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MAPPING OF TRUCK NOISE USING AN INCOHERENT APERTURE SOURCE MODEL

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INTRODUCTION

The present paper describes some results from a task done within the European research project "PIANO" which is dealing with ISO-362 Pass-by noise from trucks. The technical objective of the task was to develop a practical and fast method to estimate sound pressure at an arbitrary distance from a vehicle based on test-hall measurements around the vehicle. Such a method would enhance indoor simulation of the pass-by test, providing a more complete/global picture of the radiated sound, and enabling measurements to be taken at rather short distance from the truck. The principal frequency range for the A-weighted pass-by level is 400Hz to 3kHz.

Near-field Acoustical Holography and Helmholtz' Integral Equation are recognised as efficient tools for detailed mapping of acoustical radiation phenomena. A measured hologram - containing the sound pressure amplitude and phase information over a planar surface close to the source - allows mapping of any descriptor of the radiated sound field in three dimensions, [1-2]. Measurements are, however, required over a grid with spacing not exceeding half a wavelength at the highest frequency of interest, and the measurement area must be somewhat larger than the source. These requirements lead to an enormous amount of measurement positions, which must further be measured simultaneously to obtain consistent phase (and amplitude) information for the highly transient pass-by simulation event. It was concluded that a sparse array measurement technique is required.

Other tasks in the PIANO project had obtained good results from the use of incoherent point source models of engines in cases where the modelling of directivity is not critical, [3]. It was decided to investigate the possibilities of using a similar source model for the exterior sound field from a complete truck. The sound is then assumed to be radiated through a set of openings or apertures in the outer surface of the truck, and each of the apertures is modelled by an array of point sources. One of the main questions to be answered was related to the modelling of directivity: What is the need of modelling of directional radiation from apertures on a truck, and can this need be met to a sufficient extent by incoherent point sources?

SPATIAL COHERENCE IN THE RADIATION FROM A TRUCK

It was decided to measure the spatial coherence of the sound field radiated through one of the most important apertures in order to evaluate, how well an incoherent point source model represents the actual spatial coherence.

The spatial coherence in the apertures contains some information about the trend to form or not to form narrow beams in the radiation pattern: A very coherent aperture field will introduce interference patterns in the radiated field and possibly narrow beams if the aperture is large compared to wavelength. A coherence length which is small compared to wavelength will not typically produce narrow beams, in particular not when the aperture distribution is created by sources at some distance behind the aperture.

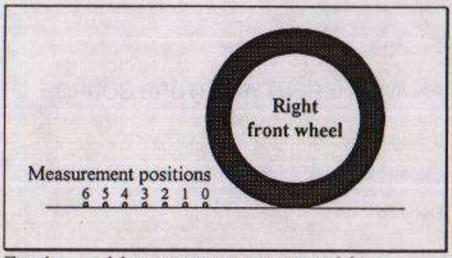


Fig. 1. Measurement positions used for mapping of spatial coherence.

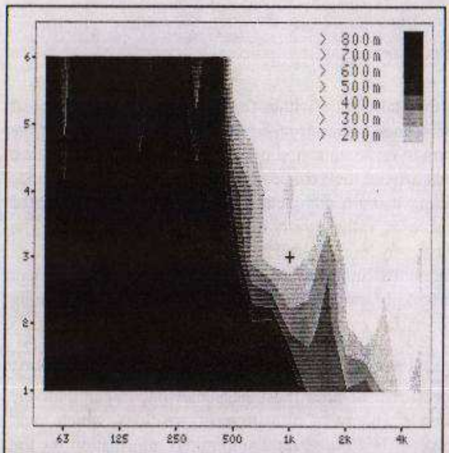


Fig. 2. 1/3-octave coherence versus frequency and distance in units of 10cm.

The aperture selected for measurement of spatial coherence was the opening between the cabin and the ground plane just behind the right front wheel, see Fig. 1. All coherence spectra were measured from a reference position No. 0 just behind the front wheel to points 10, 20, 30, 40, 50 and 60cm behind the reference position. Both 1/3-octave and 1/12-octave coherence spectra were measured, and both pressure signals and particle velocity signals were used. Modelling of the aperture radiation by volume velocity sources makes the particle velocity coherence more relevant than pressure coherence.

An analog particle velocity signal was obtained from a B&K Type 4437 Sound Intensity Analyzer with a Type 3547 Sound Intensity Probe. The driving conditions of the truck was: 1500 RPM. stationary, 4L gear, 20% load.

The 1/3-octave particle velocity coherence presented as a contour plot in Fig. 2 is defined as the squared magnitude of the Cross-power divided by the product of the two Auto powers. The x-axis shows the frequency in Hz while the y-axis represents the distance in units of 10cm. When the distance is smaller than half a wavelength, the coherence is seen to be very high, while it is in general very small for distances larger than one wavelength. Between these two limits there is a smooth transition. For the 1/12-octave spectra there is the same trend, apart from the fact that primarily between 400Hz and 1kHz there are some frequency bands with high coherence, even when the separation is larger than one wavelength. In this frequency range, some essential information may be lost by the use of the broad 1/3-octave bandwidth. Below 400Hz the particle velocity distribution is very coherent even in 1/3-octave bands. The pressure to pressure coherence showed exactly the same trend as the velocity to velocity coherence.

Considering the ISO 362 Pass-by test for trucks, the A-weighted result has the dominating contributions from the frequency range between 400Hz and 3kHz. The coherence measurements therefore indicate that it might be feasible to use a source model with a built-in small coherence length. A source model based on cross spectra between elementary sources will allow an easy exploitation of a known limit on the coherence length. We shall investigate the limiting case where all cross powers are set to zero and only Auto-powers are used in the model. Because interference are then avoided it becomes feasible to use a microphone array spacing larger than half a wavelength, i.e. a sparse array.

THE INCOHERENT APERTURE SOURCE MODELLING TECHNIQUE

The source modelling technique, that has been implemented and tested, performs the following tasks to extrapolate measured transient sound field data to larger distances:

1) Measurement: Simultaneous acquisition of sound pressure time histories from an array of microphones about 1 metre from the truck.
2) Averaging: Short-time averaging of 1/3-octave SPL Autospectra. 100ms time intervals with linear averaging has been used in the present evaluation.
3) Solution of an inverse radiation problem: For each time interval and each 1/3-octave band, solve an inverse radiation problem, fitting a source model to the measured data. The solution makes use of a Singular Value Decomposition (SVD) of the matrix of transfer functions.
4) Extrapolation: Calculate SPL values at selected positions using the source model.

The source model is defined in the following way:

- Define a set of openings (apertures) through which sound is radiated The apertures are assumed to radiate incoherent sound fields.
- Each aperture is modelled by an array of equally excited, incoherent, outwards radiating Huygens point sources, the radiation pattern of which is shown in Fig. 3.
- Ground reflection is modelled by the use of image sources.

The above source model is too coarse to describe the details of the sound field close to the source. Therefore, rather than a model of the source it should be considered a model of the sound field beyond 1m distance.

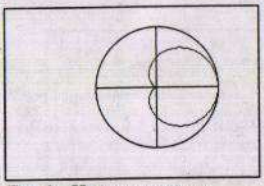


Fig. 3. Huygens pattern

The fact that the model consists of only incoherent Huygens' point sources has the following important consequences:

a) Directional beams cannot be modelled - only the broad beam from the Huygens source shown in Fig. 3.
b) Basically, diffraction around the truck is modelled by the Huygens source directivity pattern at all frequencies.

The consequence mentioned under item (b) above can be avoided to some degree by adding apertures representing the diffracted sound fields.

In the inverse problem defined under item (4) above a set of Auto-power excitations of the apertures are calculated. It turned out that a non-negativity constraint was needed in order to avoid large negative Auto-power excitations. A 10dB dynamic range of singular values was found to be a good choice.

MEASUREMENT SET-UP

Measurements were taken on the right-hand side of a SCANIA R144 LA4x2 CR19 truck in SCANIA's large semi-anechoic test hall, which has a lower limiting frequency around 200Hz. Pass-by test conditions were simulated with the truck on a dynamometer, but with the rear wheels and exhaust encapsulated. With this set-up, the front of the truck was the dominating noise source, and thus only the front was modelled by apertures and measured by a microphone array.

Fig. 4 shows a schematic top view of the truck, the microphone array 1 metre away and 6 socalled validation microphones at 2.85m distance and 1m above ground. The SPL is measured at the validation positions for the same event that is measured by the array microphones. These SPL values can be compared by SPL values calculated from the source model showing, how well the model is able to predict the propagation of the sound field to the validation positions.

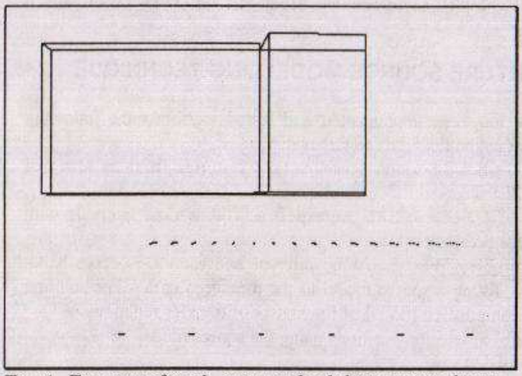


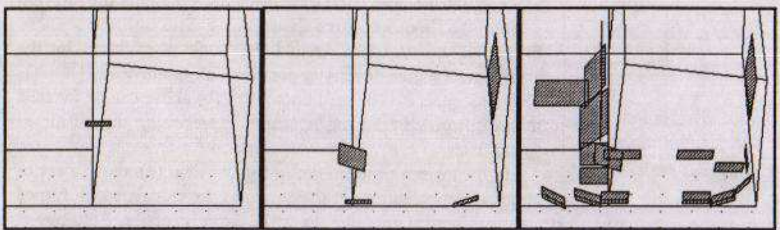
Fig. 4. Top view of truck, array and validation microphones.

The spacing in the microphone array was 40cm, and the array had 6 rows and 16 columns with the lowest row of microphones 20cm above the ground. The 40cm spacing was found to provide a sufficiently dense spatial sampling of the SPL patterns that can be produced by aperture distributions with the observed coherence lengths, see Fig. 2. Different measurement distances were tested, but the 1m distance was found to be the best. The microphones were B&K Array Microphones Type 4196, and the data were recorded by a B&K IDA front-end Type 3561.

RESULTS

Stationary conditions

In order to avoid the effects of non-stationarity and a short averaging time, a series of measurements were first taken with idling engine (about 1000 RPM). Instead of the 100ms averaging time used for transient conditions, a 500ms averaging time was used.



One aperture *Four apertures* *All apertures*

Fig. 5. Perspective view of three different aperture models.

Fig. 5. shows three different source models that were used to predict the SPL at the validation microphone positions: The first model "One" consists of only one small aperture positioned at the ground plane under the engine/gearbox region. The second model "Four" consists of 4 apertures at the presumed most important radiating apertures, i.e. at the surface of truck. The third model "All" contains 24 apertures to model in more detail a larger number of apertures.

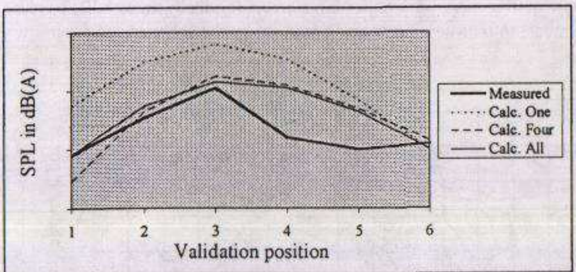


Fig. 6. A-weighted SPL at the validation positions. Tick mark interval on the y-axis: 2dB

The comparison between measured and calculated A-weighted SPL at the validation positions is shown in Fig. 6. Clearly, the source model with only one aperture under the centre of the vehicle predicts too high SPL over all validation positions except number 6. This is probably because the sound radiation is mostly centred near the surface of the truck, implying that an inverse distance correction should be based on radiation positions near the surface. The SPL predicted at the validation positions by the "Four" aperture source model confirms this hypothesis: These apertures are at the surface of the truck, and here there is a much better agreement between the measured and the predicted levels. Only, the incoherent Huygens point source model is not able to reproduce the rather sharp maximum in the directivity pattern at validation position number 3. This will of course also hold true if more apertures are added to the source model, explaining why the "All" aperture model does not improve very much the results as compared to the "Four" aperture model. The predictable conclusion is that the implemented incoherent aperture model is not able to reproduce rather sharp maxima (or minima) in the directivity pattern, no matter how many apertures we add to the model. Such maxima (or minima) will limit the achievable accuracy.

The above observation that a point source centered under the truck cannot model the radiated sound field was also made in reference [4] based on intensity vector maps.

Transient condition (Pass-by sim.)

Here, a fast acceleration in the low 2L gear was used in order to study the performance of the method under highly transient conditions. Besides the microphone signals, three different tacho signals were also recorded: RPM, Throttle and Dynamometer. The last two of these enable a Pass-by simulation to be performed. A 100ms averaging time was used for the SPL values, and the "All" aperture set shown in Fig. 5 was used.

We shall consider a 2 sec. recording of a Pass-by simulation event during which the RPM increased about 1500RPM in approximately 1.5 sec. Fig. 7 contains a contour plot of the deviation between the measured and the modelled A-weighted SPL in dB along the 6 validation positions as a function of time. Positive values indicate overestimation. The plot shows that the predicted A-weighted level is within ±1dB from the measured level over almost all time intervals and validation positions.

The model seems to work better in the present non-stationary case than in the stationary case, in particular the deviation is low during the fast stable RPM run-up part of the 2s event. For the stationary condition the worst case error is almost 2dB. An explanation can be that the assumption about spatial incoherence is more realistic in the non-stationary case than in the stationary case. An equivalent explanation is that the interference patterns of the sound field produced in stationary operation will be smoothed out when the RPM is continuously changing. Thus effectively the smooth patterns that can be modelled by the incoherent source model is approached.

The deviation in the individual 1/3-octave bands has also been plotted for each of the 100ms averaging intervals. It was general for all time intervals that above 500Hz the 1/3-octave results were within ±3dB, while below 630Hz there were rather large errors (typically up to 6dB) because of the inability of the source model to represent the beams produced by the coherent radiation.

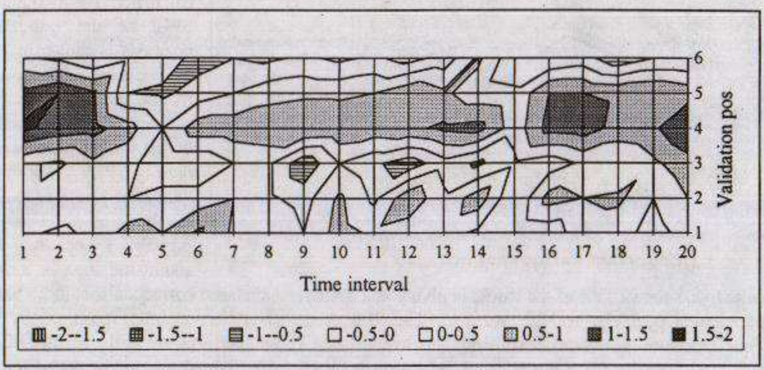


Fig. 7. A-weighted modelling error in dB versus time and position.

CONCLUSIONS

The implemented method fits a source model consisting of only incoherent Huygens point sources to a set of measured Auto-power spectra. Thereby, only very smooth sound field patterns can be modelled. For a fast acceleration the method was found to be able to predict within approximately ±1dB the overall A-weighted level at distances a few metre further away from the truck than the measurement array, provided the source model is reasonably well selected.

For the individual 1/3-octave bands, an accuracy better than 3dB was achieved above 630Hz, but below 630Hz larger errors are introduced because of the inability of the implemented source model to represent interference and highly directive radiation. Such an ability can be introduced by including Cross-powers between neighbouring Huygens point sources. Directional information can be added to the measurement by including Cross-power information between the array elements.

The method seems promising, but some extensions and improvements are needed.

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