones with signals of acceleration-measurements

4. Application

The test vehicle was a front-wheel drive car of the lower middle range. It had a four-cylinder transversely-suspended 1.6 Ltr. engine mounted at three points. The car exhibited good road behaviour and a noise level thoroughly typical for this class of vehicle. Below an r.p.m. of approx. 3000 r.p.m. the interior noise level was strikingly low. In excess of 3000 r.p.m. up to the max. r.p.m., however, very disturbing humming and howling occurred. Measurements were taken from the co-driver's position using the artificial head for obtaining evidence about the complaints. Base measurement was made during acceleration/deceleration in third gear on a straight section of good-surface road. The artificial head measurements were evaluated in the frequency range from 50 Hz to 2 kHz. The frequency range includes, between the 2nd order at 5400 r.p.m. (180 Hz) and the order 6.5 at 6000 r.p.m. (650 Hz), the first three critical, i.e. high level orders of the 4-cylinder in-line engine together with the corresponding intervening orders. The 2nd order itself is clearly identifiable over the total r.p.m. range. Order analyses with visual representation of individual orders at the measurement location for the left and right ears over r.p.m. makes it easier to distinguish between them. The 2nd order proceeds from approx. 3500 r.p.m. in a distinct level increase of a full 5 dB. Level differences between the left and right ears first become apparent from approx. 5200 r.p.m. To underline the left/right ear difference if the frequency is doubled, the 3,5th and 4th order are shown in Fig.2. In this case, clear left/right ear differences are already apparent at r.p.m. values in excess of approx. 3000 r.p.m. with level differences of up to 10 dB. It becomes clear that above 180 Hz, not only the total level increases, but also the left-/right ear differences in the artificial head measurements which contribute to the total subjectively-experienced unpleasant impression.

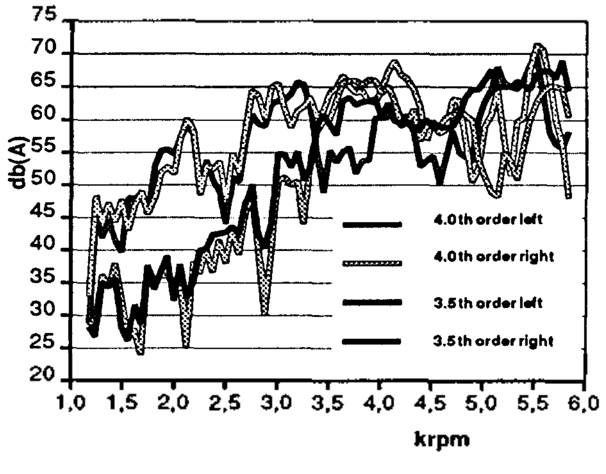

Fig. 2: A-weighted level of the 3.5th and 4th order of the left and right ear.

With binaural signals, as can be seen in the figures, the individual orders can be composed in different ways for the left and right ears. During auditory evaluation, however, it becomes clear that the unpleasant, annoying impression in these r.p.m. ranges only becomes apparent on binaural investigation. The impression is not revealed by monaural investigation. The interaural level differences of approx. 15 dB shown in Fig. 2 are situated in the frequency range from 100 Hz to 350 Hz. In natural sound exposure situations such level differences could not occur at such low frequencies. This is because in this frequency range, the shadowing effect of the head can be ignored to an even greater extent. This is why the human ear is not accustomed to such level differences at low frequencies. Such level differences occur in the interior of vehicles because of the range of transmission paths and standing waves /4/. They produce an unpleasant sensation of pressure on the ears. Another striking effect is produced when analyzing the two ear signals. Not only do significant level differences occur between the left and right ears but a higher level can occur at the left ear. The right ear theoretically exhibits higher signal components in general because of reflections from the window-pane, (the artificial head measurement system was located on the right-hand seat).

Noise in cars may arise due to airborne sound produced by intervening body components. It may also be due to structure-borne sound produced through the engine mounts and other attachment components. Purely airborne sound excitation paths can only be successfully tackled once structure-borne sound transmission has been investigated. Measurements of structure-borne sound are evaluated for in front of and behind the mounts in all spatial directions measured. Even with a very straightforward measurement procedure this means a large quantity of data is produced. With three engine mounts each to the left, right and behind, each with a triaxial acceleration sensor located in front and behind, a total of 18 measurement signals is produced (Fig. 3). It thus becomes important to find a method of reducing the quantity of data in a speedy and easily carried out manner. Airborne sound signals in the vehicle interior can be simultaneously recorded using the artificial head measurement system. This allows more rapid location of noise source and transmission paths by auditory correlation with the signals originating from the individual acceleration sensors, the parameters decisively effecting sound quality having been previously identified by listening.

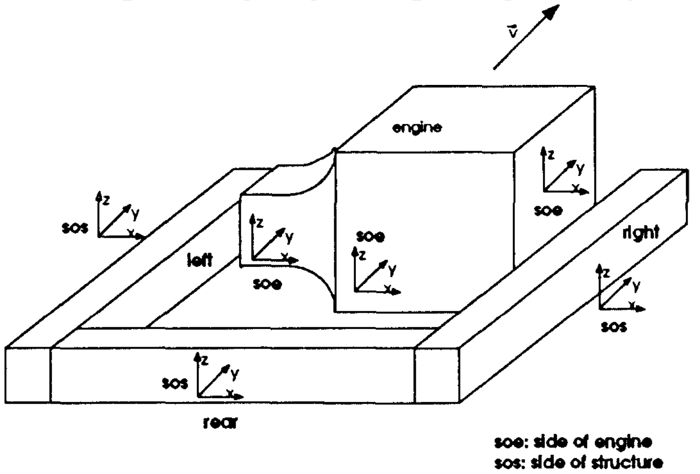

Fig. 3: Positions and directions of the three measurement-points: left, right and rear engine-mount, triaxial acceleration measurement on side of engine and side of structure (car-body)

Fig. 4 shows some characteristic curves for the various orders at the various points of measurement. Comparative auditory evaluation produced a close correlation with the noises radiated from the center rear engine mount. Structure-borne sound analysis of the results measured vertically behind the rear engine mount resulted in a distinct resonator behaviour at approx. 200 Hz. This powerful resonance indicates bodywork resonance.

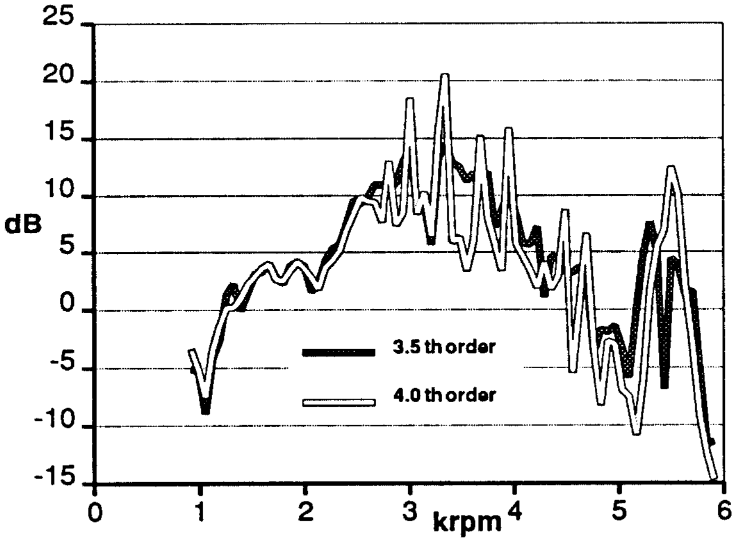

Fig. 4: Order analysis of the signals measured at the rear engine mount (z-direction), difference between structure side and engine side

5. Summary

The combination of authentic artificial head recording of sounds inside cars with a multi-channel structure-borne sound analysis system provides acoustic engineers with new possibilities of achieving the development objective of improved noise design at minimal time-cost. The approach described here, i.e. the simultaneous measurement of airborne and structure-borne sound signals using a multi-channel recording and analysis unit, represents a first step towards the measurement and analysis of very complex inter-connected data using relatively uncomplicated hardware. The additional possibility of subsequent digital signal processing also brings the objective of higher acoustic comfort a further step nearer.

Literature

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