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Blind Source Separation Applied to Indoor Vehicle Pass-By Measurements

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ABSTRACT

Indoor vehicle pass-by noise applications deal with measuring the exterior noise from a vehicle fixed on a chassis dynamometer in a large hemi-anechoic room. During a standardised acceleration test, the noise is measured with an array of microphones placed in the far-field, and the overall noise level versus vehicle position can be simulated. The indoor facility allows controlled and repeatable measurements independent of weather. For engineering purposes, pass-by contribution analysis can be included in the test leading to information about the pass-by noise contribution from major noise sources.

This work presents a novel application of blind source separation to vehicle measurements from an indoor pass-by measurement campaign. In contrast to the classical transfer path approach using point sources for modelling vehicle noise sources and combining an operational measurement with transfer functions, the blind approach does not consider a specific noise source model. It only assumes that the noise is produces by a set of independent noise sources using only a single operational measurement for a given vehicle condition as input. Near-field microphone measurements are blindly separated into independent components and further correlated with the signals measured at the far-field indoor pass-by microphones to get the time-domain contributions. Finally, we apply the indoor simulated pass-by algorithm to produce noise contribution levels as a function of vehicle position.

We discuss the specified application of blind source separation to vehicle measurements for different operating conditions from a real indoor pass-by test. Separation of tyre and engine related noise at tyre near-field microphones is verified. Furthermore, the tyre pass-by noise contribution is extracted from the overall vehicle measurement.

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INTRODUCTION

The indoor vehicle pass-by test is a simulation of a field pass-by noise measurement in a controlled environment allowing repeatable measurements independent of weather conditions. During vehicle development modifications can be tested out in a fast manner to see the immediate influence on the overall vehicle noise levels produced during a pass-by acceleration test. Besides performing the standard pass-by noise test, vehicle improvement work requires knowledge about the noise contribution from the different vehicle sources during the pass-by test. The emphasis of this paper will be on the source separation task related to indoor pass-by noise tests.

Typically, a source-path-receiver modelling concept is employed based on measured acoustic transfer functions and operational data during the vehicle acceleration. Other recent methodologies try to use pure operational data for building the transfer function model and performing the source separation task. Such methods avoid the specific measurement of transfer functions using a dedicated sound source. In this work, a blind separation approach is introduced as a time-domain operational method ideal for clear separation of engine and tyre related noise contributions. The blind approach works directly on measured time recordings from only one acceleration test.

Different practical tests were carried out to initially investigate the proposed blind separation method and evaluate the usability and accuracy with respect to noise source contribution estimation. Measurement data from an indoor vehicle pass-by test is finally analysed and compared to understand the methods capability for a real pass-by noise scenario.

INDOOR SIMULATED PASS-BY

A pass-by noise measurement is defined as the method of measuring the noise emission of a road vehicle under acceleration conditions, with various gear positions in a certain measurement range. These measurements are mandatory for automotive manufacturers in terms of product certification. For this reason, ISO (International Organization for Standardization) regulates the measurement and analysis procedures, as well as the reporting format [1]. In some cases, however, pass-by noise measurements cannot be taken out in the field because of bad weather or poor test-track conditions. In such cases, the indoor simulated pass-by noise measurement is often used. The indoor simulated pass-by measurement does offer a number of advantages such as good repeatability, flexibility and ease of use.

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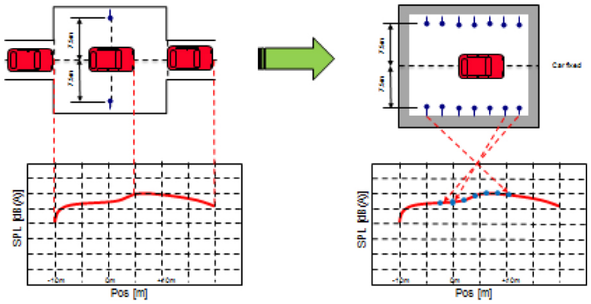

Figure 1. Field versus indoor pass-by test.

Instead of having the test vehicle pass two stationary microphones as being the standard in a field pass-by measurement, indoor pass-by setups use one or two rows of microphones placed alongside the vehicle. See figure 1 for a comparison of the field and indoor situation. The vehicle runs on a chassis dynamometer (dyno) and is accelerated in the same way it would be for a field pass-by measurement. Time histories are measured by the microphones together with vehicle parameters and dyno drum speed. A sophisticated algorithm uses information from the dyno to calculate the vehicle's position relative to the microphones as a function of time. This information is used to extract the contributing portions of the time histories that correspond to when the vehicle would have passed the standard microphone positions had it been moving. A synchronised single time history is created by stitching all of these time history sections together and interpolating across the segments' boundaries.

This synchronised single time record combined with the dyno drum speed profile represents the vehicle noise emitted during a simulated pass-by measurement. The new time history is played back through the analysis section of the system, offering the option of applying various types of frequency analysis to the time history. It can also be previewed and listened to in order to determine whether it sounds right.

The indoor pass-by system described in this paper has been developed to allow for microphone positions closer than 7.5 m from the vehicle while still providing correct results. This is extremely useful for situations where space is limited and is achieved assuming that the noise is emitted from one point (an acoustic center) as seen from the far-field. Individual acoustic centers can be chosen for the left and the right side of the vehicle. In addition, the array of microphones does not need to have full coverage of all vehicle positions since typically the room length is limited. Missing microphone positions close to the entrance or exit of the virtual pass-by track can simulated from the existing array microphones and the specified acoustic centers.

Contribution analysis can be included into the indoor testing by putting a set of near-field microphones close to the main noise sources. Traditionally a radiation model of the noise sources is made by considering a set of point sources and their source strength is estimated from operating data at the near-field microphones and additional transfer functions [2, 3, 4]. From the estimated source strength's and another set of transfer functions an estimate of the pass-by contribution for each noise source is obtained and plotted together with the measured indoor pass-by noise. Figure 2 illustrates the setup for contribution analysis with a typical result. In this work the separation of noise sources is based on signal processing rather on transfer functions between chosen source positions and microphones.

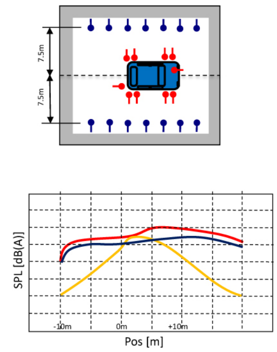

Figure 2. Indoor pass-by test including contribution analysis

BLIND SOURCE SEPARATION

Blind source separation (BSS) refer to signal processing methods with the aim of separating different source signals from a mixture of sources using little information about the source signals and the mixing process. In acoustics the mixing process of different sources at microphones is complicated by the fact that the propagation is convolutive due to delays and reflections between sources and microphones. In figure 3 the mixing of two sources at two microphones is illustrated indicating the problem of cross-talk, i.e. a microphone picks up signals from not only the nearest speaker.

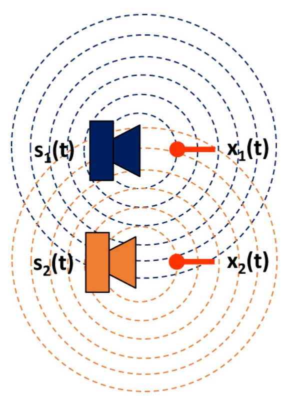

Figure 3. Mixing of two sources at two microphones indicating the problem of cross-talk.

Many different methods have been proposed in the past to solve the separation problem at the microphones, most methods focused on music and speech related problems and algorithms working in either frequency domain or time domain are reported. BSS on industrial type of signals is however rarely found. Most methods make the assumption, that the source signals are independent and other signal properties like non-stationarity may also be exploited [5].

For the current problem of separating vehicle noise sources during a fast acceleration, a time domain method for separating microphone recordings into so-called independent components (IC) is employed. The basic principle of the selected separator is to make use of a linear prediction approach to model the time correlations of a set of recorded

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mixtures, here called reference signals $\boldsymbol{p}_{ref}(t)$. A matrix of whitening filters $\boldsymbol{W}(\tau)$ of length L can be estimated from the correlations which ensures a set of whitened signals $\boldsymbol{u}(t)$ to be produced:

$$\boldsymbol{u}(t) = \sum_{\tau=0}^{L-1} \boldsymbol{W}(\tau)\boldsymbol{p}_{\boldsymbol{ref}}(t-\tau) \tag{1}$$

The feature of $\boldsymbol{u}(t)$ is that the samples of each signal $u_i(t)$ are now uncorrelated, and $u_i(t)$ and $u_j(t)$ are uncorrelated as well. All sample correlations resulting from either sources or acoustic paths are now removed, i.e. the signals are white and uncorrelated. Final step is to solve an instantaneous BSS problem looking for a matrix B which rotates the whitened data to find the most independent time series. The so-called independent components are arranged in $\boldsymbol{y}(t)$. Standard algorithms may be applied here using either higher-order or second-order statistics.

$$\boldsymbol{y}(t) = \boldsymbol{B}\boldsymbol{u}(t) \tag{2}$$

Such two-stage linear prediction approach for solving the convolutive BSS problem has been proposed for blind identification of communication channels [6] and other variants of this implementation for source separation are reported as well [7].

Before processing the measured reference microphone mixtures the data samples can optionally be down-sampled with a factor to reduce the number of samples and possibly reduce the length of the whitening filters. This so-called subband processing is a standard BSS procedure and after processing the time data can be up-sampled again [8]. Note, if the data is split into several subbands for processing, independent components belonging to different subbands must be combined to form the full-band signals again, but since the ordering of the independent components in $\boldsymbol{y}(t)$ is unknown for each subband this associated permutation problem must be solved.

The independent signals are not associated with any particular position from the setup and the order in which they appear at the output of the unmixing process is arbitrary. So to make meaningfull use of the independent signals it is necessary to identify which noise source process each IC is belonging to. The problem of labelling each IC is illustrated later in this paper when analysing real vehicle recordings.

Having separated into independent components and labelled them correctly, contribution filters can be estimated between all IC's (input) and time data at the pass-by microphones (output) as a MIMO (multiple-input multiple-output) system identification problem. Time recordings at the pass-by microphones were measured together with the set of reference microphones and the corresponding vehicle tacho data. After labelling we know which IC's can be assigned to what noise source and summing those IC's contribution to each pass-by microphone followed by the indoor simulated pass-by algorithm produces the pass-by contribution results.

EXAMPLE OF SOLVING BSS PROBLEM

In order to demonstrate the capabilities of the chosen BSS strategy for noise source separation, a simple yet challenging experimental test setup is considered. A small vehicle located in a normal room served as scattering object and two speakers were positioned around the vehicle. One box loudspeaker on the floor at the right-hand side of the vehicle and a tyre structure with built-in speaker was positioned at the rear left-hand side of the vehicle. A set of reference microphones were mounted on the floor in positions between the two considered speaker sources. Additionally an array of microphones were placed along the vehicle left hand-side to represent a set of pass-by receivers. The setup is sketched in figure 4 with only the relevant microphones for the BSS evaluation shown, i.e. two reference microphones and one receiver microphone.

Real recordings from a real vehicle measurement served as input for the two speaker sources, an engine signal consisting of engine orders only was sent to the box speaker to produce pure engine noise an another signal made by a recorded tyre signal with all engine orders removed was sent to the tyre speaker to represent pure tyre noise. Both recordings were originally taken during a pass-by acceleration test. After modification they are considered as independent signals making them amenable for BSS analysis. All time recordings for this validation case were done using a sampling frequency of 32768 Hz and about 12 seconds of data was recorded.

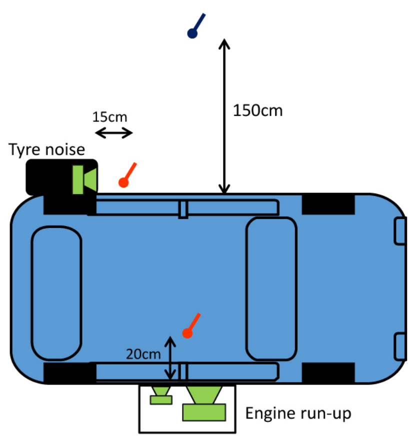

Figure 4. Speaker setup around vehicle with microphones for BSS testing.

By playing the two signals simultaneously through the speakers mixtures are created at all of the microphones in the setup, as would be the case during a real vehicle operating. Obviously the tyre reference microphone will contain mostly tyre noise and certain cross-talk from the engine speaker. The mixture at the tyre reference microphone is shown as spectrogram in figure 5 clearly showing engine order contribution at low frequencies. The advantage of the setup is that each speaker can be played solo to create the true contributions at the microphones for validation purposes. The convolutive mixture of the tyre and engine signals as picked up by the two reference microphones close to the speakers are used in the adaptive blind separation stage to generate two new signals which are independent.

Before processing the measured reference microphone mixtures the data samples were down-sampled by a factor 2 to reduce the number of samples and possibly reduce the length of the unmixing filters. In our

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case only one subband is considered so the permutation problem mentioned previously is not an issue. Next, the unmixing filters are trained using the 12 seconds of data, i.e. the whitening filters are constructed and the data whitened followed by solving an instantaneous problem. The only parameter set is the filter length of the whitening filters. The output of this procedure is two independent component time signals, which are filtered versions of the clean reference signals related to either of the two speakers. The independent components are now correlated with the input signals (the two reference mixtures) to calculate a set of time filters between IC's and the two reference microphones. Finally, we can transform each IC into a time-domain contribution at a reference microphone, which re-scales each independent component back to sound pressure at the physical microphone positions. Results for this procedure are shown in figure 6. The contribution of the two identified IC's at the tyre reference microphone is shown and for comparison we include the true individual contributions from the engine speakers and the tyre speaker. We notice that IC1 represents the tyre signal and IC2 the engine signal, and furthermore we see impressive agreement between the BSS separated contributions and the true individually measured contributions. Only very little engine noise is left in the tyre noise estimations, and vice versa, suggesting that the separation problem has been solved.

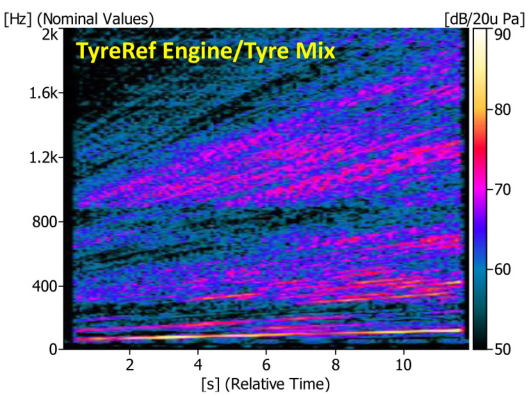

Figure 5. Spectrogram of engine and tyre mixture measured at tyre reference microphone.

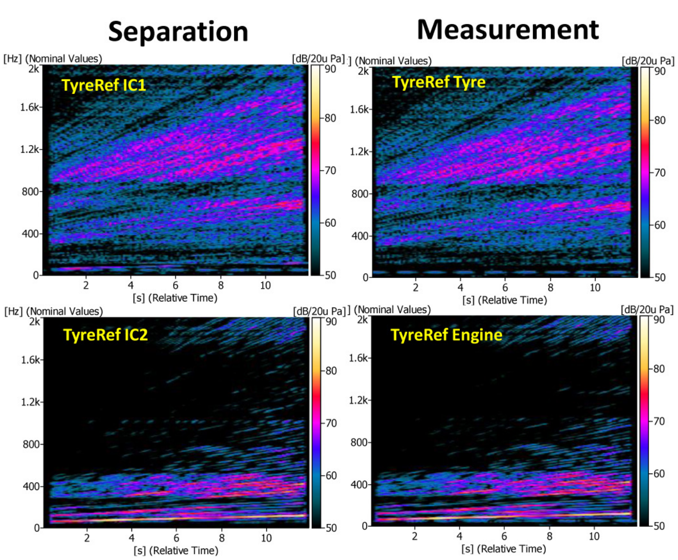

Figure 6. Spectrogram of separated components at tyre reference microphone compared to true measurements with only one speaker active.

The final step is to correlate the IC's found with the selected far-field receiver data measured simultaneously with the reference mixtures. Another set of filters are estimated from the IC's to the receiver and subsequently used to filter each IC to find the receiver contribution time signal. The average spectrum during the 12 seconds of measurement at the receiver can be plotted together with any contribution. In figure 7, the average spectrum is shown for the receiver measurement compared with the sum of the two contributions from the IC's. We observe excellent agreement between the two spectra, telling us that the two derived independent components fully describe the measured signal at the receiver.

Moreover, in figure 8 we plot the true measured average spectrum from each speaker against the independent component contribution spectrum which is identified to represent the corresponding speaker. Again, near to perfect agreement is seen suggesting that the convolutive separation problem has been solved satisfactory.

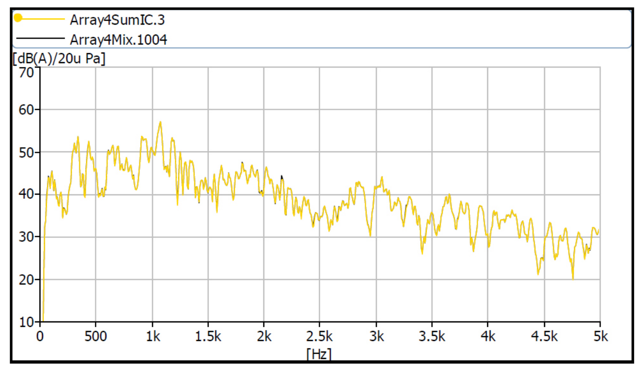

Figure 7. Average spectrum of sum of contributions (yellow line) compared to measured mixture (black line) at receiver microphone.

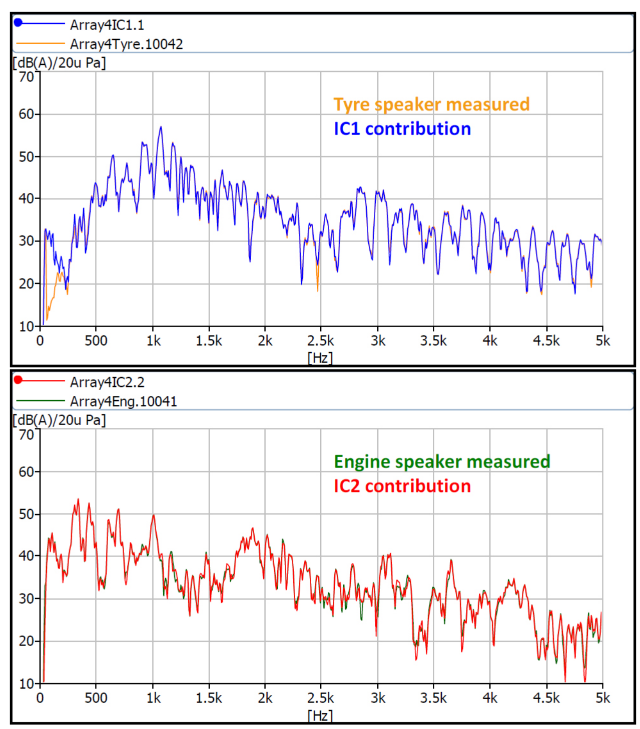

Figure 8. Average spectrum of separated component at receiver microphone compared to true measured spectrum from each speaker.

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BSS APPLIED TO VEHICLE MEASUREMENTS

A setup with a vehicle on a chassis dyno in an indoor pass-by test facility is now considered. The mid-size 4-cylinder vehicle was equipped with normal tyres and placed on the single-axis chassis dynamometer.

The test room can accommodate a single-sided pass-by test with pass-by microphones at 7.5 m, hence all results presented in the following refer to the left-hand side of the vehicle. A line array of 19 pass-by microphones with a spacing of 1 m covered 18 m of the simulated pass-by track which is limited by the length of the indoor facility. Extra microphones were added at the two array ends to form a horse-shoe array making it possible to simulate virtual microphones extending the line array. With the chosen setup 22 m of the pass-by track is covered by the 23 microphones.

The rear tyres of the vehicle are not rolling, and the front right tyre is shielded by the vehicle body, meaning only the front left tyre should be considered when modelling tyre pass-by noise contributors. Additionally, the engine and air intake are taken into account together with the exhaust orifice and the rear muffler. All these component noise sources are equipped with near-field reference microphones, in total 17 microphones around the vehicle. 4 of these microphones covered the front left tyre contact area, 2 for leading and 2 for trailing edge.

Tachometer signals for the engine RPM and the vehicle speed are acquired together with microphones described above. Different operating conditions of the vehicle were measured, full acceleration (WOT) and 50 km/h constant speed test for 2nd, 3rd and 4th gear were all recorded and a coast-down with engine shut off. A sampling rate of 16384 Hz is used for all recordings.

An illustration of the microphone setup in the facility is given in Figure 9.

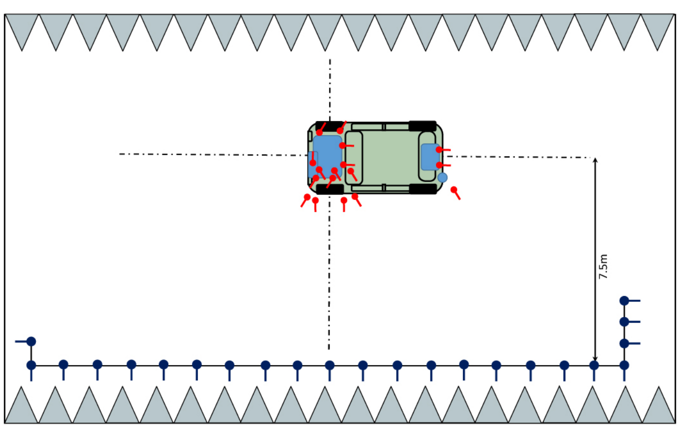

Figure 9. Indoor pass-by microphone setup including additional reference microphones.

Operating time data from the set of reference microphones is supplied as input to the blind source separation producing 17 independent component time series. A labelling procedure identifying the origin of each independent component produces two groups of signals, one group for the single tyre and another group for the remaining engine-related sources. After successful separation and labelling we will be able to identify the contribution from the tyre to any of the microphones in the setup by correlation techniques. As a consequence we can find a multiple-input multiple-output filter relating the set of independent components with the pass-by microphone time data for the same initial operating condition. If we only consider the tyre group of independent components, then we can estimate the tyre contribution time signal at every pass-by microphone and eventually the tyre noise contribution as a function of vehicle position. Figure 10 illustrates the blind separation and labelling followed by contribution analysis.

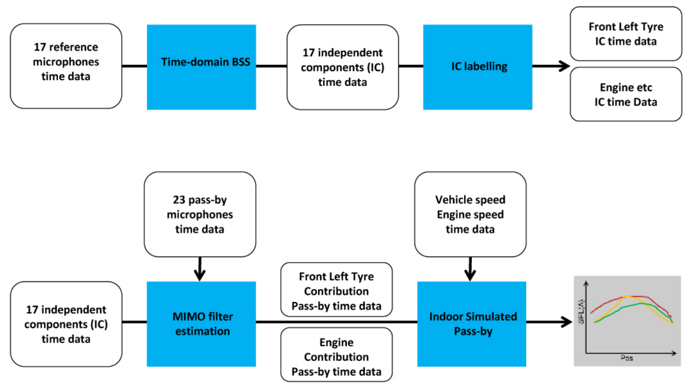

Figure 10. Blind source separation of indicator microphone data into labelled independent components (top). Pass-by contribution analysis using labelled independent components (bottom).

BSS of WOT acceleration data

Acceleration data for 3rd gear are now used as input for blind separation process in order to remove the engine related noise from that of the tyre. The full recordings of the WOT acceleration comprises around 20 seconds of data including a coast-down section. 10 seconds of time data from all 17 reference microphones is used for the blind separation into independent components following the same scheme as for speaker separation case presented previously. After the separation, a multiple-input multiple-output filter matrix is estimated taking the set of independent components as input and the reference microphone set as output. This allows to listen to the rescaled contribution from each independent source at any reference microphone. In addition, to solve the labelling problem, we establish the power contribution matrix between all reference microphones and all independent components. Each cell in the matrix provides the contribution of one independent component at the corresponding reference, see figure 11 for the result using the 3rd gear WOT data. The contributions in the matrix are wide band and all relative since all reference signals are normalised before applying blind separation. Looking at each column of the matrix we can identify where each independent component is mostly active.

Here the 4 tyre microphones are seen to contain 4 independent tyre components. We even see that two of the independent components are strong contributors at the two tyre leading edge microphones and another two components are mainly related to tyre trailing edge noise processes. Additionally these 4 tyre components contribute to the 3 reference microphones under the engine which are close to the tyre. All other reference microphones hardly pick up noise from the tyre as indicated by the contribution matrix. We can rescale these 4 tyre components to one of the reference microphones, for example the one

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closest to the trailing edge and compare with the measured data to see if we have a clean tyre noise signal. Figure 12 provides spectrogram comparison of the measured signal at the trailing edge tyre reference followed by the estimated direct tyre contribution. It appears that the crosstalk from the engine and intake has been effectively removed by the blind separation processing.

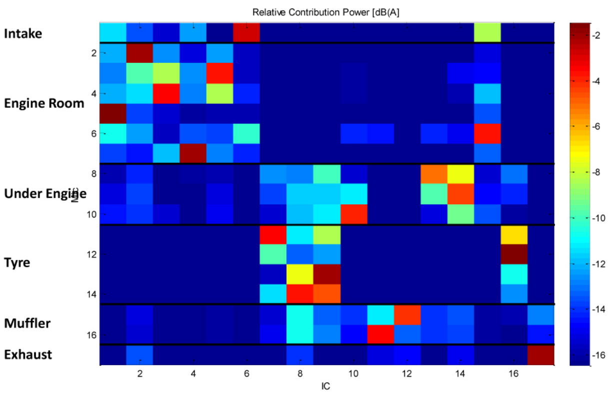
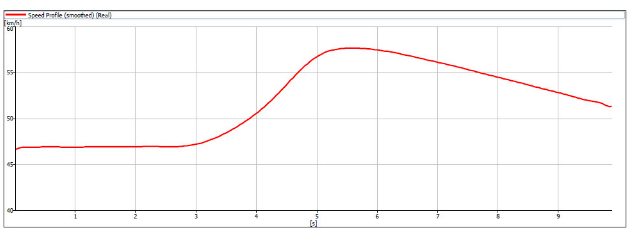


Figure 11. Contribution matrix indicating the relative power contribution from each independent component (column) to each reference microphone (row).

a)



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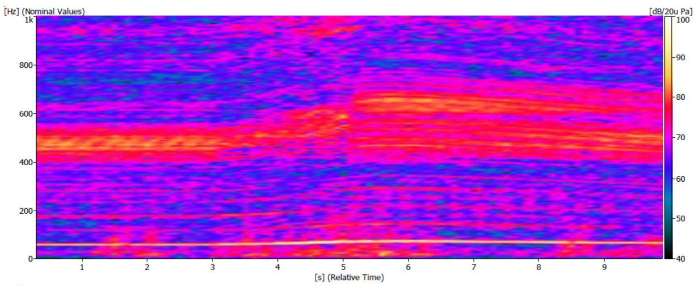

c)

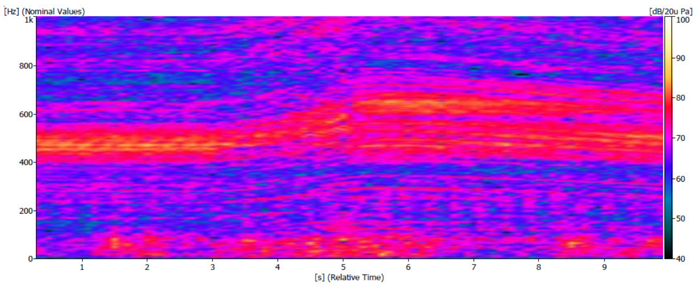

Figure 12. a) Vehicle speed profile. Spectrogram of reference microphone front left tyre trailing 3rd gear acceleration: b) raw measured c) tyre contribution.

The removal of cross-talk in particular the contribution from the engine related components is compared in terms of 1/3 octave spectra when the vehicle speed is 50 km/h during the acceleration. Results are presented in Figure 13 again for the front tyre trailing edge microphone. The removal of the engine components from the tyre microphones will affect the low frequency bands mainly. The 2nd engine order and some higher orders are clearly attenuated in the spectrum of estimated tyre contribution. Direct tyre noise dominates the frequency bands above 250 Hz.

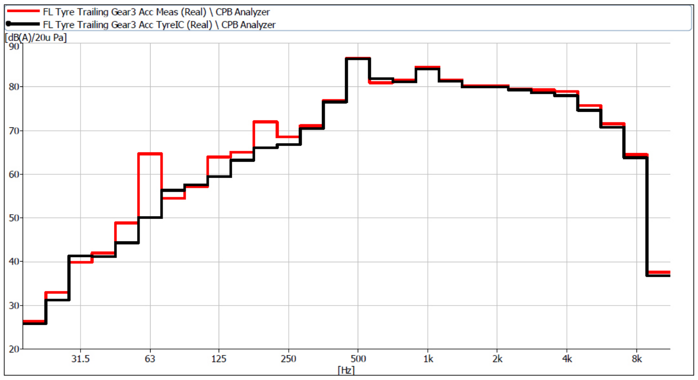

Figure 13. Third octave sound pressure spectrum for tyre trailing edge reference microphone at vehicle speed 50 km/h during 3rd gear acceleration. Raw data (red) and tyre estimated contribution (black).

Next, to perform the contribution analysis at the indoor pass-by microphones a set of filters are estimated between the independent components and the pass-by microphones using the operational data. The independent components for the tyre are passed through the filters to produce a time domain contribution at each pass-by microphone followed by an indoor pass-by simulation to get the overall SPL vs. vehicle position. A comparison is made to the indoor pass-by simulation using the measured pass-by microphone recordings. All simulations are made by setting the vehicle speed to 50 km/h at vehicle position 0 m, i.e. in the centre of the pass-by track. Obviously the tyre is a major contributor to the overall pass-by noise for this operating condition.

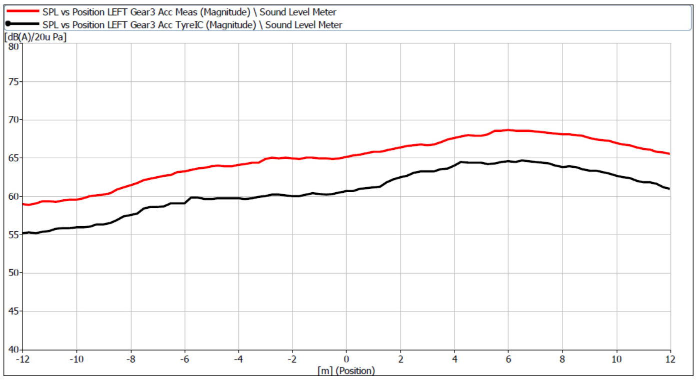

Figure 14. Overall SPL(A) vs. vehicle position for 3rd gear acceleration pass-by test. Indoor simulated pass-by measurement (red) and tyre contribution estimated by BSS (black).

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Further we may investigate which frequency bands contribute to the overall levels obtained. For vehicle position 0 m, the measured spectrum and the estimated tyre noise are compared below in figure 15. Tyre noise is seen to contribute significantly between 400 Hz and 2 kHz at this vehicle position.

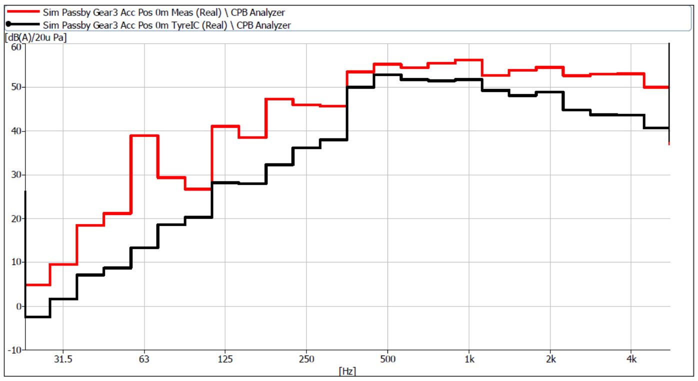

Figure 15. Third octave sound pressure spectrum of simulated pass-by signal at 50 km/h with vehicle in position 0 m. 3rd gear acceleration measured (red) and tyre noise estimation (black).

BSS of constant speed data

A similar analysis was conducted using constant speed data taken at 50 km/h in 3rd gear. Again 10 seconds of data from the recording was used as BSS input and the same set of reference microphones were considered. The processing follows the same scheme from the acceleration data processing. Again 4 independent component signals were attributed to the front left tyre. Using these 4 components we can calculate their time domain contribution to one of the tyre reference microphones. The tyre noise spectrum and the measured spectrum at the trailing edge reference microphone is plotted in figure 16. Tyre noise extraction using BSS removes some of the engine harmonics and the spectrum looks similar to the one obtained for the acceleration data at the same vehicle speed. Only difference appears to be slightly higher levels for the tyre acceleration spectrum above 1 kHz possibly due to the additional torque effect encountered by the tyre.

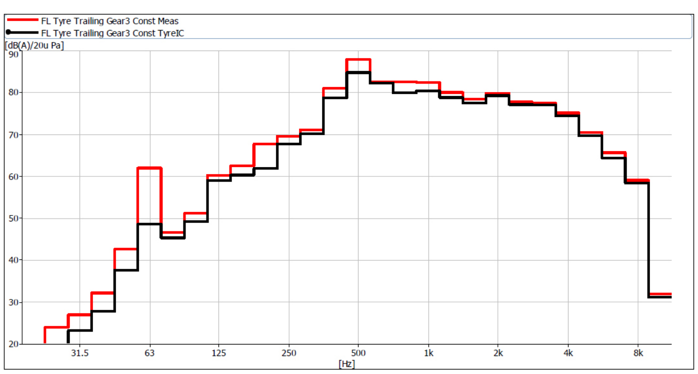

Figure 16. Third octave sound pressure spectrum for tyre trailing edge reference microphone at vehicle speed 50 km/h during constant speed. Raw data (red) and tyre estimated contribution (black).

The indoor simulated pass-by result for the 50 km/h constant speed test is plotted in figure 17 together with the tyre noise estimation. Again the estimated tyre noise contribution level is slightly lower for the constant speed test compared to the acceleration test at vehicle position 0 m, where the vehicle speed is 50 km/h in both tests.

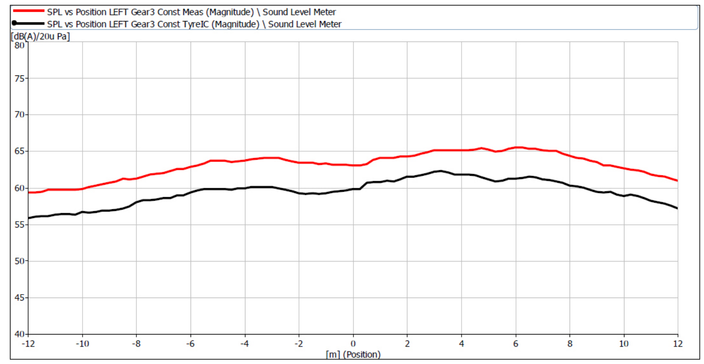

Figure 17. Overall SPL(A) vs. vehicle position for 50 km/h constant speed pass-by test. Indoor simulated pass-by measurement (red) and tyre contribution estimated by BSS (black).

Figure 18 shows a comparison of 1/3 octave spectra obtained from the indoor simulated pass-by signals corresponding to vehicle speed 50 km/h at position 0 m. Indoor pass-by measured and tyre noise contribution are compared, where the tyre noise is seen to dominate the bands from 400 Hz to 2 kHz as expected. In order to validate the tyre noise spectrum, a coast-down test with engine shut off was used to calculate the pass-by noise spectrum for the corresponding vehicle speed and position. A BSS processing of the reference microphone data for the coast-down was performed for cleaning the data from other noise sources before estimating the tyre pass-by contribution. The plot of the coast-down spectrum in figure 18 reveals fine agreement between constant speed and coast-down tyre pass-by noise spectra.

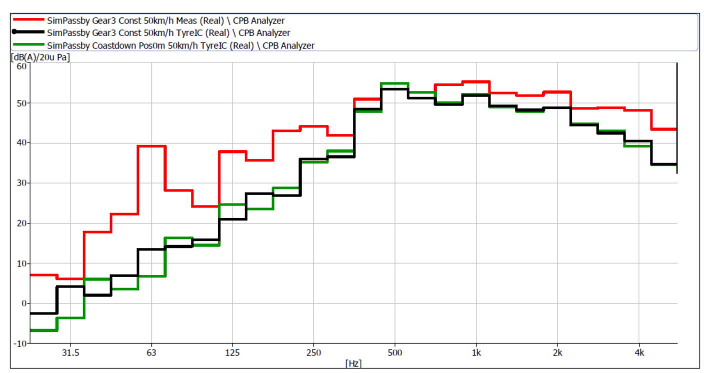

Figure 18. Third octave sound pressure spectrum of simulated pass-by signal at 50 km/h with vehicle in position 0 m. 3rd gear constant speed measured (red), 3rd gear constant speed tyre noise estimation (black) and coast-down tyre noise estimation (green).

SUMMARY

This paper introduced a new operational contribution analysis methodology based on blind source separation and independence criterion. The benefit as opposed to transfer path analysis techniques is no need to model the noise sources using point sources and no frequency response measurements with a dedicated sound source are

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required. Only a single operational measurement using reference microphones and one or several receiver microphones are sufficient for the contribution analysis.

A speaker test example was examined showing that the blind separation can deliver clean reference signals for each independent noise source. The following contribution analysis revealed almost perfect contribution results. Measurements from an indoor pass-by test were considered next to investigate the methods usability for fast and accurate tyre noise extraction even during acceleration condition. Both pass-by acceleration and constant speed tests were processed and meaningful results were obtained. Coast-down data were used to validate the constant speed results providing almost identical results.

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