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VISUALIZATION OF DOOR-SLAM SOUND BY USING BEAMFORMING

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ABSTRACT

The door-slam sound of a car consists of multiple impacts. The first impact, which is major one, normally comes from latch contact. The secondary impact, which is considered to affect the quality of the door-slam noise, occurs from various other panels and components. In this paper, we study the method that identifies the secondary impact noise to understand the kinematics of the door-slam. Beamforming method is used to identify source location. Since the duration of the door-slam noise is less than 200 ms, we used the series of overlapped data segment in beamforming process in order to have fine temporal resolution. Functional Beamforming is applied to increase spatial resolution, because we use microphone array with 33cm diameter housing 30 microphones. The effects of the overlap and the data segment length are studied to find out practically applicable setup. Laboratory tests are done to verify the processing algorithm. Two speakers which play short impulse noise are used for the tests. Artificial defects of a car door are created to simulate the faulty door. A case study of a commercial car is performed.

1 INTRODUCTION

An article on door-slam sound study [1] explains well why dwelling on such phenomena is important: “When purchasing a car, potential customers often start by opening and closing the door. Their reaction to this sound strongly influences their subjective impression of overall quality. A high-frequency metallic sound usually results in poor confidence in vehicle quality, whereas a low-frequency dominant sound reflects robustness. Vehicle manufacturers optimize the door-slam sound to make a solid first impression when potential customers consider their brand.”

Advanced technics has been carried out to understand the kinematics of the door-slam. The previous study is on the contribution analysis of the panels of a door. The study uses the operational deflection shape (ODS) of the individual contributing panels one by one, while masking the others with sound-absorbing material or heavy layers. Since the door-slam sound is the complex result of a series of consecutive events in the door lock combined with noise from panel vibrations, this measurement process identifies the door lock event sources. Moreover, the results are objectively analyzed and associated to the door lock kinematics.

In this paper, we apply beamforming method to identify the door lock event sources, where we suppose that a microphone array is located in front of a door, while door-slam events happen. If we can increase the temporal and spatial resolution of the beamforming process, we can expect to identify the door lock events and their location with relatively low measurement effort. Some sound events may be hidden behind the outer panels, what may cause distorted results. However, it still gives useful engineering information with prior knowledge on the structure of a door panel.

This paper discusses on the feasibility study regarding the spatial and temporal resolution of the beamforming method. Poor spatial resolution may decrease the usefulness of the beamforming method for door-slam sound since door-slam sound contains low frequency components. We used Functional Beamforming (FB) method [2] in this paper to increase the spatial resolution in low frequency with high dynamic range. Two speakers with various distances are located in an anechoic chamber to verify the practical resolution of FB method. We used overlap method [3] with short data segments to increase the temporal resolution of the beamforming process. If the temporal resolution of the beamforming is not enough, some of door lock events may not be visualized after processing. We experimental verified the FB method with overlap works in practical configuration. Since the FB method is carried out in frequency domain, which theoretically assumes deterministic continuous signal, very transient signal may cause distorted results. Consecutive short time signals are played by the two speakers for the experimental verification.

Case studies which deal with practical data are also performed in the paper. Artificial defects of a car door are created to simulate faulty doors. In addition, a field case is introduced to show the practical importance of the proposed method.

2 SECONDARY EVENTS OF DOOR-SLAM SOUND

The door-slam sound is the complex result of a series of consecutive events in the door lock combined with noise from panel and component vibrations. A high-frequency metallic door-slam sound, which normally follows after a main door-slam sound event, usually results in poor confidence in vehicle quality, whereas a low-frequency dominant sound reflects robustness [1]. Therefore, the identification of any secondary event is important for car makers.

A typical door-slam sound at Fig. 1 gives some practical insight on requirements of the beamforming process. Upper graph depicts raw sound pressure data of unfiltered waveform in red and band-passed waveform in blue. We can notice that the major events occur within about 160 ms, where the raw waveform shows a several low frequency peaks and the band-pass waveform emphasizes the high frequency, often problematic metallic-like sound. The first main impulsive event containing high frequency sound occurs at 45 ms and the secondary event are spaced with interval of about 15 ms. By observing the widths of the sound events, we can practically suppose the duration of the events to vary from 5 ms to 10 ms.

If we listen to the closely spaced sound events, it is not easy to notice the secondary events clearly. By plotting the trend or slowing down replay speed of the waveform helps an observer or listener to recognize the secondary events. This is because of the temporal masking effect [4] of the consecutive short impulsive sound. However, on the basis of normal listening, one can clearly recognize some metallic sound in the signal, what may cause degradation of vehicle quality.

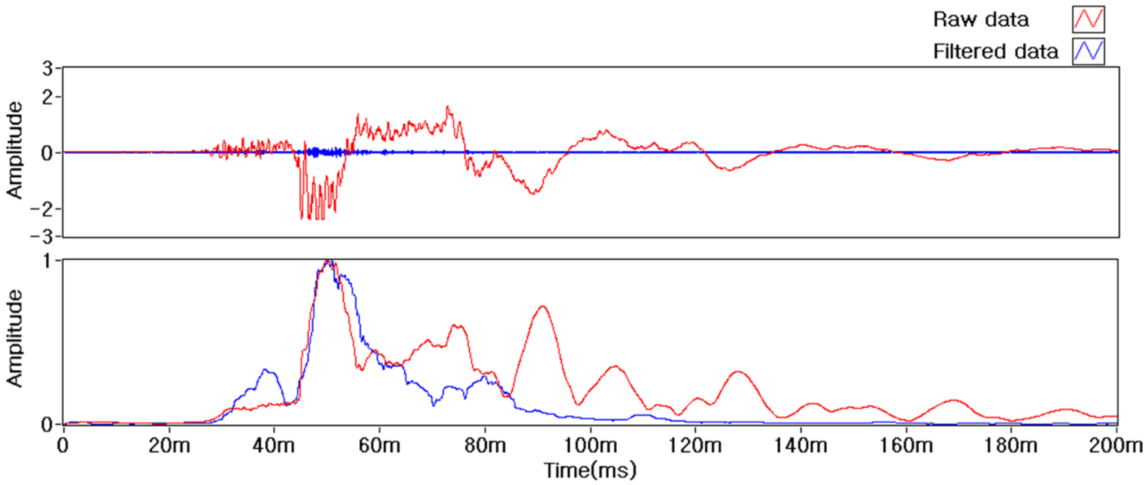

Fig. 1: A typical door-slam noise with secondary events. The top plot depicts sound pressure (Pa) and bottom plot shows normalized RMS value. The graph represented by red line represents raw data of 12.6 kHz span, and the blue line represents band-passed data in range from 3 khz to 5 kHz.

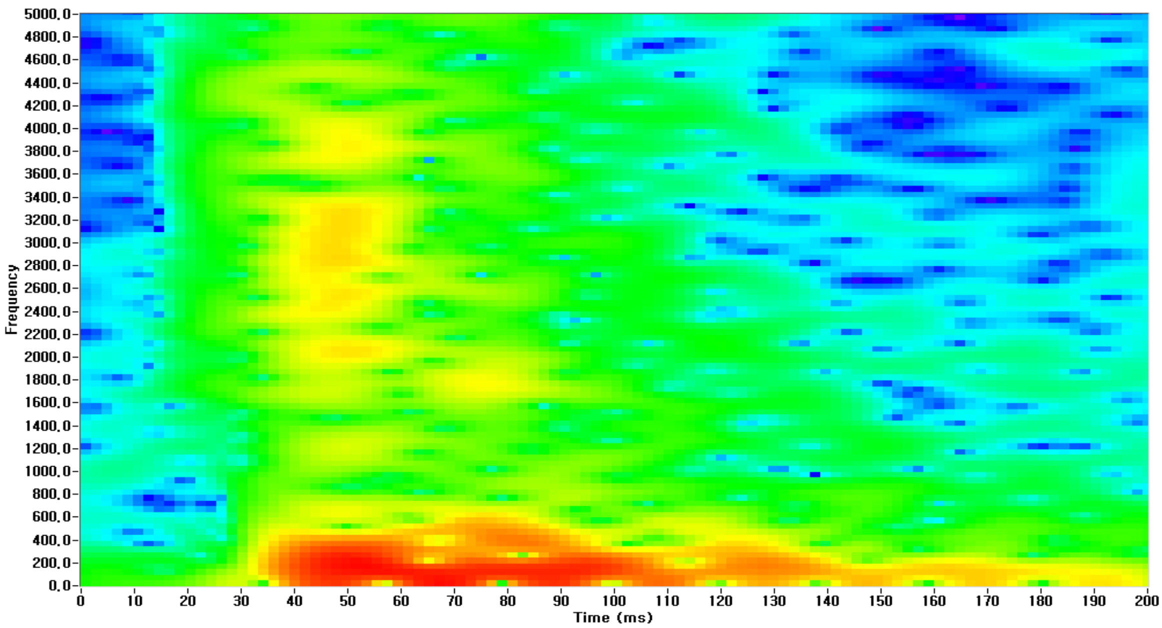

Fig. 2: Spectrogramof a typycal door-slam noise with secondary events. Frequency range 0-5 khz, time duration 200 ms.

We can get better understanding the door-slam sound character by looking also at the spectrogram at Fig. 2. At the very beginning you can see just background noise which is as usual higher for low frequencies. At about 20 ms, higher broadband frequency event starts to blend in. This suggests the event is connected with the door movement just before sealing the car interior, and this event is characterized by broadband sound in higher frequencies and completely missing the lows. At about 30 ms low frequencies start to play a role as well, but high frequencies are also very prominent. This seems to be a contact of a so-called weather strip attached at the inner side of a door, with a car frame itself, because it needs to have some damping and elasticity just before main latch even occurs. Now, we are reaching the point where the latch on the moving door impinge upon striker that is attached to the car frame and indeed, at about 45 ms based on the RMS values, all frequencies are excited what is expected from an impulse. At the same time, the door sealing more tightly to the car frame also contributes to this overall main event.

By observing closely the frequency band below 200 Hz, we see a pattern that is repeating every 20 ms, 8 times in a row and its strength is decreasing as time progresses. Since it starts with the initial main door-slam event, it is highly probable, that these events are connected with resonance of the door frame, cabin interior (buffeting), or another car component. These events are at very low end of human hearing, and as mentioned before, the low frequencies do not disturb our impression of door-slam sound. That is why we will focus mostly on higher frequencies than 200 Hz, especially at higher end, where the unpleasant noise may be created.

When checking the frequency region between 200 to 600 Hz, we can notice another prominent event centred about 80 ms. This sound is visually well distinguishable from the main latch event and since it contains all frequencies beside the very low end, it might be secondary sound of the latch, when it locks the striker. As we advance in time, at 110 ms, we notice an event that correspond to some secondary noise having also some high frequencies as seen on slight increase of pressure in band passed filter, but the origin this event is not easily understood. Some sound event in this region is although well noticeable when the waveform is replayed slowly.

It is important to note, that the data plotted in the above figures are not A-weighted and thus our hearing would perceived low frequencies more attenuated than the mid and high frequencies.

3 OVERLAP PROCESSING FOR HIGH TEMPORAL RESOLUTION

The events generated by the door-slam noise are highly transient, therefore very fine temporal resolution of beamforming calculation is necessary. Commercially available beamformer arrays provide beampower map calculation frequently between 15 to 25 times per second, i.e. refreshing an updated frame every 67 to 40 ms. Supposing our sound sources of interest are 5 to 10 ms apart, commonly used techniques cannot detect these short transient events. Therefore we take advantage of Fast Fourier Transform (FFT) Overlap Processing [3], which allows us to focus on very short spectral events that are not as long as one sample frame. The drawback of this technique is that the overlap in time domain introduces overlap also in frequency domain. It means that relative timing between the spectral events will suffer small error depending on the block size and the overlap portion.

The method of Overlap processing is depicted in the Fig. 3. At the top we can complex band-passed time domain signal composed of several events within 160 ms, essentially the same as in Fig. 1 and Fig. 2. Let's assume sampling frequency to be 25.6 kHz, data acquisition happening 25 frames per second, what corresponds to 1024 discrete time samples contained in every frame, resulting in frame duration of 40 ms. Also we assume real scenario of continuous signal, so that we have buffered data before and after the 4 blocks. Now, let's focus on the 4 non-overlapping blocks, as seen in the 2nd diagram in the Fig. 3 below, which are often times not sufficient to localize short events as discussed. This is also due to the fact, that a window is applied to each frame to smooth the time signal for better frequency representation. If we introduce the overlap at this point on discrete time data frames as in 3nd diagram, we can get finer temporal resolution. By applying 87.5% overlap to the 4 frames, we obtain 32 frames (200 fps) each still being 40 ms long, but overlapping, so that we get new spectral line every 5 ms (128 samples). In previous case it was every 40 ms (1024 samples), hence this increase the time resolution 8 times. The overlapped samples are windowed, as depicted at the bottom of the Figure 2, with the intention of focusing the energy to the centre of each frame.

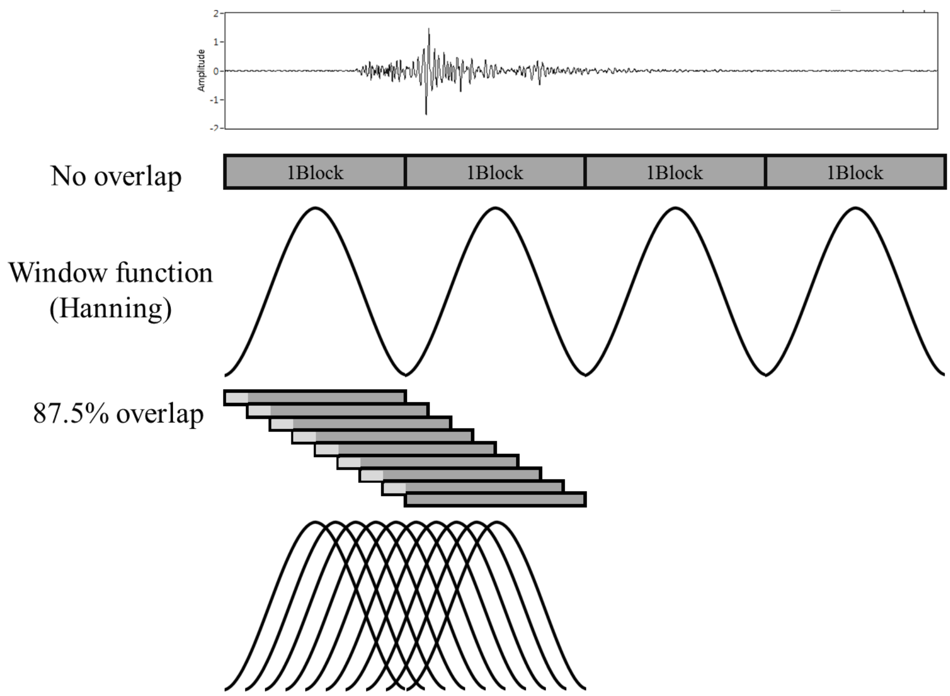

Fig. 3: Example of 87.5% overlap transform processing. From top to bottom we have, a) band-passed time waveform, b) non-overlapped frame diagram, c) Hanning window applied to non-overlapped frames, d) blocks with 87.5% overlap, e) a window applied to each overlapped frame.

The temporal resolution can be indicated by frame rate in frames per seconds (fps). We calculate the frame rate of the overlapped blocks according to Eq. 1,

$$\mathrm{FrRate}_{\mathrm{overlap}} = \frac{\#sam}{\left(1-\frac{\mathrm{overlap}}{100}\right)*\#samPerFr}, \qquad 1)$$

where *overlap* is given by percentage, *FrRateoverlap* is frame rate of overlapped signal, *#sam* is number of samples in the observed time segment, and *#samPerFr* is number of samples per one frame. Then we can derive the table below to summarize parameters of different overlaps

Overlap (%)	Sampling Frequency (kHz)	Sample per frame		Frame rate (fps)	Temporal resolution		Temporal resolution factor
		Samples	ms		Samples	ms	
0	25.6	1024	40	25.0	1024	40	1.0
25	25.6	1024	40	33.3	7680	30	1.3
50	25.6	1024	40	50.0	5120	20	2.0
75	25.6	1024	40	83.3	3072	12	3.3
87.5	25.6	1024	40	200.0	1280	5	8.0
97	25.6	1024	40	833.3	31	1.2	33.3

Tab. 1: Summary of overlap processing parameters for high temporal resolution.

4 FUNCTIONAL BEAMFORMING

In this paper, we take advantage of Functional Beamforming [2] algorithm that exceeds performance of conventional Frequency Domain Beamforming (FDBF) or Time domain Beamforming (TDBF). It utilizes Cross Spectral Matrix (CSM) to reduce sidelobes by modifying FDBF. The final generalized expression of Functional Beamforming derivation is given in the following equation,

$$b_\nu(g) = \left[g' C^{\frac{1}{\nu}} g\right]^{\nu} \qquad 2)$$

Where b_ν is Functional Beamforming map of order ν, g is a steering vector and C is cross spectral matrix. In our measurements, we use recommended order ν = 20, which defines sidelobe level of functional beamforming. As compared with conventional FDBF, the Functional Beamforming increases sidelobe rejection remarkably and allows us to measure lower frequencies reasonably from about 500 Hz while preserving the small microphone array.

5 EXPERIMENTAL STUDY WITH CAR DOOR

5.1 Measurement Configuration

This experiment demonstrate practical measurement on a front car door in semi-anechoic chamber. Fig. 4 shows symbolically the geometry of the measurement configuration for the car door. The door width is assumed to be about 1m, and the shortest distance between the microphone array and the door is 1.2m. Since reasonably strong door swing of 1.3 m/s speed, measured by a laser speed meter, should be made to generate reproducible door-slam sound, we placed the microphone array close to the door and measured the swing speed by a laser speed meter.

A commercial microphone array (SeeSV-S205) with 326 mm diameter composed of 30 microphones is used in this study. Using larger array with more microphones would improve the performance, but we selected this microphone array first and tried to tune its parameters since practical availability and manoeuvrability is also important for the field measurement.

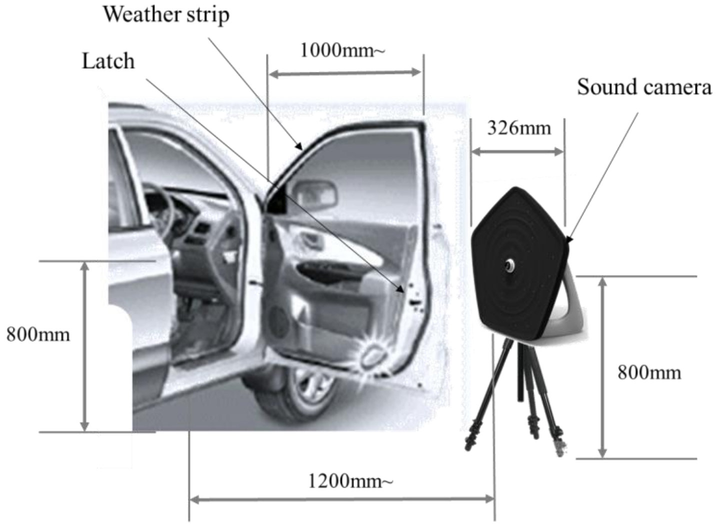

Fig. 4: The practical measurement configuration of door-slam sound with a microphone array. A commercial microphone array (SeeSV-S205) with 30 microphones and 326 mm diameter is located 1.2m away from the door.

The microphone array here has mainly the function of recording device for microphone and video data, as the post-processing analysis is conducted afterwards due to higher computational demand.

The optical camera which we are using shoots only 25 fps, thus for higher beamforming rate, one image frame has to be sometimes repeated to compensate for the frame rate mismatch. Also, a delay may be caused by the distance of the camera from the measuring object, what is not noticeable in the most measurements, but as we focus on very fine temporal events, it might play a role. The sound wave travels from the sound source to the acoustic array about 4ms, but speed of light that theoretically defines delay of image acquisition is negligible, resulting in sound processing lagging behind the optical image by up to 4 ms. For this reason, it should be taken into consideration for later analysis.

Prior to studying the measurements, it is good to notice the position of latch in Fig. 4, since it is located on the side of the door, where it impinges upon striker located on a car frame without any damping. Other components of the door are sealed with the weather strip along the edge of the inner door side, thus it should prevent direct contact of metal parts of moving door and fixed car frame, beside the latch event.

5.2 Analysis Method

The measurement was conducted on the car under study that was reported to have an unpleasant secondary sound, but the cause was not defined. We conducted the experiment by introducing a door swing of speed 1.3 m/s after which the impact of the door with the car frame followed. Recorded data contained 25 fps optical camera footage and audio recording from all microphones at sampling frequency of 25.6 kHz.

Subsequently, the signal was fed into Functional Beamforming algorithm through overlapping frame processing. Based on short impulse events to be measured and our experience, we used 128 samples long frames with 87.5% overlap. The non-overlapped frame rate is therefore 200 fps, so that the frames are 5 ms (128 samples) apart, and the frame rate of the overlapped signal turns out to be 1600 fps, with interval of 0.625 ms (16 samples) between each overlapped frame, while each frame is still being 5 ms (128 samples) long. This means that the overlap processing increased temporal resolution by factor of 8.

The parameters of non-overlapped signal are compared with overlapped signal in Tab. 2 below:

Overlap (%)	Sampling Frequency (kHz)	Samples per frame		Frame rate (fps)	Temporal resolution		Temporal resolution factor
		Samples	ms		Samples	ms	
0	25.6	128	5	200	128	5.000	1.0
87.5	25.6	128	5	1600	16	0.625	8.0

Tab. 2: Summary of overlap processing parameters for car door experiment.

5.3 Measurement Results

The measurements conducted in this section were already shown in time and frequency domain in Fig. 1 and Fig. 2 as a practical example. By analysing the waveform, you could notice that the door-slam noise has got large portion of low frequencies below 150 Hz, but since these regions are more likely to be pleasant to a human ear, we did not focus on them also due to limitations of our microphone array in low frequencies. For the beamforming analysis, it is though interesting to compare the low frequency and high frequency components, so therefore in Fig. 5, we still show you raw RMS data in black containing mostly the low frequencies and filtered RMS data in red. Also, now you can finally see the results of Functional Beamforming after the time data were pre-processed by overlaps. The beamforming results are represented by trend of maximum beampower level in each frame plotted in blue. For convenient comparison, all trends has been normalized to corresponding maximum value and are 200 ms long. For each peak of the beampower trend, we also took a snapshot of beampower map overlaid with optical camera frame.

Let’s elaborate on the results above step by step. If we focus on the raw data trend, we see that first event continuously rises from 20ms to 45ms. This is when the door almost snaps to the car frame, but before the latch hits the strike. When local maximum of beampower is detected, the beampower map localizes a focused source in the area of a laser speed meter. On the basis of our analysis, we expected the initial high frequency sound to be generated around the car door frame at the point of the contact, but we cannot see that. However, there is the possibility that the sound waves propagating outwards from the microphone viewing angle impinge upon the laser speed meter and due to scattering focus the energy at single point, what beamforming evaluates as the maximum beampower, even though there will be multiple other sources of lover amplitude. If we assume the speed meter to be 0.1 m height, the scattering phenomena would existed for frequencies above 3.5 kHz, but further investigation would have to be conducted to support such statement.

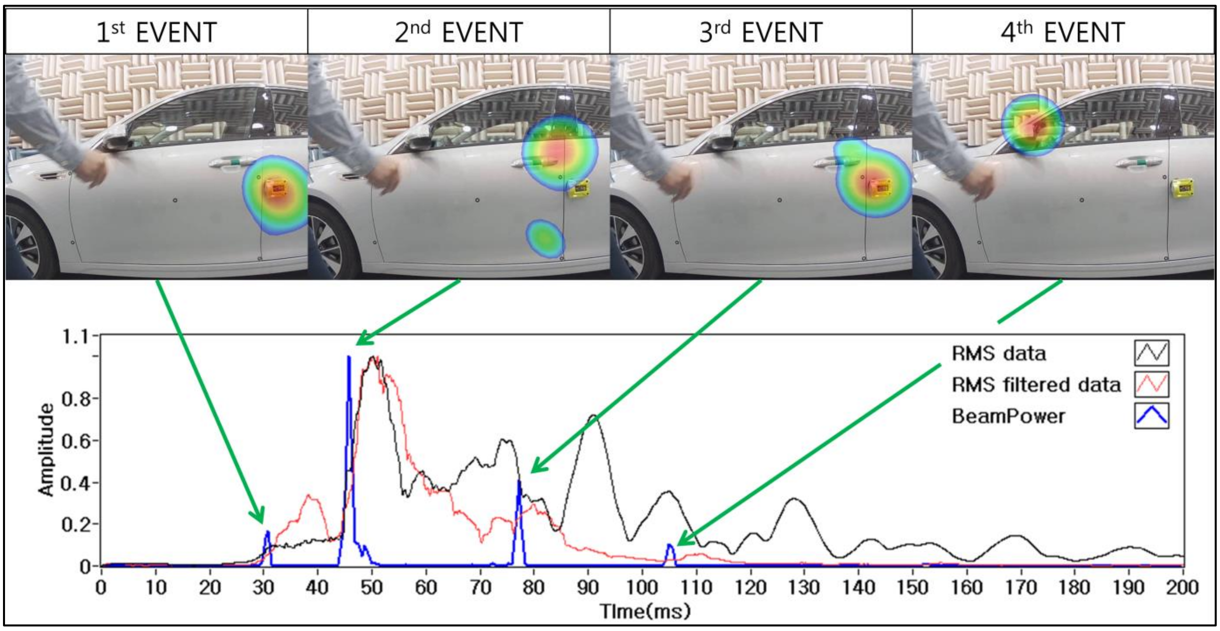

Fig. 5: The practical measurement configuration of door-slam sound with a microphone array. A commercial microphone array (SeeSV-S205) with 30 microphones and 326 mm diameter is located 1.2 m away from the door. The beampower and filtered data are limited from 3 kHz up to 5 kHz.

When we move on along the time axis, we encounter the main latch. The peak of beampower is detected at the very beginning of the event (50 ms), what suggest, that the energy is concentrated at one point spaciously and as the amplitude increases, the sound pressure level spreads out. Interestingly, the main peak of the beampower is not located at the exact position of the latch, whereas little bit upper and another lower amplitude event is localized at the bottom right corner of the door. The latch is hidden behind the metal outer cover of the door, therefore the sound needs to radiate through air gaps or by radiation of other adjacent components. To observe the origin of these sources, further vibration measurements would probably have to be taken.

The 3rd event detected by the beamforming at 78 ms suggests to be the lock of latch assembly and this time it points at the correct location of latch, even though it might be biased by the speed meter slightly. Event is detected and the main secondary event of door-slam sound.

Our final local peak of beampower is the weakest from the previous ones, but the beamformer locates the main source at 105 ms on the side mirror. This is unwanted effect of the door-slam sound and should be treated to improve the car-door sound.

6 EXPERIMENTAL STUDY WITH TWO SPEAKERS

6.1 Measurement Configuration

The practical experimental measurement suggested a character of possible sound events. To test limits of our proposed method while bearing in mind character of previously observed measurement, we set up configuration with artificially created sound sources in semi-anechoic chamber. The experiment configuration is depicted in Figure 4. We have again 1.2m distance between the microphone array and sound sources created by speakers on a bar.

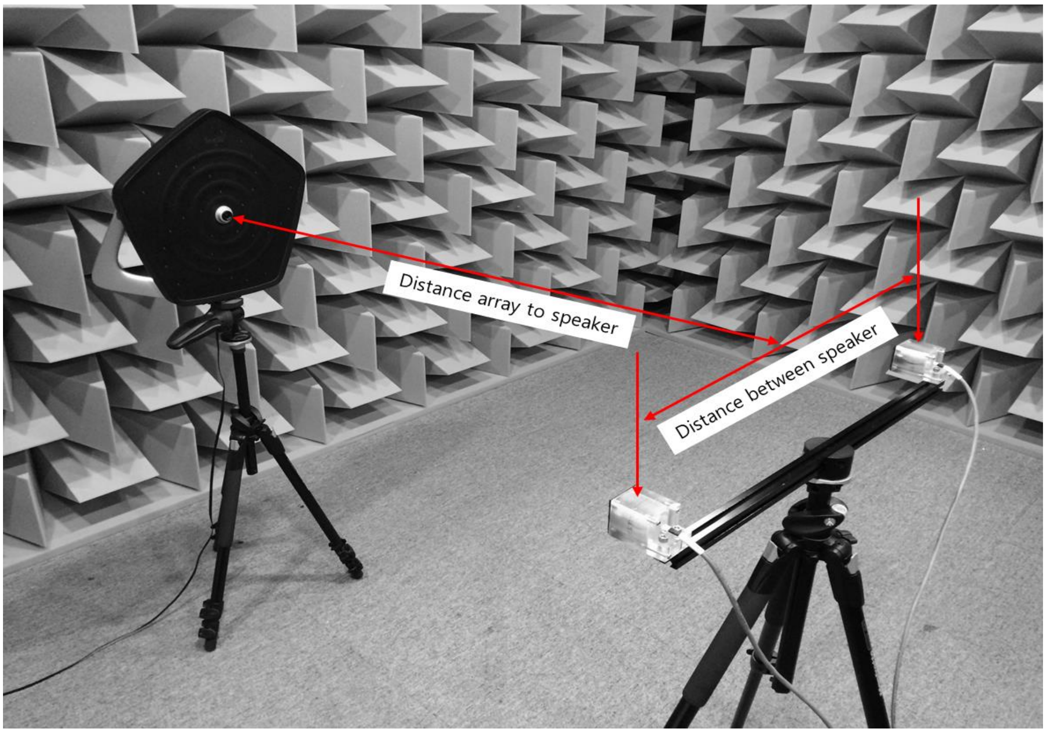

Fig. 6: Experimental configuration of speakers on a bar and the microphone array in semi-anechoic chamber.

The microphone array records the speakers whose position is adjusted to simulate extreme scenarios within 0.6 m along the bar. We generate short 5 ms long bursts of 500 Hz sine wave to imitate impulses of narrow frequency range. These consecutive bursts are separated by an interval from 5 to 60 ms in the way that right speaker reproduce the signal first and the left speaker generate the same signal with defined delay. Given that the bursts are 5 ms long and the shortest interval between signals is 5 ms, the consecutive impulses creates perceptually continuous burst, although coming from 2 different locations in time. Example of signal representation is shown in diagram below.

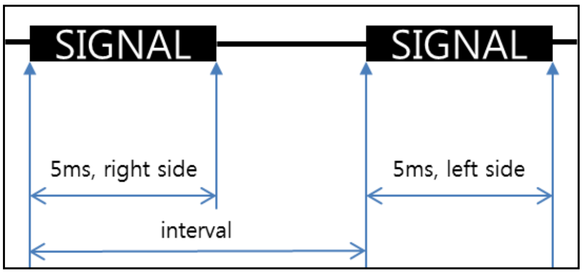

Fig. 7: Signal representation of consecutive bursts (in black) separated by an interval (in blue). The right speaker receives the signal first, after which the left speaker replay the same signal, but delayed. The time interval runs in step of 5 ms from 60 ms down to 5 ms.

The review of signal generation over speakers set-up is summarized in the Tab. 4,

Signal type	Signal duration	Interval of signal	Distance to array	Distance between speaker
Sine wave, 500 Hz	5 ms	5~60 ms	1.2 m	0.1 ~0.6 m

Tab. 3: Summary of speakers experiment configuration and signal generation.

6.2 Analysis Method

This experiment was analyzed in similar manner as the previous filed experiment in Sec. 5. The only difference is that a different sample per frame was used to enhance the precision. Thus we obtain adjusted values compared in Tab. 4.

Overlap (%)	Sampling Frequency (kHz)	Samples per frame		Frame rate (fps)	Temporal resolution		Temporal resolution factor
		Samples	ms		Samples	ms	
0	25.6	256	10	100	256	10.00	1.0
87.5	25.6	256	10	800	32	1.25	8.0

Tab. 4: Summary of overlap processing parameters for speakers bar experiment.

Only important thing to note here is that we use resolution of 1.25 ms, what should be sufficient for 5 ms impulse burst.

6.3 Measurement Results

After running though the measurements as summed up in Tab. 4, we obtained Tab. 5. We checked that it is impossible for limiting cases of our experiment to use conventional FDBF using Delay and Sum (DAS) technique even though we pre-process the signal with overlaps. This is mainly due to the low frequency character of the signal, which was tuned to 500 Hz. If we apply instead Functional Beamforming, we achieve good results even for limiting case of very short interval (10 ms) and quite short distance (200 mm) between sound events.

Distance \ Interval	60ms	40ms	20ms	10ms	5ms	w/o functional BF
600mm	Good	Good	Good	Good	Not Good	Not Good
400mm	Good	Good	Good	Good	Not Good	Not Good
300mm	Good	Good	Good	Good	Not Good	Not Good
200mm	Good	Good	Good	Good	Not Good	Not Good
100mm	Not Good	Not Good	Not Good	Not Good	Not Good	Not Good

Tab. 5: Experimental result overview for speakers bar experiment

In Fig. 6 we can observed some results mentioned in the table above. You can observe successfully localized events, as well as incorrectly or imprecisely found events.

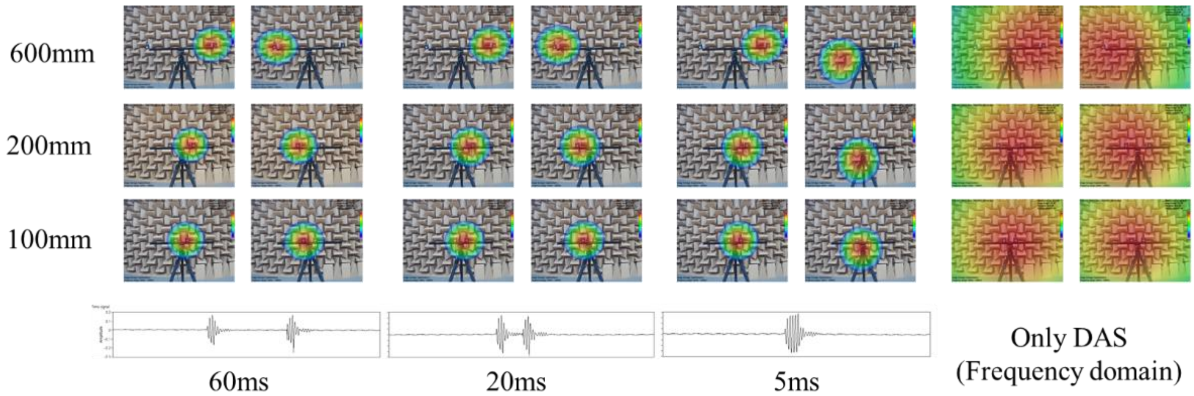

Fig. 8 The results of speakers bar test.

This study has supported our previous field experiment, because most of the events were at least 10 ms apart. Also we see that events closer than 200 mm are more likely to be erroneous.

7 CASE STUDIES WITH CAR DOOR

7.1 Artificial Defects

To compare cases of normal door and faulty doors with some defect, we introduce artificially created defect that we can study further. Firstly, a weather strip removed with the assumption it will generate lots of secondary noise. The experiment was conducted in the same manner as in Sec. 5. Because we compare 2 set of measurements, we have to synchronize them first. This was done by aligning the main sound event of the latch, what might be prone to a slight error. In the table below you can find a few more details of the measurement configuration.

<table>
<tr><th></th><th>Condition</th><th>Door closing speed</th><th>Door position</th><th>Distance to array</th></tr>
<tr><td>Normal condition</td><td>Normal</td><td rowspan="2">1.3 m/s</td><td rowspan="2">Left side front</td><td rowspan="2">1.2 m</td></tr>
<tr><td>Artificial defects</td><td>Removed weather strip</td></tr>
</table>

Tab. 6: Test conditions of normal and defected car door.

In the Fig. 9 we compare filtered RMS values as well as peaks of beampowers for normal and faulty door with corresponding beampower maps. We can notice that in time domain, large increase of sound pressure at 80 ms as well as 140 ms occurs. This is although not prominent for beampower. This is due to the fact, that these events are mostly located in lower frequency spectrum.

We can notice that the faulty door first event occurs before the normal door. This might be caused by high frequencies generated by already by the edge where the weather strip is missing, and thus it accurs before the latch of normal door. From the beamforming data we can not see any indices supporting this evidence.

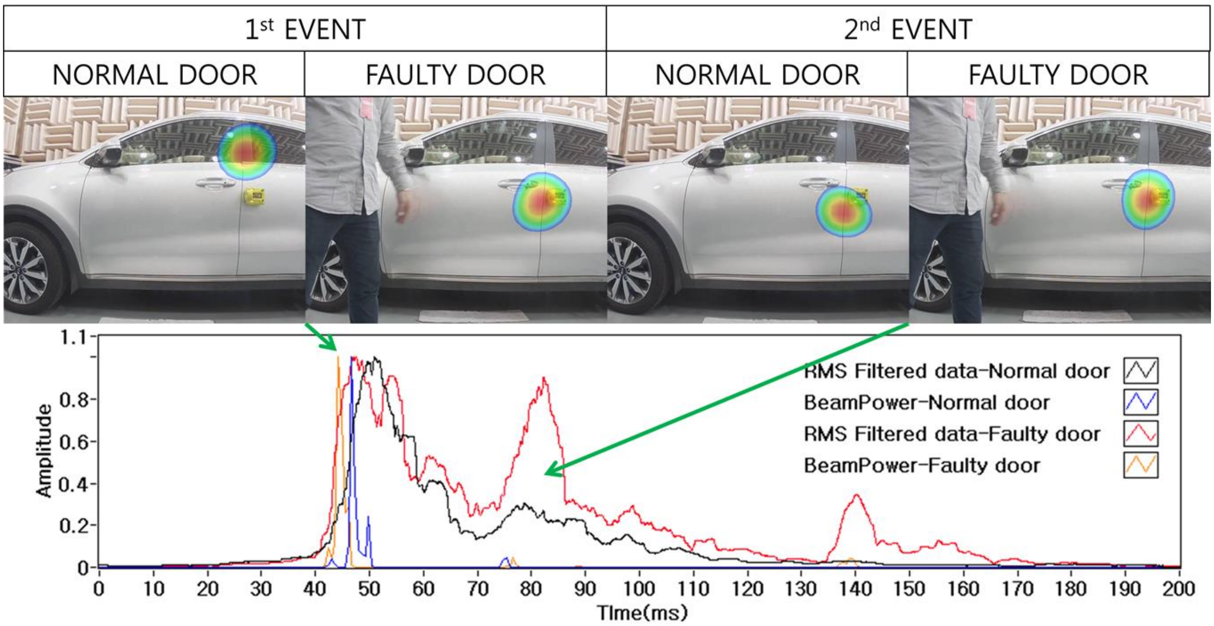

Fig. 9: Comparison of car door measurement under normal and defected condition. Filtered RMS data and beamforming data of both conditions are normalized compared. Band-pass filter from 3 kHz to 5 kHz is applied.

Since the high frequency beamforming did not show good guidance on how to find the differences in a beampower, we took band-pass filter in low frequency band which you can see in Fig. 10. Here we can see much more spurious peaks in beampower for the faulty door. The first event shows the source position somewhere on the door shielding for normal door, but the faulty shows the same source at the edge of the door, where the weather strip is missing. The consecutive 2 events within 15 ms appear at the same location for the faulty door. Thus we can easily locate one of the problematic areas. The second event shows similar beampower level, but the source location is located at higher part of the door where the weather strip is missing and partially at the point where normal door localize the event. This means that the prominent sound events occurs mostly at the edges of car door. The last 3rd event is dominant only for faulty door, and it's again consecutive event probably caused by periodicity of previous one. The normal beampower here is just a noise since the beampower is significantly low.

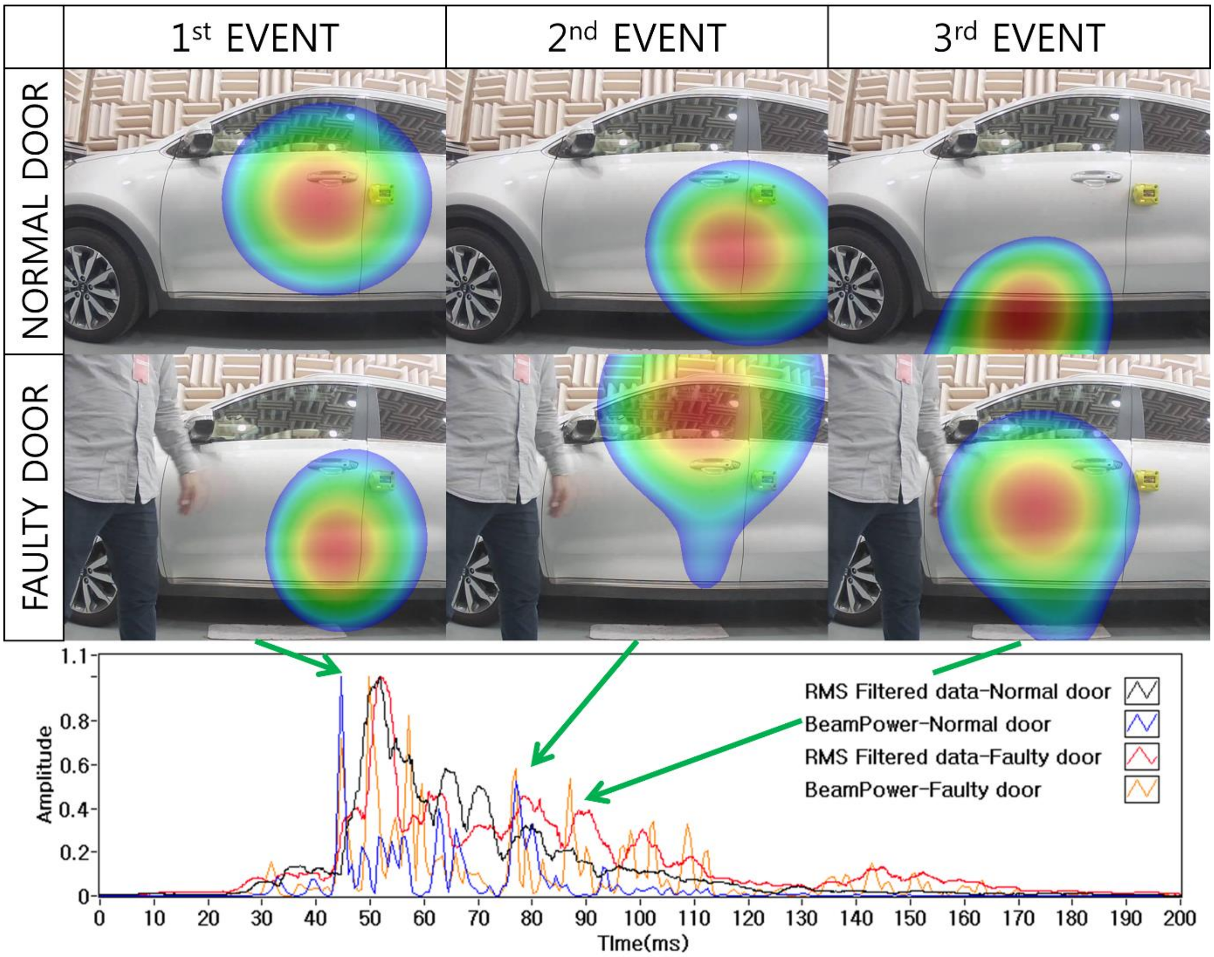

Fig. 10: Comparison of car door measurement under normal and defected condition. Filtered RMS data and beamforming data of both conditions are normalized compared. Band-pass filter from 500 Hz to 1,500 Hz is applied.

It is difficult to show the results by still images, but when watched to continuous measurement, the faulty doors are easily identifiable by beampower following the door edge.

8 CONCLUSION

The technique for visualizing short noise sources of several millisecond was studied using beamforming method. Firstly, applying overlap processing in frequency domain improved temporal resolution dramatically. Secondly, spatial resolution of beampower algorithm was also increased by using Functional Beamforming algorithm.

The method was subjected to a field measurement of a car door-slam noise, where it was possible to detect events 15 ms apart. Test of limiting intervals in time and space on speakers configuration supported the previously conducted field measurement and exposed limits of the suggested method. Evaluation of the measurements by local beampower maximums indicated complex behaviour of door-slam sound by revealing origin of focused impulsive sound. It also demonstrated intuitive measure of major door-slam events and suggested that time domain trend is not always a good indicator of impulse events under similar conditions.

Finally, artificially defected door measurement was compared with normal door measurement and it was attempted to distinguish the effect of the defect on beamforming measurements.

The suggested phenomena were observed on the basis of the measurement results and common sense, therefore thorough analysis using vibration analysis or other detailed measurements should be implemented to support the findings and continue the research.

ACKNOWLEDGEMENT

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