Appendix B Development and testing of advanced piezoelectric speakers

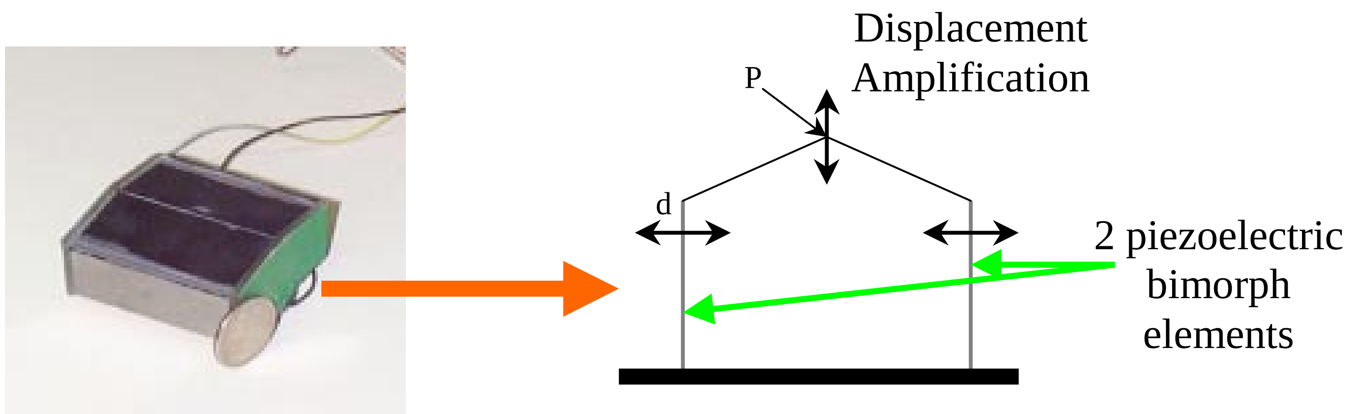
During the experiments presented in this thesis, the active control of power train noise and road noise was achieved with two types of acoustic sources. First, conventional audio speakers were used. These electrodynamic speakers are those commonly used in the entertainment system of cars. Second, compact lightweight piezoelectric based speakers were used. The latter acoustic source was cooperatively developed by Material Systems Inc, Penn State University and Virginia Tech. In this Appendix a few characteristics of the piezoelectric source are presented.

Figure B.1 shows the speaker throughout different stages of its assembly. In Figure B.1 (a), the driver is shown beside a quarter coin for scaling purposes, and to the right, a schematic presents the principle of the driver. It is composed of two piezoelectric bimorph elements. The piezoelectric elements are clamped to the base on one end and linked to the motion amplifier on the other end. The motion amplifier is the bent surface that links the two piezoelectric elements. When the two elements are driven out of phase, the horizontal displacement d of the piezoelectric element is converted into a vertical displacement of point P. The driver was designed such that displacement P is greater than the displacement d (more details regarding the design of the drivers are given by Jonhson in [55]). The amplification is necessary because a large displacement is required to radiate noise at low frequencies. This will be later explained in Figure C.1. Figure B.1 (b) shows three piezoelectric double amplifier drivers, which are enclosed in a six-inch PVC cylinder. Balsa wood was fixed to the top of each of the drivers to ensure proper connection of the motion amplifier to the diaphragm. The speaker in its final stage is shown in Figure B.1 (c), with the diaphragm glued to the balsa wood connectors and attached by a rubber edge suspension to the cylinder in order to ensure free boundary conditions at the outer ring.

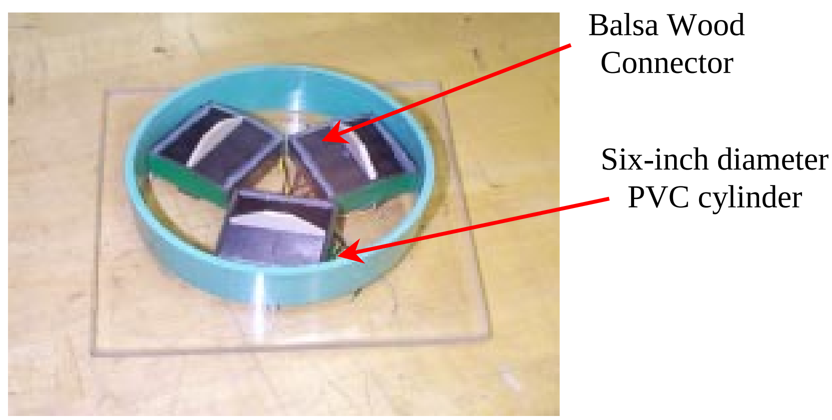
The next generation speaker is shown in Figure B.2. Its principle is the same as the advanced speaker described above, but in this case five elements are used to drive the diaphragm. In this version of the speaker, the weight and height have been reduced. In the first version, the speaker is 5.5-cm tall and weights 600 grams, although lighter materials could be used for the outside cylinder. The second version is only 2.5-cm tall and weights 285 grams. In the next generation speaker the displacement generated by the drivers at low frequency is limited. Therefore the diaphragm displacement is too small to generate enough output to control power train noise at frequencies below 350 Hz.

In order to characterize the advanced piezoelectric source (first generation), velocity measurements of the diaphragm were performed with a laser vibrometer, while it was excited with random noise band pass filtered between 100 and 500 Hz. Figure B.3 shows a schematic of the diaphragm with the velocity measurement positions. Velocity measurements were taken at 19 evenly spaced points around the outer ring as well as 12 evenly spaced points across the diameter. In the schematics, the measurement points are shown on the schematic relative to the three drivers and the diaphragm.

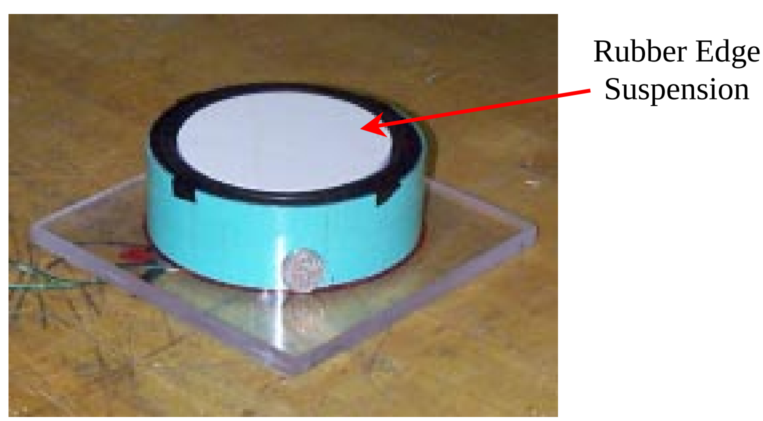
Figure B.4 shows the velocity measured on the diaphragm at the driver location for the first generation source. In Figure B.4 (a), the amplitude of the velocity is shown as a function of the driving frequency. Above 300 Hz, the amplitudes of the three drivers are the same. Below 300 Hz, the amplitude of driver 3 is lower than that of the two other drivers. The response of drivers 1 and 2 is almost the same in the entire frequency band (100 to 500 Hz), although between 120 and 200 Hz, the amplitude of driver 2 is larger that of driver 1. Figure B.4 (b) shows the phase between the input voltage and the velocity measured on the motion amplifier of the driver. It can be seen that drivers 1 and 2 have the same phase in the frequency band of interest, while driver 3 leads the two others below 175 Hz, and then lags between 175 Hz and 350 Hz. For frequencies above 350 Hz, the three drivers are in phase. In conclusion, the three drivers have very similar dynamics above 350 Hz, while the amplitude difference and phase lead or lag may induce some type of rocking motion of the diaphragm at lower frequencies. This type of motion results in lower sound radiation efficiency.



(a) Principle of the driver



(b) Top view of the speaker without diaphragm



(c) View of the speaker with diaphragm

Figure B.1 Advanced speaker

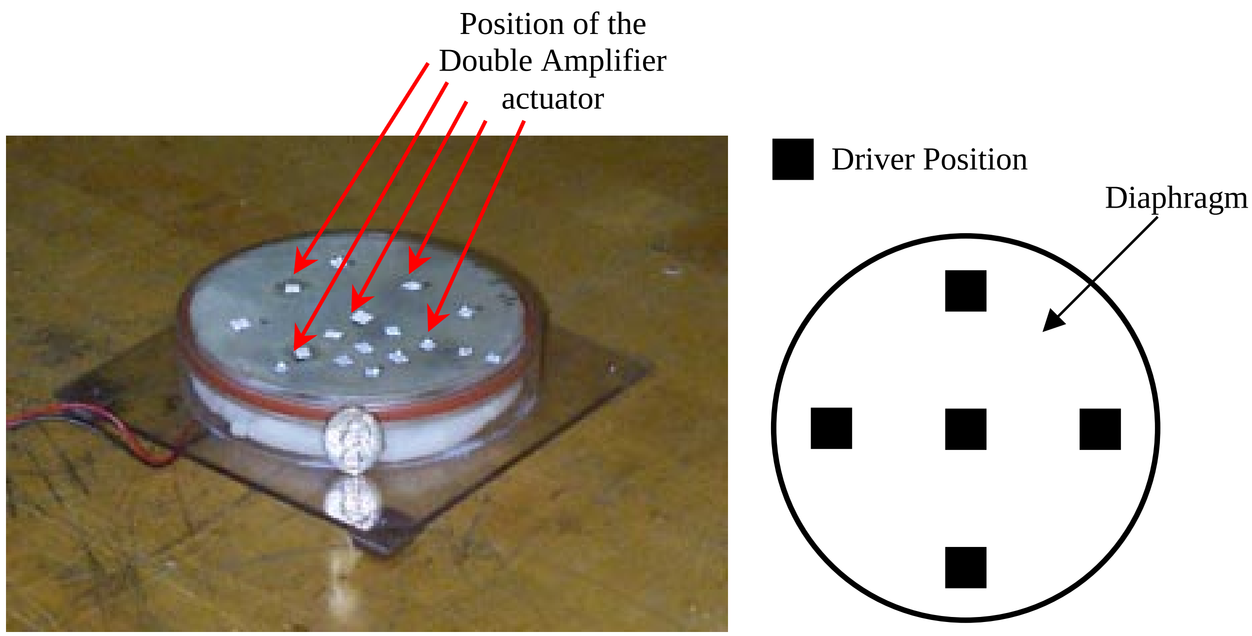


Figure B.2 View of the next generation speaker

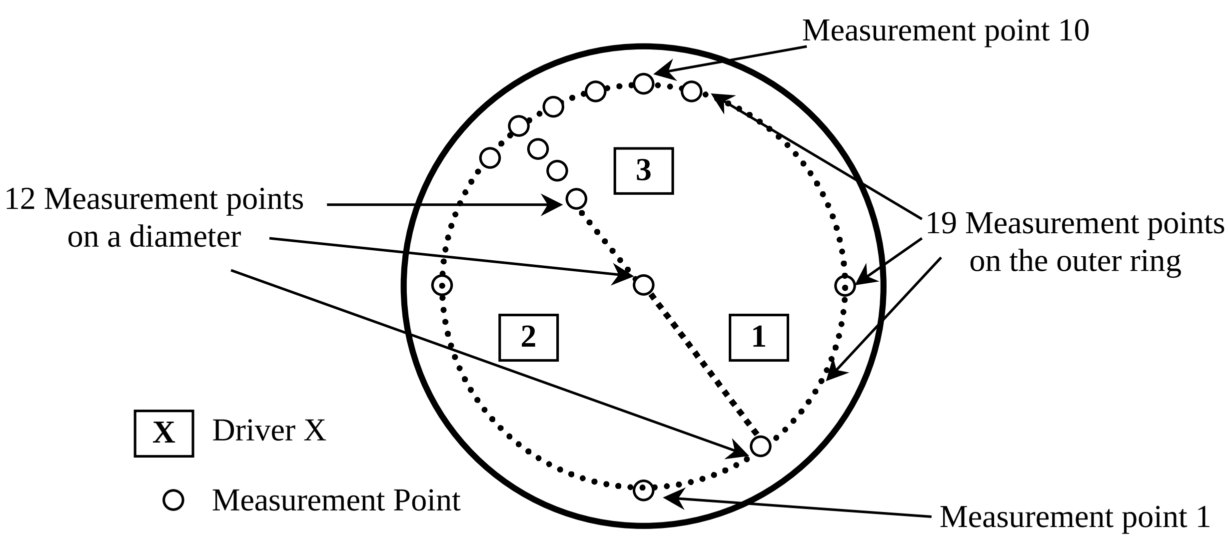
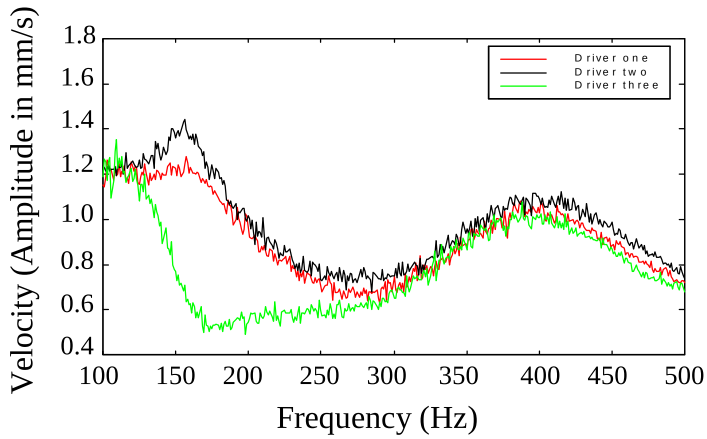


Figure B.3 Schematic of diaphragm with measurement points

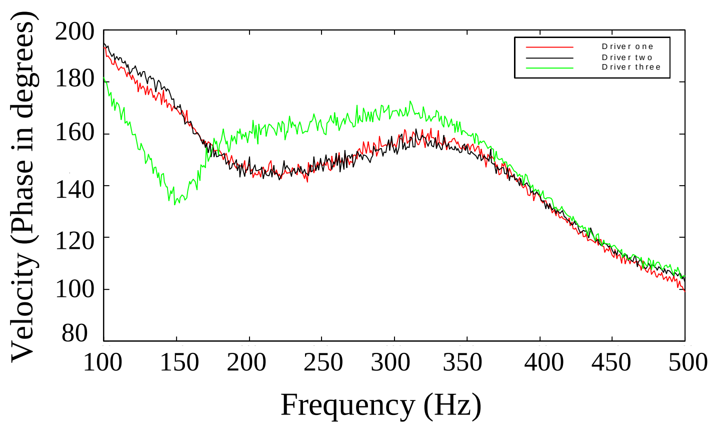
In order to investigate the overall velocity field on the diaphragm of the first generation source, the velocity measurements taken at 19 points evenly spaced along the outer ring of the diaphragm are plotted in Figure B.5. A linear interpolation was used between these points. The frequency resolution is one hertz, and the interpolation is also linear in the frequency domain. Figure B.5 (a) shows that the amplitude of the velocity is lower around point 10 for frequencies between 140 and 300 Hz. Figure B.5 (b) shows that all the points are in phase for frequencies above 350 Hz, but near point 10, there is alternatively a phase lead below 175 Hz and then a phase lag up to 350 Hz. Point 10 displays similar characteristics to driver three, which is located on the same radius. It is important to note that there is no significant phase and amplitude difference between the points other those shown at point 10, which are caused by driver's three different characteristics. This means that there is no dynamic behavior of the diaphragm along the circumference in the frequency range 100 to 500 Hz. Had a mode appeared around the circumference of the plate, a phase shift of 180 degrees would have appeared in Figure B.5 (b), and a node of vibration would have appeared in Figure B.5 (a).

In Figure B.6, the same plots are shown for points located on a diameter. All the points are vibrating in phase with the same amplitude, except point number 6 (center of the diaphragm). There is a 50-degree phase difference between the center point and the other points. The amplitude of the center point is of the same order as the amplitude at the other points. Therefore, there is no resonance in the plate in the frequency range of interest. The phase difference is due to the different dynamic behavior of driver 3.

In conclusion, there is no resonance in the diaphragm in the 100 to 500 Hz frequency band. The diaphragm itself behaves like a rigid piston and therefore is a good sound radiator. Nevertheless, it was observed that the three drivers did not have the same behavior. This resulted in a rocking type of motion for frequencies below 350 Hz, therefore decreasing the efficiency of the source in radiating sound. Because the phase difference was only of the order of 20 to 30 degrees, the vibrating behavior of the speaker was very close to be piston-like, thus maximizes radiation efficiency.

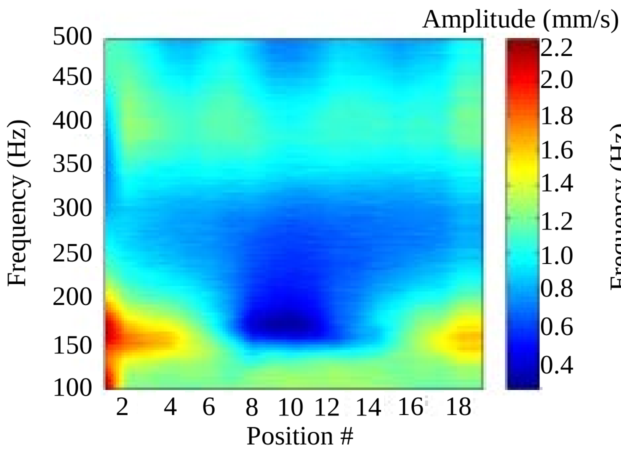


a. Amplitude

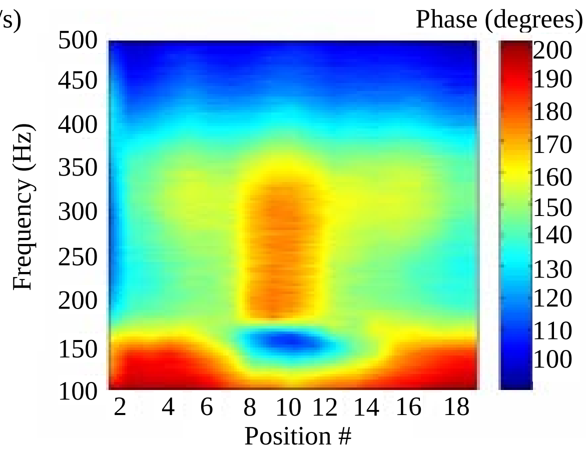


b. Phase

Figure B.4 Response at the driving points

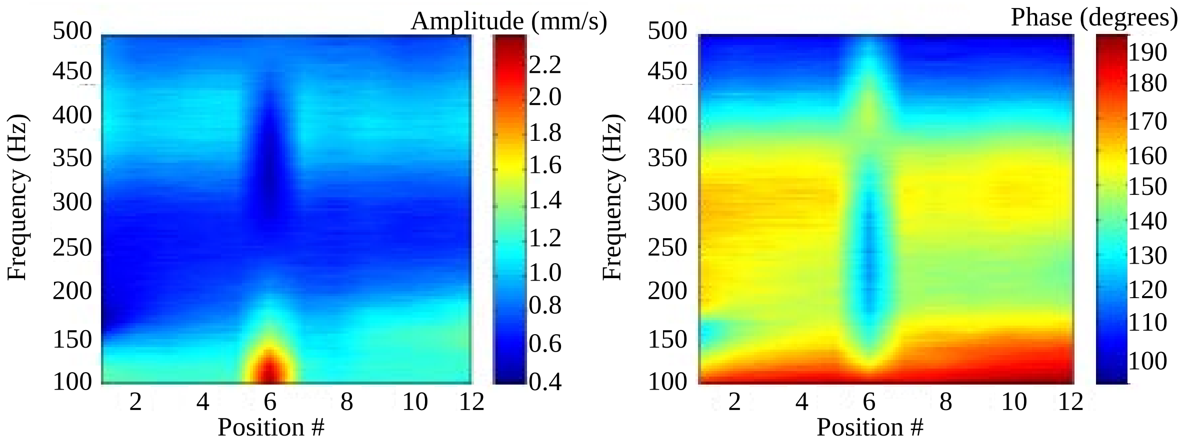


a. Amplitude



b. Phase

Figure B.5 Velocity field on outer ring



a. Amplitude b. Phase

Figure B.6 Velocity field on a diameter