Estimating Contributions of Vehicle Pass-by Noise Sources

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Abstract: This paper deals with the source separation task related to indoor pass-by noise tests. Several different approaches are discussed. The classical transfer path modelling concept making use of operational data together with acoustic transfer functions is explained and a time-domain implementation is verified for a real operating vehicle. Pass-by noise contribution from components such as engine, intake and tyres are estimated and ranked as a result of such processing. Another and completely different source separation methodology is introduced in terms of a blind source separation method for clear separation of tyre noise from engine related noise. Features of the two methods are discussed and results for the same indoor pass-by dataset presented.

Keywords: Vehicle pass-by noise, contribution analysis, transfer path analysis, blind source separation

1. 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 and several different approaches are discussed.

Typically, a source-path-receiver modelling concept is employed based on measured acoustic transfer functions and operational data during the vehicle acceleration. Other recent methodology tries 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 time-domain based source-path-receiver model will be explained as the classical methodology to perform contribution analysis. The presented implementation has the advantage that processing of data is done directly on measured time recordings with the aid of measured transfer functions. Next, 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 recording from only one acceleration test.

Different practical tests were carried out to compare the investigated methods and evaluate their 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 capabilities for a real pass-by noise scenario.

2. Indoor Simulated Pass-by Test

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 noise measurement does offer a number of advantages such as good repeatability, flexibility and ease of use.

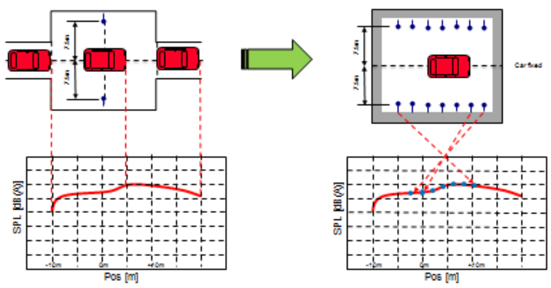

Figure 1: Field and Indoor pass-by test

Instead of making 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, see figure 2 for such an example.

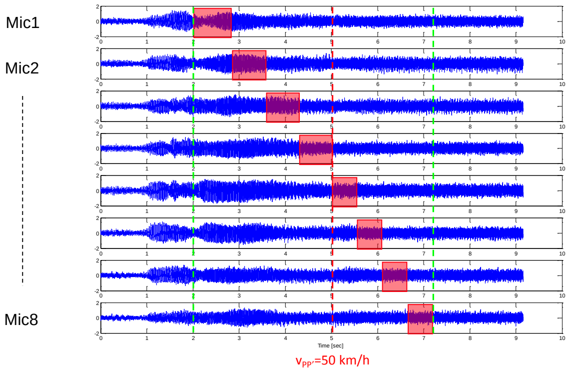

Figure 2: Example of stitching together a simulated indoor pass-by time history from 8 indoor pass-by microphones.

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 size 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. This latter feature is employed in this study.

3. Source Path Contribution

In addition to obtaining the overall pass-by noise levels from the operating vehicle individual source contributions are useful when looking for optimizations to be done. Contribution analysis is often considered using transfer path analysis techniques, here referred to as source path contribution (SPC) techniques. An airborne SPC model is defined for the vehicle modelling the radiated noise from powertrain components and tyres. The model for each component consists of a set of point sources placed at noise source locations. The source strength during vehicle operation is determined indirectly from close indicator microphones and acoustic transfer functions. Figure 3 shows a typical setup with point source positions and indicator microphones around noise sources. In this paper a pure time-domain version of the classical matrix inversion method is described and applied on recordings of vehicle acceleration data. The same time-domain SPC model can be applied to different operating conditions.

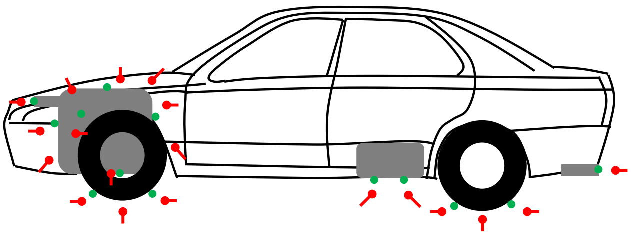

Figure 3: SPC model of vehicle noise sources

In step 1, the measured transfer function matrix between all sources and all indicator microphones is inverted and turned into inverse time filters $\boldsymbol{H}(t)$ which are convolved with any indicator operating dataset to produce estimated source strengths as time data:

$$\boldsymbol{q}_{src}(t) = \boldsymbol{H}(t) * \boldsymbol{p}_{ind}(t) \qquad [1]$$

All source strengths for the entire vehicle model are typically calculated in a single step using the full matrix approach. A more recent sub-matrix approach considers only the source and indicator microphones for each component source so a set of smaller matrices are formed compared to the full matrix [2]. Solving the matrices in an appropriate sequence allows to reduce the effect of potential crosstalk between noise source components. The benefit of having to deal with smaller matrices for components only is a smaller condition number compared to the full matrix needing proper regularisation of the matrix to obtain useful source strengths.

Step 2 involves further convolving the estimated source strengths with transfer functions representing the paths between source positions and pass-by microphones. Each contribution at a pass-by microphone is expressed as a sum over component point sources:

$$p_{rec}(t) = \sum g(t) * q_{src}(t) \qquad [2]$$

As a result we get the estimated contribution from each component noise source to each of the pass-by microphones as time data synchronised with the original recording for the considered operating condition.

Final step is to employ the indoor simulated pass-by algorithm using the estimated source contributions for the pass-by microphones and the tacho information from the original recording. The different steps in the SPC based contribution analysis for indoor pass-by are shown in figure 4.

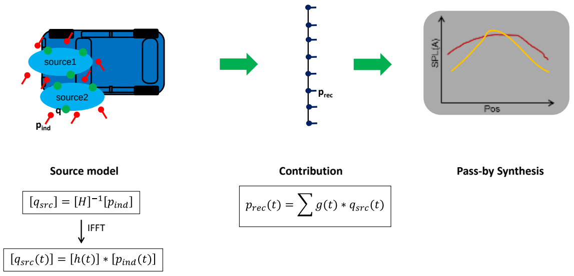

Figure 4: Pass-by SPC

4. 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 sensors is complicated by the fact that the propagation is convolutive due to delays and reflections between sources and sensors. Many different methods have been proposed in the past to solve the separation problem at the sensors, 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 [3].

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

$$\boldsymbol{u}(t) = \boldsymbol{W}(t) * \boldsymbol{p}_{ref}(t) \qquad [3]$$

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. Final step is to solve an instantaneous BSS problem looking for a matrix ***B*** which rotates the whitened data to find the most the independent time series, the independent components in the vector of time series $\boldsymbol{y}(t)$. Standard algorithms may be applied here using either higher-order or second-order statistics.

$$\boldsymbol{y}(t) = \boldsymbol{B} \cdot \boldsymbol{u}(t) \qquad [4]$$

Such two-stage linear prediction approach for solving the convolutive BSS problem has been proposed for blind identification of communication channels [4] and other variants of this implementation for source separation are reported as well [5].

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 unmixing filters. This so-called subband processing is a standard BSS procedure and after processing the time data can be up-sampled again [6]. 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 independent component order 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 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. The setup and the steps involved in the BSS based contribution analysis for indoor pass-by are shown in figure 5.

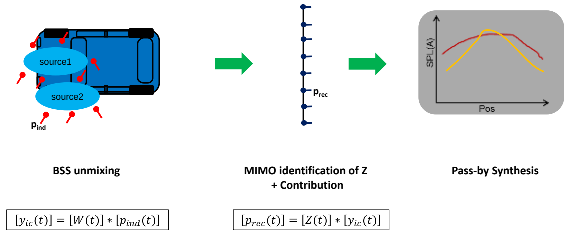

Figure 5: Pass-by BSS

5. Experimental Indoor Pass-by Test

A setup with a vehicle on a chassis dyno in an indoor pass-by test room is now considered. The test room could only 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. The midsize passenger test vehicle was equipped with normal tyres making tyre contribution to pass-by noise significant. In total 25 indicator microphones were placed close to potential noise sources (engine, intake, mufflers, exhaust and tyres) of the vehicle and 20 source positions were distributed among these noise sources. The contribution from the right-hand side tyres to the left-hand side pass-by noise is neglected in this study, hence no indicator microphones were placed close to these tyres. 12 pass-by microphones covered the left hand-side of the vehicle. The spacing between the pass-by microphones was 1 m for the microphones closer to the vehicle whereas other microphones were spaced by 2 m. A picture of the single-sided indoor pass-by setup is shown in figure 6.

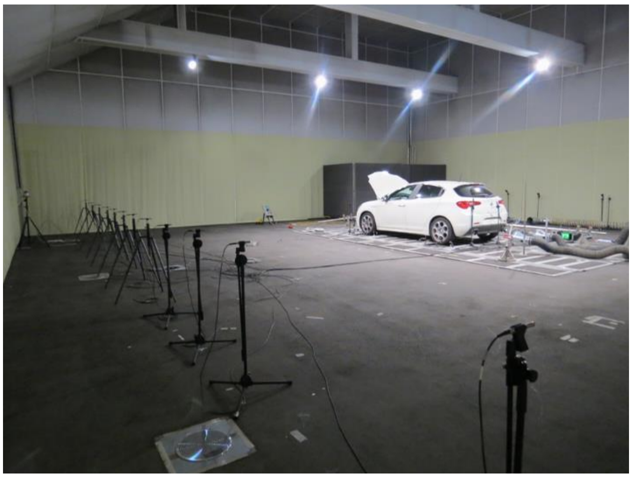

Figure 6: Indoor Pass-by Measurement Setup

The layout of sources, indicator microphones and pass-by microphones is provided below in figure 7, indicating as well the positions of the considered noise source components for this particular vehicle.

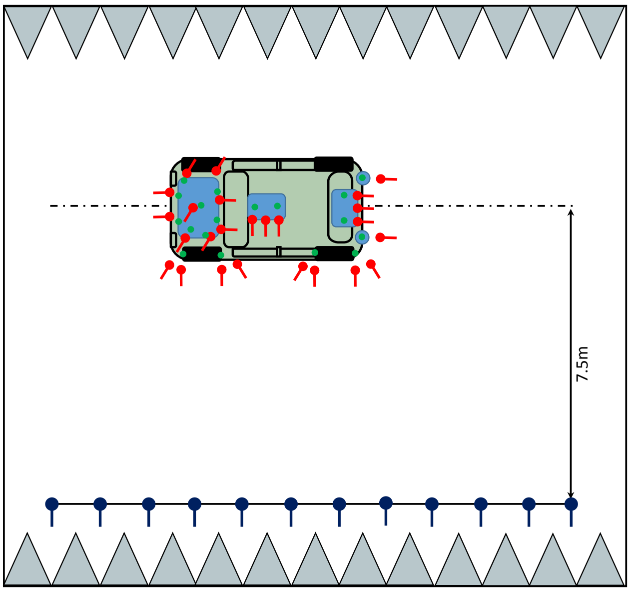

Figure 7: Setup in semi-anechoic chamber

Two separate measurement tasks must be completed to do the indoor pass-by test including the additional contribution analysis. For different pass-by conditions (acceleration and constant speed test) time data of all microphones in the setup and the required tachometer pulses were recorded with a sampling rate of 16384 Hz. For acceleration tests, a full recording of the run-up is done including the relevant data for the simulated indoor pass-by test. Following the operational measurements, a volume velocity source was used to measure acoustic transfer functions from a source position to all microphones in the setup, i.e. all indicator microphones and pass-by microphones are included in the transfer function measurement. This is repeated for every source position of the vehicle SPC model. The frequency range considered for these tests was up to 6.4 kHz limited by the sound source. The sound source used is shown below in figure 8 with a hose attached.

Figure 8: Sound source used for acoustic transfer function measurements

The volume velocity source estimates the frequency dependent source strength output at the hose opening from two microphones in an adaptor close to the opening, hence no calibration of the source itself is needed. The flexible hose between speaker and the adaptor makes it easy to move around from one position to the next, and engine room positions can easily be included as well.

Figure 9: Two-microphone adaptor of sound source located in engine room

6. Results of SPC Processing

An acceleration test in 3rd gear is analysed using a dataset performed as described previously. The synchronization condition chosen here is 50 km/h at the center (x=0 m) of the virtual pass-by track according to the new ISO 362 test procedure. From that condition the simulated pass-by time signal is constructed and turned into overall SPL(A) as a function of the vehicle position inside the virtual pass-by track. This process is carried out for the recordings made at the pass-by array microphones during the acceleration test and also for the source contributions resulting from the SPC analysis of the indicator microphone recordings and the corresponding transfer functions. From the initial set of source and indicator positions a subset was selected to avoid numerical problems during the calculation of source strengths. 24 indicator microphones and 15 source positions were used for the SPC contribution analysis and the component sub-matrix solution approach described earlier was adopted with an appropriate sequence to minimize the influence of crosstalk between source components. The result of summing all source contributions and compare with the indoor pass-by result can be used to verify that all pass-by noise contributors were picked up by the indicator microphones. Processing results for the acceleration operating condition are shown in figure 10. Notice, that the result is shown from vehicle position -10 m to +10 m although the pass-by microphones only covered the vehicle positions from roughly -4 m to +10 m, so the extrapolation capability of the indoor pass-by calculation has been used. We observe fine agreement between the indoor pass-by result and the sum of all contributors from the vehicle SPC model, i.e. all significant noise sources are included in the analysis. Individual contributions reveal dominating engine noise contribution to pass-by noise with intake and tyre noise contributing significantly as well. The exhaust outlet is a major contributor towards the exit of the pass-by track.

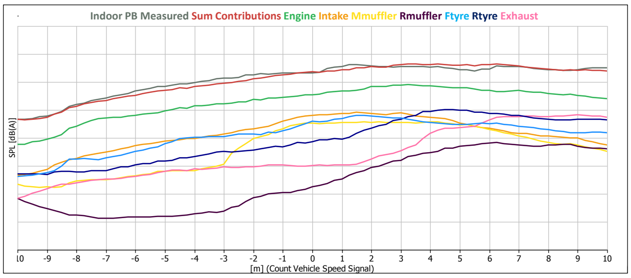

Figure 10: Indoor simulated pass-by result and source contributions for 3rd gear acceleration

For a given vehicle position the 1/3 octave band levels can be investigated to see how the peak overall SPL(A) is composed. Figure 11 provides the 1/3 octave contribution levels at vehicle position +4 m. Acceptable agreement between what is measured by the pass-by microphones and the model prediction (Sum Contributions) is found. Engine contribution is dominating most of the frequency bands with significant tyre contribution at higher frequencies in particular in the 1 kHz band.

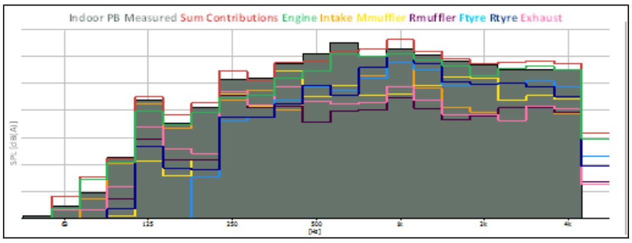

Figure 11: 1/3 octave contribution analysis corresponding to vehicle position +4 m during acceleration pass-by test. Indoor pass-by result and SPC source contributions.

The SPC modeling of the vehicle revealed fine agreement between the noise prediction and the direct result from the pass-by microphones however the individual source contributions are by nature more difficult to validate. The attempt taken here will be to make use of the described blind separation technique to estimate the pass-by noise contribution from the front and the rear tyre, respectively, and compare with the SPC prediction.

7. BSS Processing

The measured set of indicator recordings can serve as input data (reference microphones) to the blind separation process of identifying a set of independent components for the noise processes during vehicle operation. In this study 23 reference microphones were selected from the 25 available indicator microphones. 2 engine room indicator microphones were discarded. From the 3rd gear acceleration recordings, 12 seconds of data were picked representing the run-up/down part, and this time data was down-sampled to a sampling frequency of 8192 Hz to reduce the amount of data. In effect, only the frequency content up to 4096 Hz is considered.

The blind separation of the 23 reference microphone channels results in 23 independent component time signals which are sorted according to their power contribution at the 23 reference microphones. The power contribution of each IC to each reference microphone is calculated in the band up to 4096 Hz and A-weighted to adapt to pass-by measurements. As a result, we will have a 23 by 23 matrix of power contributions from each IC (column) to each reference (row) used as input to BSS. Figure 12 is a result of this procedure for the full 3rd gear acceleration condition. The highest contribution levels indicate the physical origin of the IC's.

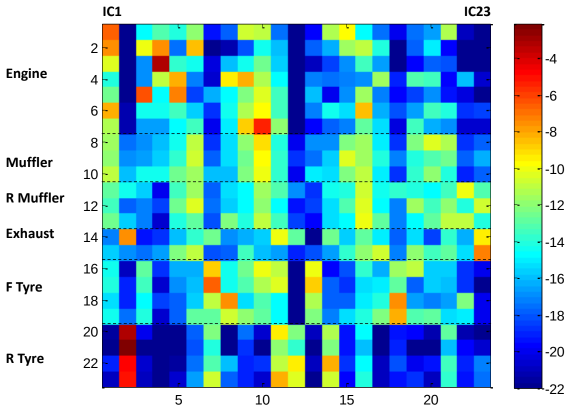

Figure 12: Matrix of full-band power contribution of each independent component to each indicator microphone.

4 of the independent components were selected to represent noise processes caused by the front tyre and another 4 independent components represent the rear tyre.

Further, to understand if all the derived 23 independent components can represent the measured noise at the pass-by microphones the multiple input-multiple output problem between all independent component signals and all pass-by microphone signals is solved to obtain a matrix of time filters. All 23 independent components can be filtered and summed at one of the pass-by microphones and we can compare with the actual measured signals during the run-up and coast-down. The average spectrum comparison between the measurement and sum of all independent component contributions is performed for pass-by microphone #5, see figure 13. Excellent agreement between what is measured at this pass-by microphone and what can be explained by the 23 independent components is observed, only above 1.6 kHz we see some deviations.

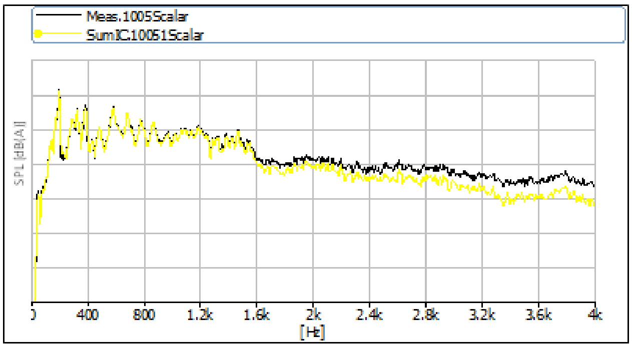

Figure 13: Average SPL(A) spectrum at pass-by microphone #5 during gear 3 acceleration. Measurement (black) and sum of all IC contributions (yellow).

Having established the matrix of filters between each independent component signal and each pass-by microphone, we can calculate and listen to the contribution from each independent component at a pass-by microphone. Furthermore, the contributions of the 4 identified independent components for each of the two tyres are summed at every pass-by microphone and the resulting time signals are combined with the original tacho signal recordings for indoor simulated pass-by evaluation. As a result we get an estimate of the front tyre and the rear tyre pass-by noise contribution provided by the BSS approach.

An overview of the BSS processing based on the data from the described setup is shown in compact form in figure 14.

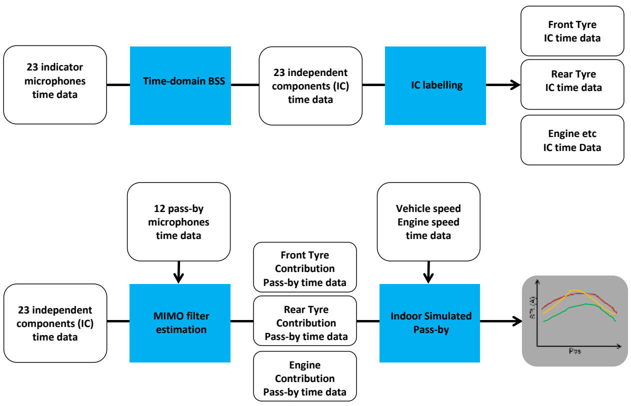

Figure 14: BSS processing of indicator microphone time data and pass-by contribution analysis

8. Tyre Pass-by Noise Estimates

Finally we will compare the estimates of tyre noise contribution during the pass-by acceleration test obtained from BSS and SPC. Both methods provide the contribution from either the front and the rear tyre to the left hand side pass-by noise as detailed in the previous sections.

Comparison of the front tyre contributions relative to the overall vehicle pass-by noise is provided in figure 15. The BSS estimation shows higher levels than SPC for all vehicle positions and especially towards the exit of the pass-by track they agree quite well. Similar result is obtained for the rear tyre contributions, see figure16.

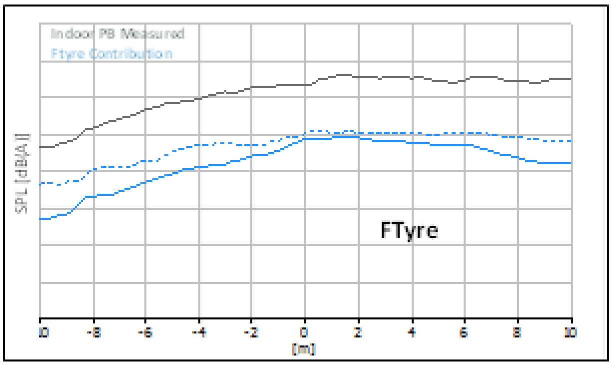

Figure 15: Front tyre contributions to pass-by noise during gear 3 acceleration. SPC (solid) and BSS (dashed).

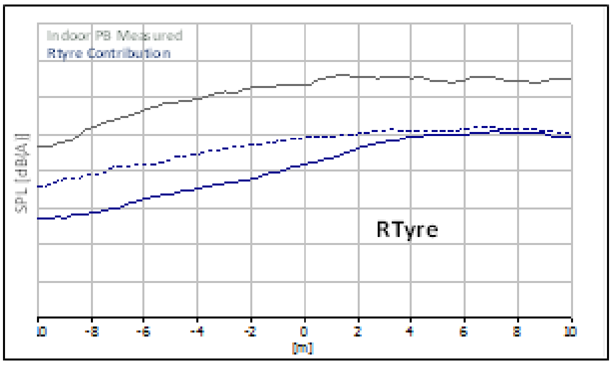

Figure 16: Rear tyre contributions to pass-by noise during gear 3 acceleration. SPC (solid) and BSS (dashed).

In addition to comparing the overall SPL levels for the two methods we can investigate the 1/3 octave spectra at a certain vehicle position, here we choose the +4 m position which is close to the maximum of the overall vehicle noise. Again we compare the spectra of the front and rear tyre contributions from either SPC and BSS. The measured spectrum at the same vehicle position using the pass-by array microphone recordings is provided in the same plot for comparison.

The front tyre contribution spectrum, seen in figure 17 shows that the 1 kHz band is dominating which is as expected. Above 500 Hz the estimated contributions agree quite well, and this is the range where the tyre is contributing to the overall radiated vehicle noise.

The rear tyre contribution spectra as shown in figure 18 reveal even more comparable spectra obtained from the two methods. Again with the 1 kHz band dominating the tyre noise contribution. Further we can deduce that the total tyre noise at this vehicle position is the main contributor at frequency bands 1 kHz and higher.

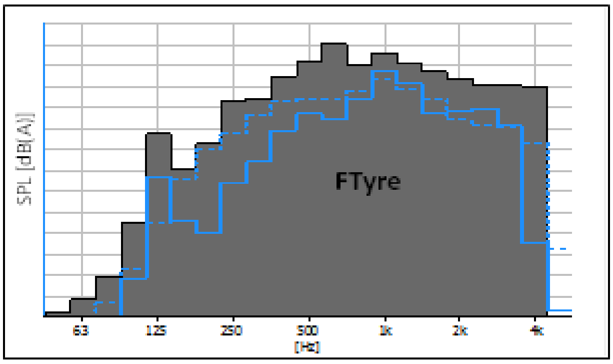

Figure 17: 1/3 octave spectrum at vehicle position +4 m during gear 3 acceleration pass-by test. Indoor PB measured (grey) and front tyre contributions (SPC=solid, BSS=dashed).

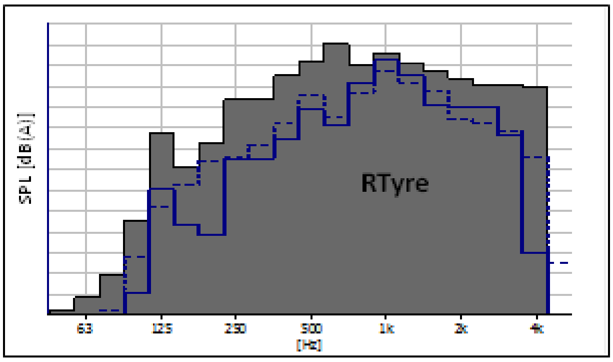

Figure 18: 1/3 octave spectrum at vehicle position +4 m during gear 3 acceleration pass-by test. Indoor PB measured (grey) and rear tyre contributions (SPC=solid, BSS=dashed).

9. Conclusion

This paper has described indoor vehicle pass-by noise measurements for performing noise source contribution analysis. Two different methods for estimating vehicle noise source contributions were described. The vehicle SPC model tries to model all major noise sources using point sources and by combining operational acceleration data and transfer functions a real test case was used to provide results and verify this approach. The predicted pass-by noise from the vehicle SPC was compared with the indoor simulated pass-by result to verify the sum of all modelled contributions. Good correspondence was found. Individual source contributions are more difficult to verify, the attempt described here was to use an operational blind source separation technique for decomposing into at least individual tyre and engine-related noise contributions. Considering the assumptions in SPC and BSS, fine agreement between predicted tyre pass-by noise contributions were found. The BSS approach for noise source separation needs more examination to determine how many reference microphones are needed to have adequate separation of vehicle noise sources. Further validations of both methods for accurate contribution analysis will be done.

10. References

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11. Glossary

BSS: Blind Source Separation

IC: Independent Component

ICA: Independent Component Analysis

ISO: International Organisation for Standardization

MIMO: Multiple Input Multiple Output

SPC: Source Path Contribution

SPL: Sound Pressure Level