Indoor pass-by noise engineering:

a motorbike application case

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ABSTRACT

Pass-by noise testing is nowadays a well-defined procedure in the development process of motorbikes. Manufacturers facing issues of non-compliance with regulations are looking for techniques to quantify the subsystem noise contributions, enabling the validation of designs for pass-by noise targets, early in the design process.

Masking techniques are nowadays often used to separate the noise source contributions. However, since these techniques are time consuming and also have an influence on the operating conditions, motorbike companies are seeking for faster solutions.

In this study, a time-domain TPA method was investigated and tested on a Piaggio Beverly 350 in an indoor pass-by noise test. The method consists in the application of time-domain filters, derived from FRF measurements, to microphone measurements close to the noise generating components. The results are time histories of the acoustic loads and partial contributions to the array of target microphones on the two sides of the testing room. The synthesized target response signals are mixed together into an overall pass-by noise level by taking into account the speed profile of the motorbike.

The TPA method helps engineers to quantify the noise contributions to the overall pass-by noise level, with a remarkable time saved compared to the masking approach.

Keywords: Transfer Path Analysis, Exterior noise regulation

I-INCE Classification of Subjects Number(s): 13.2.2

1. INTRODUCTION

Road transportation noise is growing concern among people which, particularly, refers to motorbikes as the most annoying environmental noise sources (1). For this reason legislations define pass-by noise test procedures that have to be observed in order to comply with the maximum noise emission limits (2). Nevertheless current legislations are going to be reviewed in order to define better, and more constrained, test procedures reflecting the reality of urban traffic noise. The result is an updated standard including a combination of Wide Open Throttle tests (WOT) and constant speed tests (3). The more constrained test procedures will force motorbike manufactures to adjust on one hand the noise emitted level, while on the other will leave less room to play with how the motorbike sounds (4).

Pass-by noise testing is nowadays a well-defined procedure in the development process of motorbikes. Manufacturers facing issues of non-compliance with regulations are looking into techniques allowing to set targets for the different noise sources (intake, engine, gearbox, exhaust, tires, etc) and by doing so to frontload the pass-by noise performance into the design process. Masking techniques are often used to separate the contribution of the closely spaced noise sources. However, since these techniques are time consuming and also have an influence on the operating conditions, motorbike companies are seeking for alternative and faster solutions to identify the noise source contributions.

This paper presents a linear time-domain Airborne Source Quantification (ASQ) method applied on a Piaggio Beverly 350 on data measured in the context of an indoor pass-by noise test. The proposed method consists of applying time-domain filters, derived from FRF measurements, to microphone recordings measured in the close vicinity of the noise generating components. The results are time

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histories of the acoustic loads and their partial contributions to the array of target microphones on the two sides of the testing room. The synthesized target response signals are finally mixed together into an overall pass-by noise level by taking into account the speed profile of the motorbike.

The described method allows to quantify the noise contributions of the different subsystem components to the overall pass-by noise level, with a remarkable time saved compared to the masking approach.

The paper is organized with the following structure: in the chapter 2 the linear time-domain ASQ technique is presented, reasons to use this approach are discussed; then in chapter 3 the method is tested and validated in a motorbike indoor pass-by noise test. Results of the source contribution analysis are presented for the operational run-up condition (ISO 362-2007).

2. THE TECHNIQUE

Airborne Source Quantification (ASQ) is a technique, related to Transfer Path Analysis, adopted to separate different airborne noise sources and evaluate their individual contribution toward a specific target level. It can be applied to the outdoor, as well as to the indoor pass-by noise testing (5). Indoor testing has gained importance among vehicle (automobile, motorbike) manufacturers because of its simplicity in the measurement setup. Independence from weather conditions, the high tests repeatability and the possibility to extend the setup for more in-depth analysis are additional advantages of the indoor testing compared to the outdoor.

In the case of motorbike indoor pass-by-noise test, the motorbike is placed on a chassis dynamometer in a semi-anechoic chamber with the objective of simulating the same operational conditions as on the road. Linear arrays of pass-by microphones are mounted along both sides of the test vehicle covering the distance of the test (from -10m to +10m). The pass-by noise level is computed by interpolating the noise levels measured from the pass-by noise microphones by taking into account the speed profile of the motorbike measured from a tacho sensor mounted on the roller bench.

The proposed technique consists of 4 different steps: in the first step the linear ASQ model is developed, then the time domain synthesis of the loads and contributions to each target location are computed. Synthesized contribution signals are mixed together into an overall pass-by noise level by taking into account the speed profile. Finally each contribution to the pass-by noise overall level is analysed.

2.1 Linear ASQ model

The first step of the process consists of developing the frequency domain ASQ model. For a motorbike pass-by noise testing application, the proposed technique is based on a linear ASQ model. The presence of closely spaced and cross-correlated noise sources makes the assumption of incoherent loads, fundamental to use the power-based ASQ model, unrealistic.

The linear ASQ method consists of discretizing the noise radiating components in coherent point sources (patches) (6), respecting a spacing of less than half of the acoustic wavelength for the maximum frequency of interest. This would represent a limitation in case of automobile pass-by noise. However for a motorbike pass-by noise application case, since the source noise signature is characterized by low frequency and sharp harmonics and, next to this, the radiating surfaces dimensions are relatively small, the linear ASQ approach can be considered a suitable method to obtain reliable pass-by noise contributions results. In order to ensure the method accuracy up to 2kHz, patches of 8x8cm were considered. A total of 41 sources was sufficient to discretize the complete radiating surfaces.

The method is based on the source-transfer-receiver concept that allows to evaluate the contribution of each noise source toward a target microphone (7). Figure 1 presents an overview of the source-transfer-receiver concept. The synthesized pressure response at each pass-by noise target microphone location can be expressed using equation 1:

$$y_k(\omega) = \sum_{i=1}^{n} NTF_{ki}(\omega) \cdot Q_i(\omega) \tag{1}$$

where y_k represents the summed of the n sources contribution at the k target microphone, Q_i the acoustic loads and NTF_{ki} the noise transfer functions between each load and each target.

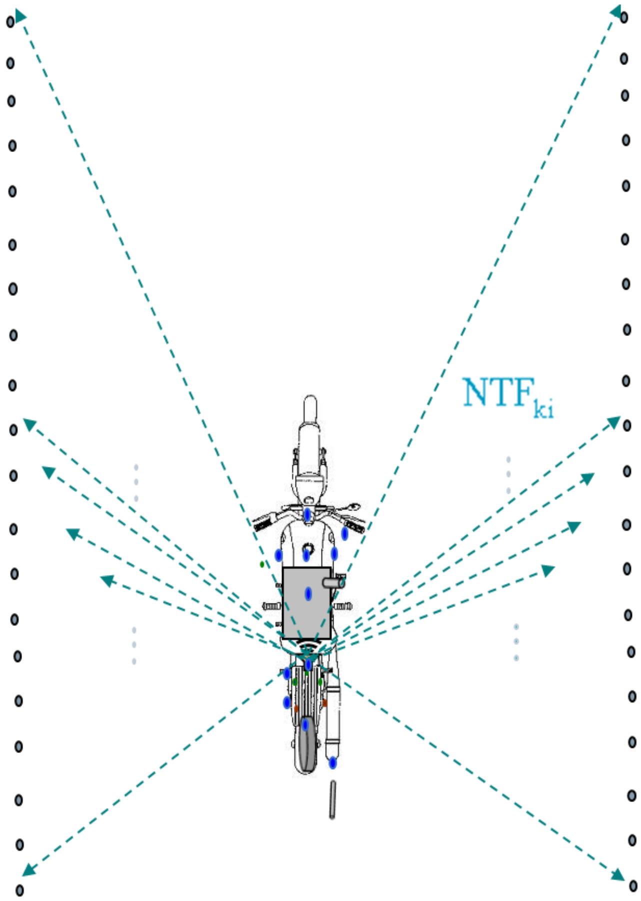

Figure 1 – Source-transfer-receiver concept

Acoustic loads Q_i are identified using an inverse estimation approach. A set of indicators microphones is randomly distributed in the close vicinity of the noise sources. A local noise transfer function matrix H_{ij} is measured between each source location and all the indicators during a separate test. The operational loads are then identified from the indicators synchronously measured during an operational test by inverting the local transfer function matrix (Equation 2):

$$Q_i(\omega) = \left[H_{ji}(\omega)\right]^{-1} \cdot u_j(\omega) \quad (2)$$

Where Q_i are the in-operation acoustic loads, u_j are the indicators microphones and H_{ij} is the matrix containing the local noise transfer functions. The inversion is performed for the complete matrix including all the cross-terms. The number of indicators is selected higher than the number of sources, respecting an over-determination factor to ensure the stability of the matrix inversion. As can be noticed, equation 2 is a linear formulation of the load identification, the phase relation between sources and indicators is maintained.

The complete ASQ model is then composed by a matrix of transfer functions measured from each source location to each pass-by noise target microphone, and a matrix of local transfer function measured from the loads to the indicator microphones. Both transfer functions matrices can be measured in a direct way from each source location to all the indicators and all the pass-by noise microphones simultaneously reducing considerably the measurement time.

In the motorbike application case presented in this paper, the transfer functions were measured in a direct way using a calibrated volume velocity source characterized by a frequency range spanning from 150Hz to 10kHz. Alternatively, reciprocal procedures could be followed.

The linear ASQ model is applied in the complete frequency range measured by the transfer functions, although above 2kHz the amount of point sources is not sufficient anymore to fulfil the rule of thumb of one source every less than half of the acoustic wavelength for the maximum frequency of interest. Stretching the linear method at high frequency is only an approximation, suited for a motorbike pass-by noise application case, to make the technique simple and computationally fast in getting contribution results, yet maintaining the correctness of the contribution results with minimum errors.

2.2 Time domain synthesis

In this step time domain loads and partial contribution of each load to the target microphone locations are computed by the use of FIR filters derived from the frequency-domain ASQ model. FIR filters are directly applied to the measured indicators time data to synthesize the acoustic loads and their partial contributions to the targets. Partial contributions are then summed together to obtain the total contribution to each of the pass-by noise microphone target. Fast FFT Convolution filters are used to perform the required time-domain filtering. This FFT-based implementation makes use of the well-known Overlap-Add method. A proper filter pre-processing (treatment of delays, etc.) is important, making sure that the filters are causal and do not generate artefacts in the synthesis.

Time-domain synthesis allows to obtain streams of time data (loads, partial contributions, summed contributions) enabling dedicated pass-by processing both in time and frequency domain. By replaying the synthesized time data, sound quality analysis for subjective perception assessment can be performed.

Figures 2 to 4 show the time-frequency map comparison between the measured target (above) and the time-domain ASQ total contribution result (below) for a run-up case for three pass-by noise microphones (front: -5.79 m, centre: 0.217 m and back: 5.355 m). As can be noticed, the linear approach is able to correctly predict the sharp harmonic components in the low frequency region of the spectrum below 1,5kHz, while, as expected, at high frequency some differences can be noticed.

However, since the noise level at high frequency is more than 10dB lower than the low frequency one, the error committed by applying the linear ASQ method in the complete frequency range (150Hz-10kHz) can be considered negligible.

Similar time-frequency maps can be produced for each of the noise sources contributions to each of the target pass-by noise microphone.

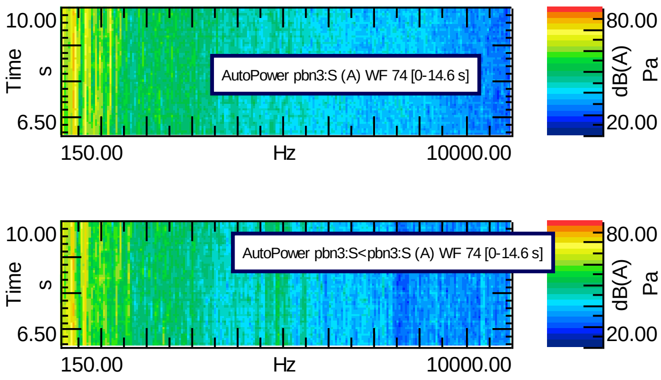

Figure 2. – Time-frequency map of the measured noise (above) and the total synthesis (below) for the front pass-by noise microphone (position = -5.79 m)

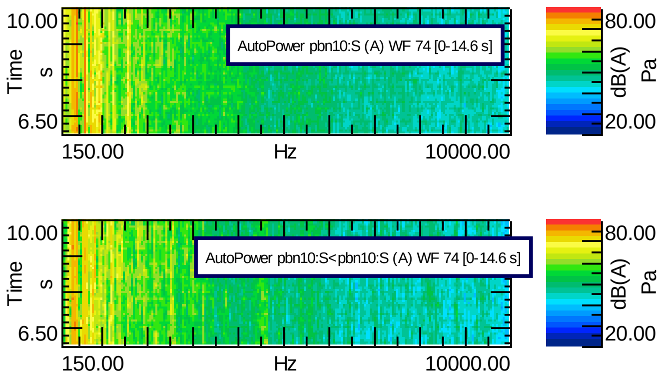

Figure 3 – Time-frequency map of the measured noise (above) and the total synthesis (below) for the centre pass-by noise microphone (position = 0.217 m)

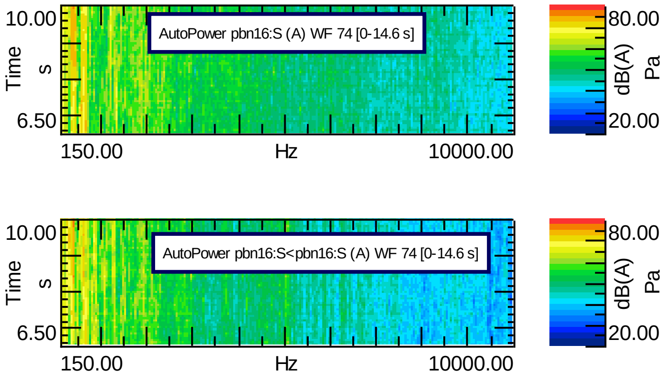

Figure 4 – Time-frequency map of the measured noise (above) and the total synthesis (below) for the back pass-by noise microphone (position = +5.355 m)

2.3 Pass-by noise synthesis

In the third step of the method, pass-by sounds are generated for the zero position (position = 0) on the microphone array by recombining the target responses synthesized in the previous step by taking into account the speed profile of the vehicle measured from the chassis dynamometer.

The pass-by sound is generated by running through the different target microphones, from the front towards the back, and meanwhile mixing the sounds of the closest two microphones.

2.4 Pass-by noise contribution analysis

The synthesized pass-by noise signals allow several interesting analyses such as: the analysis and ranking of the different noise source contributions during a pass-by, and detailed time-frequency analyses.

3. MOTORBIKE APPLICATION CASE

The described technique was tested and validated with an indoor motorbike pass-by noise test. The motorbike tested was a Piaggio Beverly 350 IE, as shown in figure 5. The described time-domain linear ASQ method was applied to compute the main noise sources contribution to the measured pass-by noise level.

Figure 5 – Motorbike indoor pass-by noise application case

3.1 Instrumentation

A total of 6 main noise sources was considered: engine, transmission, intake, gearbox, exhaust and tire. Figure 6 presents a back view of the tested motorbike showing some of the considered noise sources. The noise radiating surfaces were divided in 41 patches with a dimension of 8x8cm each. A total amount of fifty-nine indicators were distributed randomly in the close vicinity around the considered noise sources. A sufficient over-determination between sources and indicators was required in order to obtain a well-conditioned matrix ensuring a stable solution of the matrix inversion. A total of nineteen target microphones were mounted on the right side of the test room. The transfer functions were measured in a direct way by positioning the calibrated volume velocity source on each source location. The used calibrated source had a frequency range excitation of 150Hz-10kHz. A total amount of 3198 noise transfer functions were acquired in half day.

One of the crucial points of the transfer path analysis is that the noise transfer functions are characteristics of a linear time-invariant system, and they are also representative for every operational condition. Therefore once the transfer functions are acquired, the system must remain invariant. If the system is modified and its dynamic behaviour is changed, the transfer functions need to be measured again.

In order to obtain a similar system behaviour as in operational conditions, transfer functions were measured by placing a weight of 50kg on the motorbike seat, simulating the presence of a rider. The shock absorbers of motorbikes were very soft so that when someone was sitting on it a large displacement on the height of the seat was observed, with consequent modifications of the system characteristics. Additionally the motorbike was firmly fixed at the front wheel to the ground in order to avoid excessive movements during the operational tests. Depending on the frequency, excessive variations of the motorbike position may introduce from small to large deviations from the identified system characteristics. System modifications larger impact the high frequencies compared to the low frequencies.

The instrumentation of the pass-by noise engineering test took in total 2.5 days, including indicators microphones positioning, pass-by noise microphones arrangement and transfer functions measurement. Once the setup was ready the operational tests took half of a day. The complete pass-by noise test campaign took in total 3 working days.

Operational measurements were performed using smooth roll surfaces in the chassis dynamometer. Different operational conditions were performed from a constant speed tests to wide open throttle tests. Pass-by noise microphones and all the indicators were measured synchronously at 25600Hz of sampling frequency.

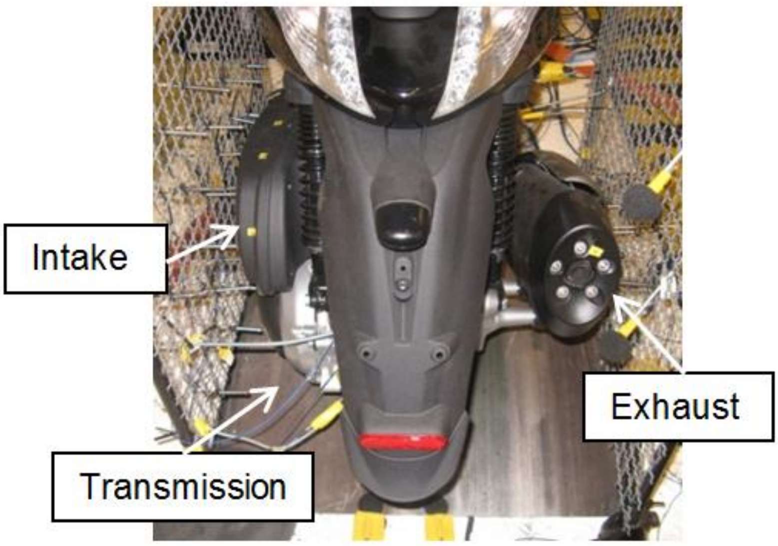

Figure 6 – Back view of the tested motorbike. Some of the noise sources are shown: intake, transmission and exhaust.

3.2 Results

Figure 7 presents the pass-by noise overall level results in function of the motorbike positions for the right side of the pass-by test. The results are obtained by tracking the time evolution of different source contributions during the test.

The differences in the source ranking are clearly observable. As expected the back tire reveals to be the less dominant source, while the transmission has the largest contribution to the right side of the pass-by noise for the complete test. Even if the transmission is positioned on the left side of the motorbike, as shown in figure 6, it has a large contribution to the pass-by because the emitted noise radiates through the wheel toward the right side without obstacles. While the noise contribution of the intake, mounted as well on the left side of the motorbike and well-shielded toward the right side, shows a small level decrement in the middle of the pass-by test. Finally the exhaust contribution shows a significant increase when the motorcycle is passing by.

The total contribution is clearly very similar to the measured right side overall pass-by level. Small deviation in the total noise synthesis can be attributed to slight movements of the motorbike in acceleration phase during the operational tests.

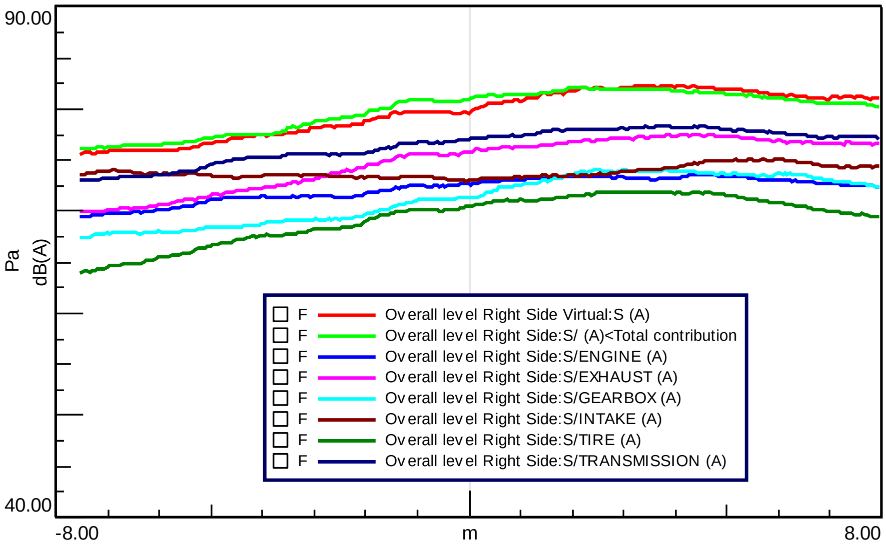

Figure 7 – OA-level of source contributions in function of the motorbike position for ISO 362 run-up

4. CONCLUSIONS

A linear Airborne Source Quantification method for source contribution analysis has been applied on an indoor motorbike pass-by noise application case. The method consists on a linear transfer-path-receiver concept used to separate the closely-spaced and cross-correlated noise sources and evaluate their contribution toward the pass-by noise target microphones.

The ASQ model is then converted in a time-domain fashion by deriving time-domain FIR filters from the measured transfer functions. FIR filters are applied to microphone recordings measured in the close vicinity of the major noise components (engine, transmission, intake, gearbox, exhaust and tire). The results are time histories of the acoustic loads and their partial contributions to the array of target microphones on the two sides of the testing room. Finally the synthesized target response signals are mixed together into an overall pass-by noise level.

The method proved to provide realistic results for pass-by noise contribution analysis of a motorbike application case in the frequency range from 150Hz to 10kHz. Results were obtained in 3 days with a remarkable time saved compared to the masking technique.

Future work will focus on extending the frequency range of the synthesized pass-by noise down to lower frequencies using volume velocity sources with lower cut-off frequency.

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