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NOISE ANALYSIS INSIDE AN ELECTRIC VEHICLE DURING A RUN UP ON THE ROAD AND ON THE CHASSIS DYNAMOMETER

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Abstract: *Acoustic tests were made on an electric car operating on the road and on a roller bench in order to analyze the noise inside the passenger compartment generated during acceleration. Waterfall diagrams of the sound pressure level were plotted with fixed sampling and tracked against the rpm of the motor. It was concluded both from the tests and from the analysis that the car was rather quiet, and most of the noise came from tire-road interaction and from the aerodynamic turbulences. Along with this broadband noise, some tones were detected, corresponding to the 24, 48 orders of the electric motor. Order sections were extracted from the waterfall diagrams. The orders from the two tests were compared and the differences analyzed with respect to the environment conditions. The noise from the chassis dynamometer raised the pressure level of the order related phenomenon and a semi-stationary averaging was applied to lower it.* ***Keywords:*** *electric car, waterfall analysis, order cuts, semi-stationary averaging*

1 INTRODUCTION

Electric cars are perceived by the public as quiet cars in general. In the city traffic they are potential threats for pedestrian, cyclists and blind people because their approach is hard to detect in time. For this reason governments all over the world are discussing and working on draft legislations to impose a minimum level for the emitted noise.

In a previous study performed by the authors on an electric car in operating conditions [4], it was revealed that along with the noise produced by the contact of the tire threads with the road surface and by the aerodynamic turbulences, some tonal components were perceived by the driver and occupants. These tones were associated with the electric motor orders [5,7].

Orders are harmonics of the rotating speed of moving elements. In this case, the considered elements are the rotor from the electric motor and the shafts from the gearbox. They generate vibrations determined by the electromagnetic forces between the magnets on the rotor and the poles on the stator, respectively by the gear mesh. To analyze these orders, the proper operating conditions had to be chosen for testing.

This paper proposes two kinds of testing, a run up of the car in normal operating conditions on the road and another one in a controlled environment, namely on a chassis dynamometer (chassis dyno) placed inside a semi anechoic chamber as can be observed in Figure 1.

For these tests, the car was instrumented with tacho sensors to register the rotational velocities of the wheels and with microphones placed inside the passenger compartment according to ISO 5128:1980 [8], and inside the motor compartment.

Figure 1. Electric car testing on the chassis dyno inside an semi anechoic chamber

The purpose of the tests was to use the measurements in order to create maps of the noise relative to the rpm of the electric motor, which are known as waterfall diagrams. Once these were created, it was possible to analyze the orders individually by extracting them from the waterfall diagrams.

But order extraction can be tricky and the quality of analysis depends on some aspects. This paper treats the problem of order sections shape, which can influence the percent of order energy/noise used for integration. Another discussed issue was the smearing produced by the order in frequency domain during the time interval needed to acquire a noise sample.

2 IMPORTANCE OF ACQUISITION TIME AND TRACKING PARAMETERS FOR DATA PROCESSING

The analysis of a waterfall diagram is influenced by the quality of the acquisition. The subject of analysis is the noise measured in the passenger compartment during a transitory state like the run-up of a vehicle. The process of plotting a waterfall diagram of the noise signal involves calculating spectra by the use of FFT (Fast Fourier Transform) at different increments of rpm. But during the time interval needed for the calculation of one spectrum, the rotational speed changes and produces a shifting of the fundamental frequency of rotation and of its orders. This phenomenon is called smearing [2].

The paper focuses on the analysis of the electric motor orders especially the 24th and 48th.

2.1 Road measurements conditions

The car was accelerated from 0 to 94 Km/h in approximately t=12 seconds. The rotational speed of the electric motor was acquired and reached a maximum RPM_{max}=6500 rpm, which is equivalent to a maximum fundamental frequency of the rotor of 108.3 Hz. The approximate frequency sweep of the orders over one second is determined by dividing the frequency range of the order to the total time of acquisition:

$$Sweep = \frac{RPM_{range}}{t \cdot 60} \times Order, \qquad (1)$$

where $RPM_{range} = RPM_{max} - RPM_{min}$

The obtained values for the orders of interest are listed below:

- 9 Hz/s for the fundamental frequency (1st order)
- 216 Hz/s for the 24 order
- 432 Hz/s for the 48 order

This aspect was important when choosing the right frequency resolution for the FFT. For a 20 Hz resolution, the time interval of a sample is 0.05 seconds, according to the formula Δf=1/Δt. By choosing these parameters, the obtained order sweep is approximately 10.8 Hz for the 24 order and 21.6 Hz for the 48 order. With a sampling frequency of 40960 Hz and a frequency resolution of 20 Hz, one FFT block will contain 2048 lines frequency lines, and the energy of one order will be captured in one line.(see order extraction explained in section 4)

Another important issue was choosing the best rpm increment to track the FFTs against the rotational speed of the motor. The time interval dt_i between two adjacent time frame beginnings must be smaller than the fixed sample rate Δt, so that information won't be lost. In this way order sections will capture all the order energy during a run up.

A first step is to calculate the slew rate SR of the rpm, which represents the rpm variation in a unit of time.

$$SR \approx RPM_{range}/t = 541 rpm/s \qquad (2)$$

The slew rate is not constant over the whole acceleration time, but is a good approximation in order to choose a proper rpm tracking increment to trigger the acquisition for the FFTs.

$$dt_i = RPM_{increment}/SR = 0.046 \text{ s}, \qquad (3)$$

where i=1, …, 259

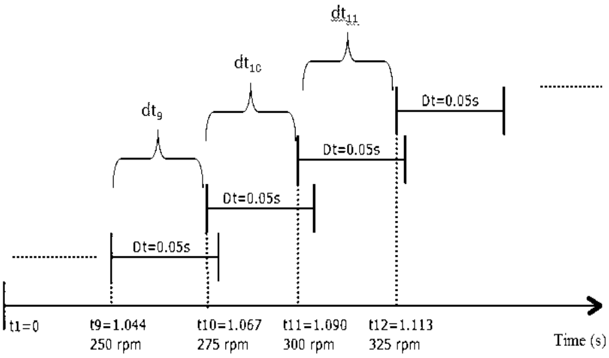

Figure 2. Tracking time frames on a continuous time signal

For $RPM_{increment}=25$, a triggering period $dt_t \approx 0.046s$ was obtain. This is not constant over the whole acceleration, depending on SR, but being smaller than $\Delta t=0.05$ s it satisfies the condition $dt_t < \Delta t$, providing a small overlap of the frames like it is exemplified in Figure 2.

A waterfall diagram was plotted in Figure 3 to show how FFTs are tracked against the rpm increment in a 3D map. The figure represents a zoom in focused on the peaks corresponding to the 48 order, aligned along a straight line.

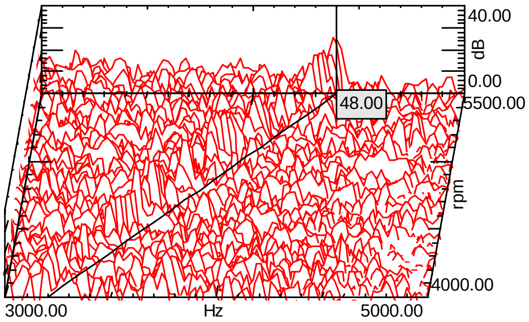

Figure 3. Waterfall diagram composed from FFTs

To obtain a waterfall diagram with a more refined frequency resolution a longer time was needed to perform a run up. This was done in a controlled environment, on a chassis dynamometer located in a semi anechoic chamber at LMS International Leuven as it can be seen in Figure 1.

2.2 Chassis dyno measurements conditions

An acceleration of the car from 2 Km/h to 100 Km/h was performed on a roller bench. With a controlled constant rpm sweep rate from $RPM_{min}=138$ rpm to $RPM_{max}=6900$ rpm, the car reached the top speed in 49 s. The smaller slew rate $SR = 138rpm/s$ means that the sweep of fundamental frequency of the rotor and of its orders takes place on a smaller bandwidth than during the run up on the road:

- 2.3 Hz/s for the fundamental frequency (1^{st} order)
- 55.2 Hz/s for the order 24
- 64.3 Hz/s for order 27.96
- 110.4 Hz/s for order 48

A frequency resolution $\Delta f = 4$Hz was chosen for the FFT in order to obtain an order sweep band as large as the one from the road measurements. This will be important when comparing the order sections. The time frame to calculate a FFT is therefore Δt=0.25 s, during which the orders will sweep over the following frequency bands: 13.8 Hz for order 24, and 27.6 for order 48. The energy content of order 48 will be spread over 5 frequency lines, and the one of order 24, over 3 frequency lines. With a sampling frequency of 40960, the total number of lines is 10240 per each frame. The FFTs were tracked starting from 200 rpm till 6900 rpm.

3 WATERFALL DIAGRAM ANALYSIS:

With the parameters chosen as established in the previous section, two waterfall diagrams were plotted for each operating condition. Both of them are represented as color maps, having the amplitude of noise corresponding to colors as shown on scale from the right side of the graphs. The one in Figure 4 contains information about the noise measured on the road while the one in Figure 5 about the noise on the chassis dyno.

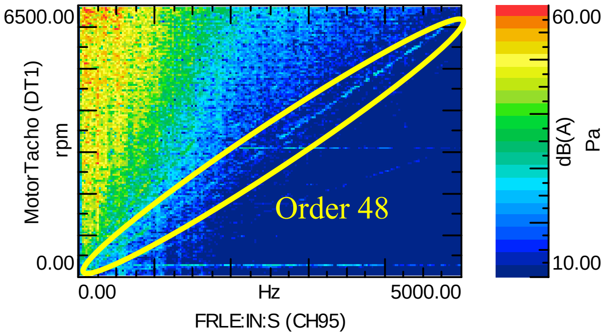

Figure 4. Waterfall diagram of the noise measured on the road

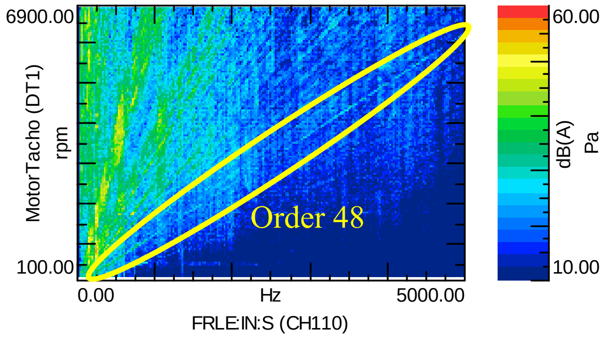

Figure 5. Waterfall diagram of the noise measured on the chassis dyno

The first conclusion when analyzing the two diagrams is that the broadband noise is predominant when performing the test on the road while tire related orders are dominating the sound spectrum when accelerating on the chassis dyno. Resonances are seen over the whole frequency range only when the tests take place on the chassis dyno and are crossing the visible orders.

Order 48 is clearly visible over the whole rpm range on the colormap containing the data from the road measurements and confirms the high frequency sweeping tone that is heard by the driver and passenger during the run up. On the other side, analyzing the colormap from the chassis dyno run up, it's observed that order 48 is sometimes masked by the background noise.

The same thing happens with order 24 which is visible in the frequency range of 0 Hz – 1000 Hz on the colormap with road measurements and can hardly be distinguished on the chassis dyno noise map.

4 ORDER EXTRACTION AND ANALYSIS

To understand further what's happening with the orders under the two different circumstances, an order analysis is proposed. The analysis is done on order sections which are appropriate to describe the evolution of the energy of an order during the measurements [1].

4.1 Order sections definition

A section can be imagined as a 2D slice through a 3D waterfall diagram. In reality every value on the 2D graph represents the square root of sum of squares of the FFT coefficients in a band centered on an integer multiple of the fundamental frequency of rotation [3].

$$rms_s = \sqrt{\sum_{k=0}^{N-1} X_{ks}^2}, \qquad (4)$$

where X_{ks} is the modulus of the coefficient k from the FFT.

The X-axis of a section corresponds to the Z-axis of the waterfall, namely the rpm scale, and the Y-axis coincides with the Y-axis from the waterfall which represents the amplitude scale.

An order section is a section centered on the frequency of an order, which changes constantly as a function of the tracking parameter, in this case the rpm.

4.2 Order extraction methods

There are four options to set the bandwidth on which the energy is integrated, depending on how is the energy spread over the whole rpm range:

- A fixed order band allows the frequency bandwidth of integration to increase with the rpm value.
- A percentage (%) order band means that the bandwidth of integration increases both with the order and with the rpm value.
- A constant frequency bandwidth permits the user to choose a fixed integration bandwidth for every order.
- A fixed number of frequency lines can be used to define the bandwidth of integration

To decide on the appropriate option the following action was taken. FFTs were extracted from the waterfall diagram of the noise inside the passenger compartment at a 1000 rpm and at 4500 rpm. The purpose was to observe if the energy of the order is spread different depending on the rotational velocity. The FFT of the signal from the microphone inside the motor compartment was plotted in the same graphs as a reference.

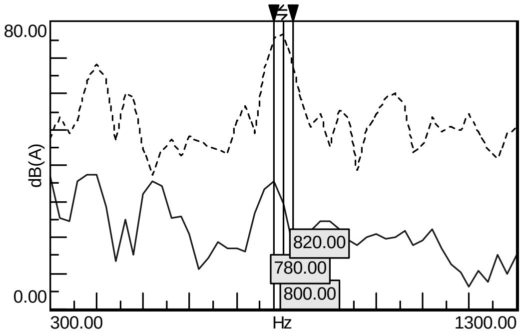

Figure 6. FFT extracted at 1000 rpm

The solid line in 0 represents the FFT of the signal measured inside the passenger compartment, and the dashed line, the FFT of the signal from the motor compartment measured at 1000 rpm. The window is zoomed between 300 and 1300 Hz to focus on order 48, which corresponds to a frequency of 800 Hz.

In Figure 7, a zoomed window between 3200 Hz and 4000 Hz shows the two spectra which are represented with the same lines as in the previous figure. The time signals of the FFTs were taken at 4500 rpm. The peak of the order 48 corresponds to the frequency of 3600 Hz.

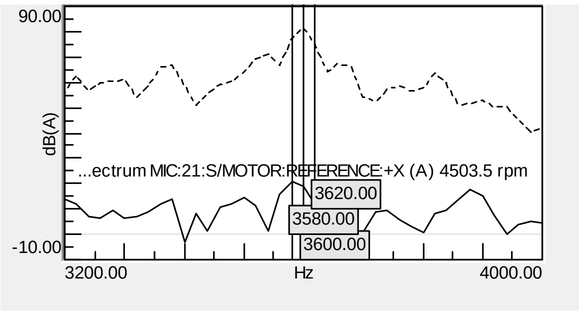

Figure 7. FFT extracted at 4500 rpm

As seen in the two figures above, the width of the peaks corresponding to order 48 doesn’t seem to vary with the rpm value. The same conclusions came from the analysis of the 24 order, but the width of the peak was smaller.

As a consequence, a constant frequency bandwidth of 20 Hz was chosen to extract the sections corresponding to order 24 and a 40 Hz bandwidth for the sections of order 48. The same settings were chosen for both sets of data: the road noise map and the chassis dyno noise map.

4.3 Order analysis

The extracted orders are displayed in the two figures below. In Figure 8, order 24(solid line), corresponding to the road measurements, and order 24 (dashed line), corresponding to the chassis dyno measurements, are plotted on the same graph. The rpm range of interest is 0-2500 rpm, interval where the order is visible on the colormap of noise measured on the road. In this interval the sound pressure level (SPL) of the order corresponding to the road measurements is smaller than the one from the chassis dyno. On the other hand, the frequencies of the peaks overlap.

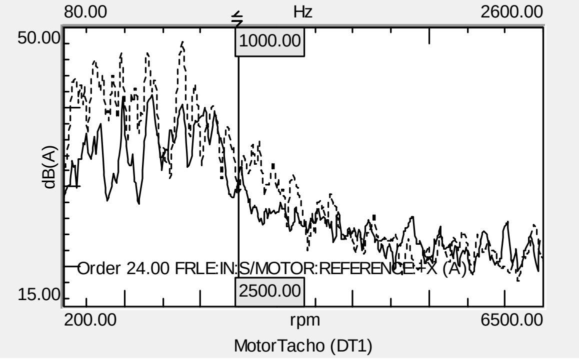

Figure 8. Order sections 24 measured inside the passenger compartment; chassis dyno (dashed line); on road (solid line).

Figure 9 represents the diagram of order 48 processed from the datasets of two tests discussed above. The same phenomenon happens in this case, the SPL of order 48 from the road measurements being smaller than the one from the chassis dyno.

An investigation was made on the data measured with the microphone mounted inside the motor compartment. Order 48 was extracted from the two test cases, and plotted in Figure 10. The SPL of the order seems to fit quite well all over the rpm range.

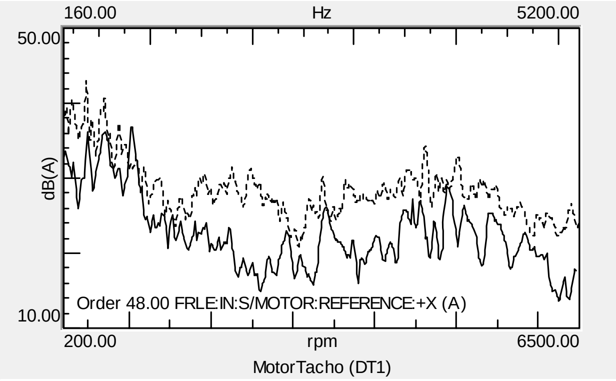

Figure 9. Order sections 48 measured inside the passenger compartment; chassis dyno (dashed line); on road (solid line).

The overall level of the SPL on order 48 measured inside the motor compartment is much bigger than the one of the orders measured inside the passenger compartment, with a peak close to 96 dB at 4600 rpm, in comparison with almost 40 dB at 500 rpm for the second case.

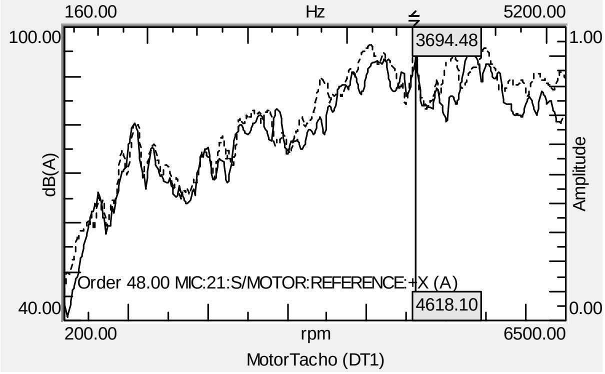

Figure 10. Order 48 measured inside the motor compartment; on the chassis dyno (dashed line); on the road (solid line)

A first explanation of the difference between the orders sections measured in the passenger compartment could be that the low level of the order is masked by noise present in the chassis dyno room. On the other hand, the order level measured inside the engine compartment is too big to be covered by noise, so that is why the two graphs appears to fit.

A second explanation could be that the load on the motor is bigger on the chassis dyno, than on the road. But this is in contradiction with the fact that the SPL in the motor compartment is the same in both cases.

Another assumption is that the time interval in which a run up is made on the road is too short for the responses at different resonant frequencies to stabilize, so the peaks of the resonances are lower than in the case of the run up made on the chassis dyno.

4.4 Reprocessing the chassis dyno data with semi-stationary averaging

If the assumption is made that the difference of sound pressure level between the two order sections is due to external noise, than this effect can be reduced by linear averaging consecutive spectra from the waterfall diagram. This procedure is called *semi-stationary averaging*. By applying it, a 4 rpm increment was used to track the spectra against the rotation velocity of the motor, and then every nine consecutive spectra were linear averaged into a single one with a 50% overlap. The frequency resolution was changed from 4 Hz to 20 Hz to obtain the same settings as for the road measurements. The resulted averaged spectra were used to form new waterfall diagrams, and orders sections were extracted again. To compare the differences between the two methods of processing, a waterfall diagram with a semi-stationary averaging was plotted in Figure 11. Order 48 can be seen clearly now on the diagram, and the noise level near the order is less visible.

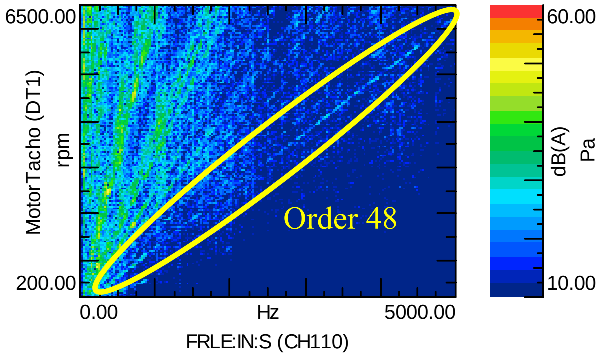

Figure 11. Waterfall diagram processed with 20 Hz resolution and semi-stationary averaging

The important orders were extracted from the reprocessed waterfall diagrams and compared with the ones extracted from the road measurements. In Figure 12, order 48 from both measurement sets was plotted. This time the level of the orders was almost identical over the whole rpm range.

To prove that the method doesn't change the order level measured with the microphones inside the motor compartment, orders 48 are plotted again in Figure 13. The dashed line represents the order 48 from the roller bench measurements with the new processing settings, and as it can be seen the level is identical with the one measured on the road and represented with solid line.

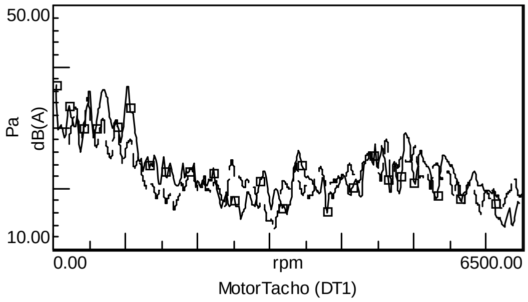

Figure 12. Order sections 48 measured inside the passenger compartment; chassis dyno with semi-stationary averaging (dashed line); on road (solid line).

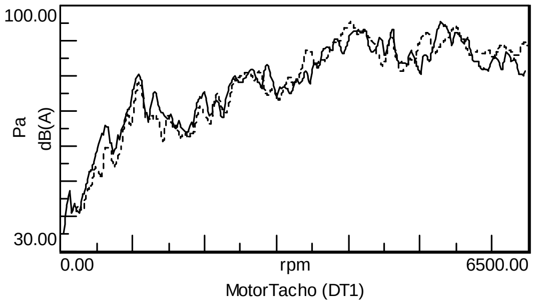

Figure 13. Order 48 measured inside the motor compartment; on the chassis dyno with semi-stationary averaging(dashed line); on the road (solid line)

5 CONCLUSIONS

In order to analyze the sound pressure level inside the passenger compartment of an electric car during a run up, two types of tests were proposed, one on the road in the presence of wind noise and road noise, and one on the chassis dynamometer, in a controlled environment, namely a semi-anechoic chamber.

Fixed time frames, tracked against the rpm of the motor, were transformed into frequency spectra with different processing settings according to the total acquisition time. A slower acceleration of the car on the chassis dyno (49 s) than on the road (12 s), permitted choosing a more refined frequency resolution for the first case (4 Hz instead of 20 Hz for the second case)

The resulted spectra were put together with respect to the rpm of the motor to form 3D color maps. A first interpretation of the two diagrams showed that what is believed to be the road and wind noise is visible on road colormap but not on the chassis dyno one. Instead, in the second case, there are visible stationary waves that interfere with the orders of interest and which are not present on the colormap of the road measurements.

A semi-stationary averaging of several consecutive spectra was performed on the measurements from the chassis dyno in order to reduce the level of the noise coming from the stationary waves on the extracted orders. The method offered the desired results, and lowered the level of the order measured inside the passenger compartment to fit the level of the orders from the road measurements.

To prove that the method doesn’t affect the order related phenomenon but only the noise, the levels of the orders measured inside the motor compartment were plotted together before and after the reprocessing, and didn’t change in amplitude.

As a final conclusion, it was proved that an electric vehicle can be subjected to acoustic tests both on the road and on the chassis dyno, with a few mentions. The fast acceleration on the road doesn’t permit a refine frequency resolution for the FFT and the road and wind noise masks the lower orders. To obtain a smaller frequency resolution and remove the unwanted wind and road noise it is advised to perform the measurements on the chassis dynamometer. When doing so it has to be taken in consideration that the low level of the order related phenomenon measured inside the passenger compartment can be masked by the background noise present in the chassis dynamometer chamber. To minimize the unwanted effect, a semi-stationary averaging like described in section 4.4 is advised.

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