Developing beam-forming devices to detect squeak and rattle sources by using FPGA

Youngkey KIM[1]; Jungoo KANG[2]; Myunghan LEE[3]

[1,2] SM Instruments Inc., Korea

[3] Hyundai Motors, Korea

ABSTRACT

Industry's high interest on squeak and rattle leads the development of a beam-forming device. Detecting squeak and rattle (SR) noise has been one of the best applications of the beam-forming devices. Localizing the SR noise sources is the most important step of the whole SR noise reduction efforts. In addition, the SR noise mainly consists of high frequency components and the beam-forming has better performance in high frequency range. Successful beam-forming devices for SR noises need to have fast data processing ability in order to detect transient behavior of the SR noise. The paper introduces how digital technologies are used to develop high speed beam-forming device. Since beam-forming process mainly consists of basic mathematical operation, such as addition, delay and multiplication, the process can be implemented in a Field Programmable Gate Array (FPGA) Chip. Because the FPGA has real-time MHz fixed loop rate, the processing loop rate is not the problem anymore. In this paper, two types of beam-forming devices developed by using FPGA are introduced. Application examples show the performance of the devices.

Keywords: Sound Visualization, Beam-forming, FPGA, Squeak and Rattle Noise

1. INTRODUCTION

Many squeaking noises are created when a linear motion is introduced on metal contacting metal, or when rubber is forced over a metal pulley. When metal is forced against metal combined with a linear motion a harmonic vibration is created that is sometimes audible at a high frequency range. In any squeak situation, the location of the squeak is sometimes the hardest task to determine (1).

A rattle or rattling noise can be one of the most frustrating sounds in a vehicle. If the gap between two neighboring components is not sufficient, they may generate a rattle while hitting each other in their resonance frequencies. Rattling sounds can be generated by almost any part of the vehicle. A rattle can be generated when the vehicle is in motion or when the engine is running with the vehicle stopped. Moreover, a rattle can be generated by the audio speakers when they generate low frequency and high intensity sounds. The first step to repair the rattling noise is locating the region in which the sound is being generated from.

A microphone array which implements beam-forming method is one of the best devices to detect SR noises since it locates noise sources graphically. There are several commercial beam-forming devices that convert the sound signals of the array into amplitude contours. The devices collaborate with optical cameras to overlay the contours onto the optical images. Therefore, it is easy to detect the locations of the noises by taking the noise images with these devices. By taking several noise images per second, the devices provide noise videos. Normally, the noise images and videos have better quality in high frequency range, since the performance is inversely proportional to the wavelength of the noise (2).

There are, however, some challenges for existing devices to be used in detecting SR noises. The devices need to have fast response to detect transient behavior of the SR noises. Most SR noises happen irregularly and quickly. Sometimes they happen in a few milli-seconds and disappear. Many of the existing beam-forming devices have been developed for powertrain noises and tire-road noises,

[1] youngkey@smins.co.kr
[2] jgkang@smins.co.kr
[3] hannie@hyundai.com

which are normally quasi-stationary. Moreover, PC was the main platform of the process, which results not enough frame rate in most cases. Therefore, it is required to develop a beam-forming device which can detect highly transient noises.

This paper introduces the basic operational principle, the design process and the performance of the beam-forming device. In addition, the paper explains what kinds of digital technology are used to implement this device. MEMS (Micro-Electric Mechanical System) and FPGA (Field Programmable Gate Array) technologies were used to increase the image update rate. This paper also introduces examples of the applications that show the performance of this device.

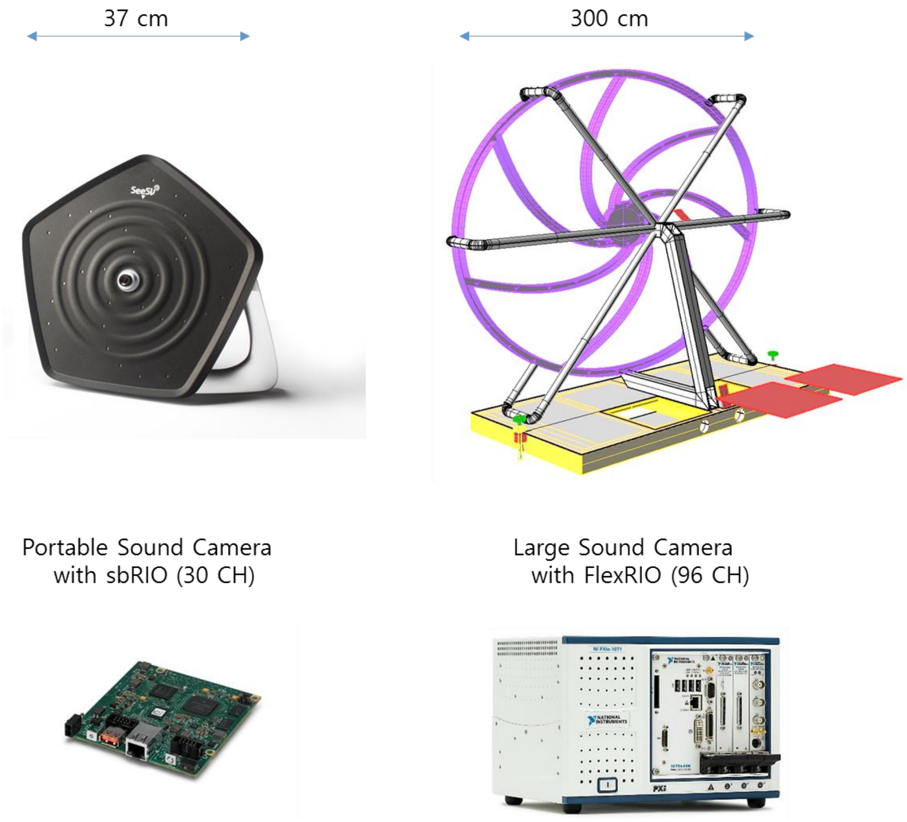

Figure 1- The beam-forming devices and their controllers. They are designed for the detection of squeak and rattle (SR) noises by using FPGA. The devices have a high image update rate (25 images per second).

2. BEAM-FORMING METHOD

2.1 Principle of Beam-forming

If we form an array with microphones, it is able to have directional characteristics which are useful to identify noise sources. Adding up the output signals from the microphones amplifies the signals in a normal direction. The signals from different directions are canceled out during the summation process, since they have different phases from each other (Figure 2). This process is very similar to creating a beam of waves in a normal direction; therefore we call it a beam-forming process.

Since a microphone array has highly directional characteristics, we could scan every possible direction to localize noise sources. We may want to draw the contour of noise amplitude to visualize source distribution. This is the main idea of beam-forming devices. The scanning or rotation is performed by imposing an electrical delay in each microphone. If we assume that we actually rotate the array in a certain direction, time delays are imposed in every single microphone as shown in Figure 2. Therefore, imposing electrical delays in microphones can virtually rotate the array. Since the virtual rotation is an electrical process, we could scan a whole direction in a short moment.

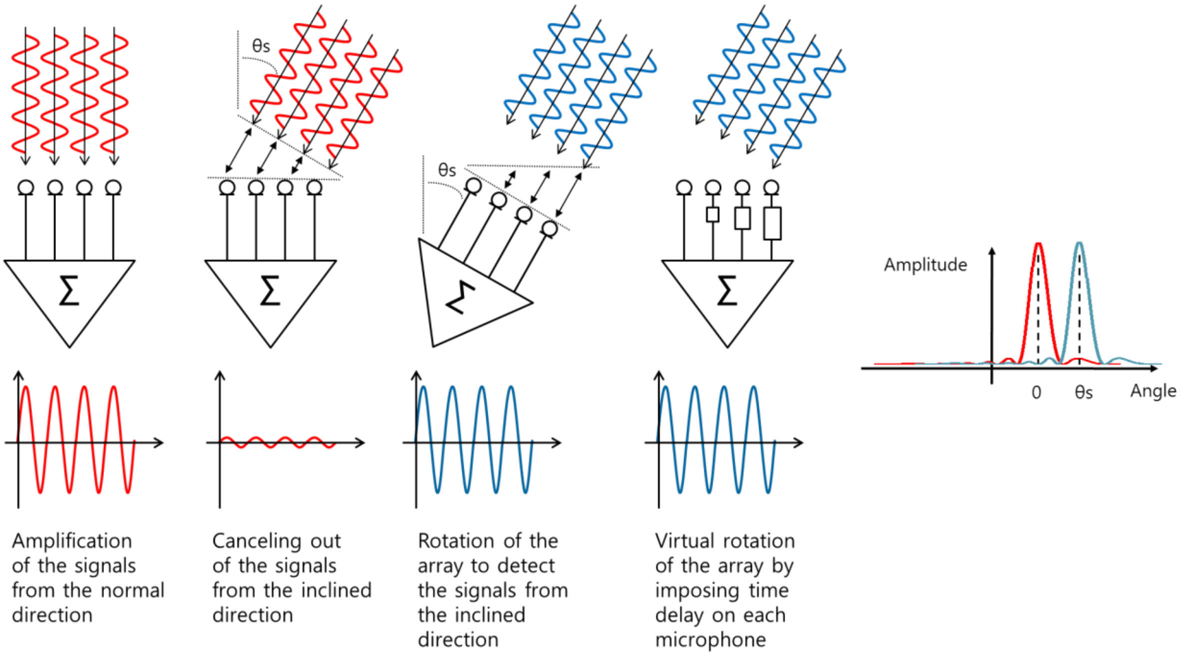

Figure 2 - The principles of beam-forming devices. Summing up the output signal of the microphones makes the array as a directional noise detector. By virtually rotating the array, we can scan the possible directions of the noise sources.

2.2 Performance of a Microphone Array

The performance of the microphone array is evaluated by spatial resolution and signal to noise ratio. They are determined by the numbers of microphones, the array size, the distance between microphones, and the pattern of the array. Since they have closely related, point noise source is assumed to quantify the performance indexes. The resultant beam pattern due to a single point source is measured to calculate the indexes. The beam width by a point source is considered as the spatial resolution. The side lobe level is considered as noise floor. Figure 3 shows the indexes graphically. The beam width is measured at the half power height, which is -3dB below of the maximum power (Bw3dB). The difference between the maximum power and the largest side lobe level is called Maximum Side-lobe Level (MSL) and it represents the inherent signal to noise ratio of a microphone array.

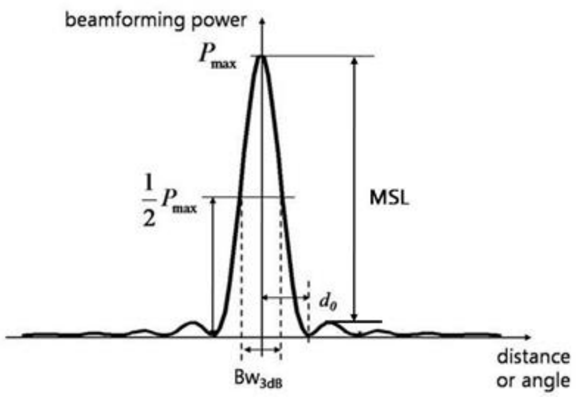

Figure 3 - The Performance indexes of a microphone array. Bw3dB, which is the half power beam width, represents the spatial resolution and the Maximum Side-lobe Level (MSL) indicates the signal to noise ratio.

The pattern of microphone array can be determined by numerical simulation (2). We can compare spatial resolution and for candidates. A microphone array normally has irregular pattern since regular one shows low MSL. In this paper, we took a curbed poke pattern since it shows reasonable performance and it is manageable shape for manufacturing. A total of 30 or 96 microphones were used depending on the size of a microphone array. Figure 4 shows the performance comparison of 4 candidate array shape.

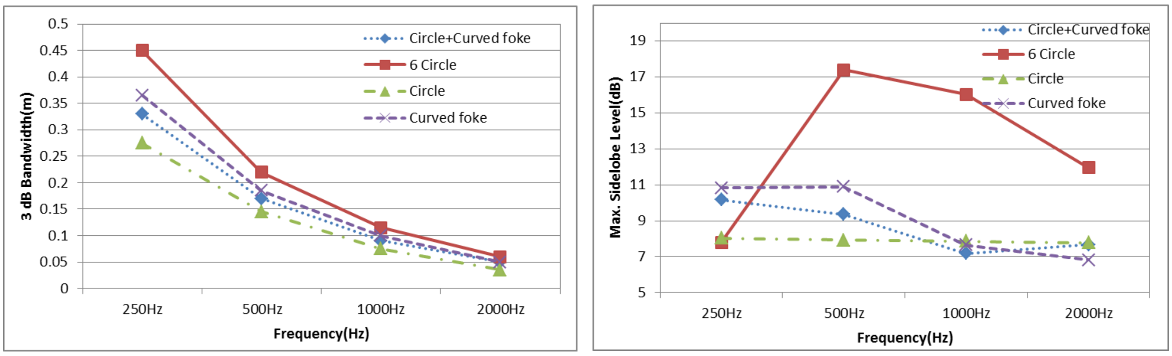

Figure 4 - The 3dB beam width and MSL of a 30 channel microphone array with 35 cm of a diameter.

3. Digital Technology for Microphone Array

3.1 Digital MEMS Microphone

Micro Electro Mechanical System (MEMS) is a technology derived from the semiconductor manufacturing process which integrates micro meter sized mechanical components and electronic circuits. The process of manufacturing a MEMS microphone creates smaller and more inexpensive microphone in comparison to the traditional ECM. MEMS microphones enable dramatic advancements in multiple-microphone applications such as microphone arrays. Both the MEMS and ECM have the same principle in which capacity changes between a back plate and a membrane. The capacity change is caused by the sound, passing through an acoustic hole, that moves the membrane modulating the air gap comprised between the two conductive plates. There are two types of MEMS microphones in terms of out signal. Analog MMES microphone converts sound into a corresponding voltage output. Digital MEMS microphone gives digital output such as pulse density modulation (PDM) and I2S signal. In this paper, we used a digital MEMS which produce PDM signal.

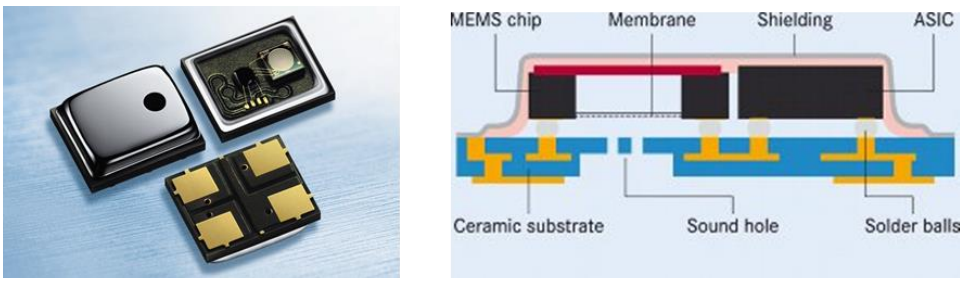

Figure 5 – MEMS microphone and it's inside structure. The capacity change is caused by the sound, passing through an acoustic hole, that moves the membrane modulating the air gap comprised between the two conductive plates

The performance of MEMS (Micro-Electric Mechanical System) microphones have been upgraded as mobile industries become large. The MEMS microphones are highly reliable and have flat responses in the frequency range of human voice. For example, a MEMS microphone from Analog Device, ADMP 441 has flat responses from 60 Hz to 15,000 Hz, which covers the frequency range of SR noises. Figure 6 shows an example of the measured frequency response of a MEMS microphone, ADMP 441. Moreover, a digital MEMS microphone is equipped with an analog-to-digital converter in it. It converts the analog signal into the digital pulse train. Therefore, we do not need to use separate analog-digital converter modules anymore. Since the array for SR noise should be small and light, we used the digital MEMS microphones for the array.

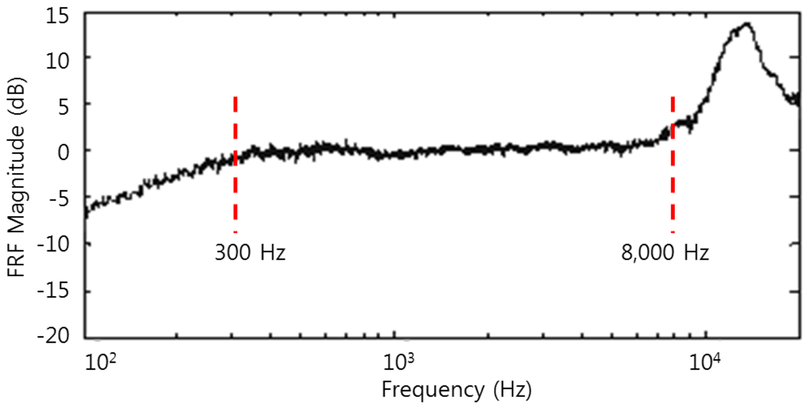

Figure 6 - The frequency response function (FRF) of a MEMS microphone, ADMP 441. The FRF compares the response of the MEMS microphone to the reference microphone, which is B&K 1/2” microphone (B&K 4176).

3.2 FPGA Implementation of Beam-forming Algorithm

The beam-forming devices require lots of calculation since they need to provide as many noise maps as possible per second. Especially, the beam-forming devices for SR noises need to update the noise maps more rapidly since they need to detect highly transient noises. To solve this issue, many commercial beam-forming devices are using high performance computers and digital signal processing boards. However, the configurations are not proper for a small portable device and it requires large resources for a large microphone array.

Field Programmable Gate Arrays (FPGAs) are semiconductor devices that are based around a matrix of configurable logic blocks (CLBs) connected via programmable interconnects. FPGAs can be reprogrammed to desired application or functionality requirements after manufacturing. This feature distinguishes FPGAs from Application Specific Integrated Circuits (ASICs), which are custom manufactured for specific design tasks. Although one-time programmable (OTP) FPGAs are available, the dominant types are SRAM based which can be reprogrammed as the design evolves.

Table 1 – Comparison of CPU and FPGA technology in terms with beam-forming implementation. (CPU: SM Instruments’ Model SeeSV-S200, FPGA: SM Instruments’ Model SeeSV-S205)

Subjects	**CPU**	**FPGA**
Method	Serial Calculation	Parallel Calculation
Data Type	Double Precision	Fixed Point
Beam-forming Method	FFT-Based Beam-forming	Time Domain Beam-forming
Frame Rate	5 fps	25 fps
Frequency Range	10 individual freq.	Whole freq. band
Hardware	High Performance PC	Embedded Hardware

There is no limitation in calculation speed of FPGA theoretically, since FPGA performs parallel processing. It operates in a real-time megahertz clock. That is why it is compared ASICs, which is a pure hardware. Only the amount of binary operations determines the types and capacity of the FPGA chips. Therefore, we convert the conventional beam-forming algorithm into binary operation and implemented it in an FPGA chip. The devices we develop scans a whole virtual direction in 40 milliseconds. The result gives us a noise video that has the update rate of 25 frames per second. In addition, time domain beam-forming was implemented with the series of band pass filters. Therefore, whole frequency band signal can be analyzed in real time, while only couple of frequency components were displayed in the previous CPU based processing.

In this study, commercial FPGA boards were used to implement the beam-forming devices. A small portable array runs on a small National Instruments' sbRIO based FPGA board. It handled 30 channel microphone signals. A large array runs on a National Instruments' PXI based FlexRIO board. It processed 96 channel microphone array data and generates 25 images per second.

4. Application Examples

Several examples were taken to verify the performance of the beam-forming device that is manufactured for SR noise detection. Figure 7 shows the noise images of the rattle noises generated from the dashboard module of a passenger vehicle. The images were taken while the manufacturer of the module was performing high frequency shaking tests in order to screen out the squeak and rattle noises.

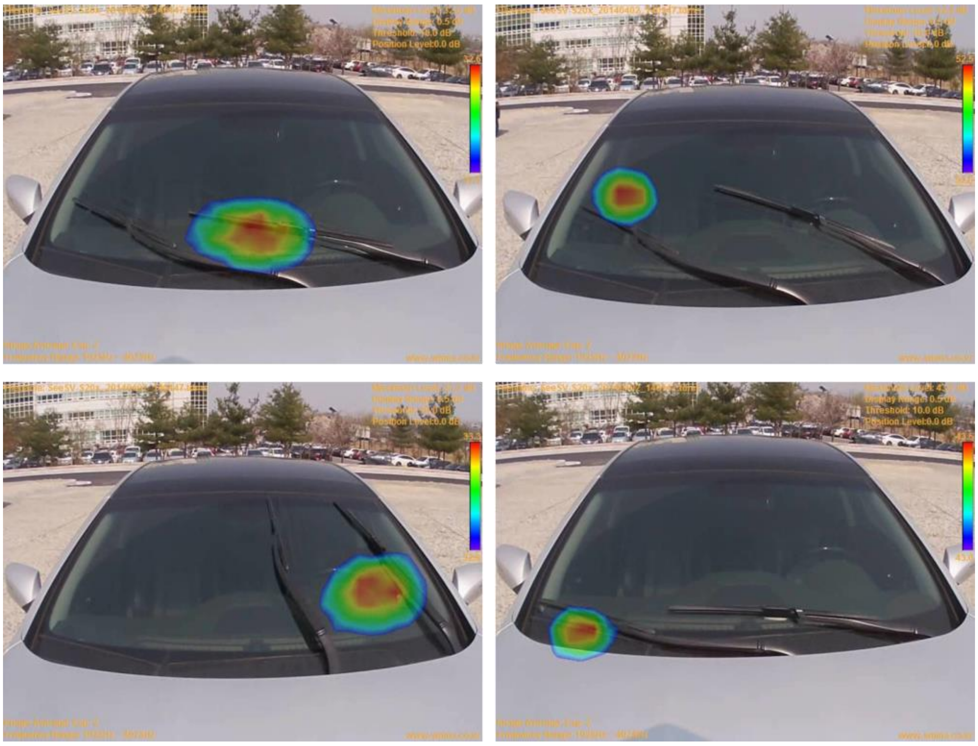

Figure 7 - The detection of squeak noise generated from widow wipers. The rainbow contour shows the magnitude of beam-formed signals at each location.

5. CONCLUSIONS

This paper introduced the principle of the beam-forming devices and explained how we used digital MEMS microphones and FPGA technologies to develop beam-forming devices. By using digital technologies, the devices can generate 25 images per second. A small portable array runs on a small National Instruments' sbRIO based FPGA board. It handled 30 channel microphone signals. A large array runs on a National Instruments' PXI based FlexRIO board. It processed 96 channel microphone array data and generates 25 images per second.

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