Chapter 6 Conclusions and Recommendations

6.1 Conclusions

A research and development program for the active control of noise in the cabin of a Ford Explorer was initiated. It was conducted in two stages. First, a test cavity was built for optimization of the locations of the control sources and error sensors. Second, active control of power train and road noise inside the automobile cabin was investigated and performed with conventional audio speakers and piezoelectric based advanced speakers. The main conclusions of this research are as follows:

First, it was shown that global control of the pressure field inside this three dimensional cavity was not very sensitive to the locations of the error sensors and control sources. Because of its dimensions and shape, the dynamics of the test cavity were similar to the dynamics of the car. Therefore it was concluded that the secondary sources could be located at the positions of the stereo system speakers for the control of the automobile cabin noise. It was also concluded that the best location for the error sensors was close to the ears of the driver and passengers because in terms of acoustic comfort, noise reduction is more important at these positions.

Second, experimental active control of power train and road noise was implemented in the cabin under various test conditions. It was shown that active control of power train noise was feasible with two conventional speakers, two error sensors and three reference sensors from 40 to 500 Hz. Attenuation of 6.5 dB was obtained at the error sensors and a zone of quiet was created around the head of the driver and front passenger. The zone of quiet is approximately a sphere of 45-cm radius (in which the attenuation is greater than 3 dB). It was also shown that active control of simulated road noise (one wheel excited by a roller covered with rough aggregate) was feasible between 100 and 500 Hz with two reference sensors, two error sensors and two conventional speakers as control sources. Attenuation of up to 12 dB was recorded at one of the error sensors for this test case.

Third, it was shown that the control of power train noise was feasible with the piezoelectric based speakers above 150 Hz. Due to the low output of these sources at frequencies below 200 Hz (see Appendix C), it was not possible to control those harmonics of the engine firing frequency, which were below 150 Hz. These sources were also used for the control of simulated road noise. No control of the sound pressure was obtained at the error sensors below 200 Hz. However, attenuation of 7 dB was measured at the error sensors between 200 and 400 Hz.

General conclusions of this work are as follows.

1. A finite element model of the test cavity was created and experimentally validated for frequencies below 200 Hz.   The natural frequencies and mode shapes of the model matched those of the experimental set-up. The model also included modal damping that was experimentally measured and applied to the model. The disturbance created by the vibration of a steel plate clamped to one side of the cavity was measured and applied to the model. Computation of the pressure field inside the cavity due to this disturbance showed similar trends, both in the case of the model and in the case of the experimental set-up.

2. A Matlab code was written for simulation of active noise control in the cavity. This code used data obtained with the finite element model. Control results obtained with the simulation matched those obtained experimentally. It was shown that on resonance the spatial distribution of the sound field after control obtained with the model was very close the sound field after control measured experimentally.

3. Optimization of the locations of the control sources and error sensors was achieved with a genetic algorithm applied to the model. It was shown that global control of the sound

field was achievable in the cabin when four control sources and six error sensors were used. Although the genetic algorithm was efficient at finding a solution for global control, it was shown that the solution was not very sensitive to the locations of the control sources and error sensors. Therefore the control can be performed with the speakers of the vehicle entertainment system.

4. The optimized configuration of the control sources and error sensors was used to perform control of harmonic disturbances as well as pseudo random noise band pass filtered between 40 and 400 Hz. Two conclusions were drawn. First, global control of the pressure field in the cavity was achievable with four control sources at frequencies where less than four modes contribute to the response in the cavity (i.e. on resonance or at frequencies where the modal density is low). Second, in the case the system is over-determined, the attenuation of the sound pressure level at the error sensors is lower than in the case the system is fully-determined. In the case the system is over-determined (the number of error sensors is greater than the number of control sources), the attenuation achieved away from the error sensors is higher than in the case the system is fully-determined.

5. The technology was applied to the automobile cabin of 97 Ford Explorer for the control of the power train and road noise. It was shown that the sound field in the automobile was very damped. Therefore the number of modes that significantly contribute to the acoustic response is high for frequencies above 60 Hz. It was shown that no global control was possible in the cabin with four control sources, but that it was possible to create a large zone of quiet around the head of the driver and the passenger.

6. The active control of power train noise was performed between 40 and 500 Hz, using commercially-available speakers and state-of-the-art piezoelectric lightweight compact speakers. A simulation tool based on experimental signal from the error and reference sensors was designed to compute the maximum reduction achievable at the error sensors. The results of this simulation were used for the optimization of the locations of the reference sensors. It was shown that using three reference sensors, all the peaks of the frequency response could be lowered down

to 1 dB over the background noise of the engine. The total reduction in the frequency band was 8 dB with the optimized configuration of error sensors.

7. Reduction of the sound pressure level of up to 7 dB at the error sensors was achieved both in the case two commercially-available speakers or two state-of-the-art piezoelectric speakers were used. It was shown that the dimension of the zone of quiet depends on the number of secondary sources. In the case where four secondary sources where used, spillover occurred only in the corner of the volume scanned (head and torso of the driver and passenger).

8. The feedforward algorithm was applied to simulated road noise. In a first experiment, the front wheels of the car were set on a smooth roller. The rotation of the roller induced the noise in the car. It was shown, that the noise measured inside the cabin was highly dominated by the harmonics of the roller rotation. Nevertheless, this experiment showed that active control of a disturbance due to the contact of the front wheels with a smooth surface was feasible with four reference sensors. In a second experiment, the left front wheel of the car was set on a larger roller (10-feet diameter) whose surface was made of rough aggregate. The sound pressure measured in the cabin in these conditions was similar to the sound pressure measured when the car is driven on a coarse road. Reduction of 10 dB in a large frequency band (100 to 500 Hz) was achieved at the error sensors when two conventional speakers and two error sensors were used. When the two piezoelectric sources and two error sensors were used, no control was achieved below 150 Hz. Reduction of 2.5 dB was obtained at the error sensors between 100 and 500 Hz. Nevertheless, reduction of 7 dB was achieved at the error sensor between 200 and 400 Hz.

9. The system was also applied to the control of real road noise with the vehicle travelling on a rough road. A principal component analysis was performed to determine the number of reference sensors. It was shown that a large number of reference sensors were required to control the sound pressure level at the error sensor when the car was driven on a coarse road. Due to hardware limitations, only four references were used. Their location was optimized to control the sound pressure level on the side of the passenger. One control source (conventional speaker) and one error sensor were used during the tests and reduction of 2 dB at the error sensor

was obtained between 100 and 200 Hz. Simulations showed that eight references would be required for reasonable control at the driver and passenger head.

6.2 Recommendations

Several recommendations for future work on this project are as follows.

1. During this work, the error sensors were positioned at location of the head of the driver and passenger. For safety and comfort matters, this is not feasible. The sensors have to be located in the ceiling above the head or in the headrests. In that case, a different algorithm has to be implemented. The goal should be to drive the signal of the error sensor such that the pressure at the head location is minimized (not to minimize the pressure at the sensor).

2. As it was pointed out, the damping in the cabin is very high, and the number of degrees of freedom of the system is consequently high. For global control, a system with more control sources should be used. In that case, optimization of the locations of the actuators and error sensors is necessary. Since no accurate acoustic model of the interior cabin is available, the method presented on the test cavity should be coupled with an experimental approach. The experimental part would consist in measuring the transfer functions between candidate actuators and candidate error sensors.

3. Regarding the active control of road noise, as shown in the principal component analysis and the simulation on partial coherence, eight reference sensors were required to achieve broad band control. The hardware, which was used during the tests, was set up for a maximum of four reference sensors. If only two error sensors and two control actuators are used, a controller with eight reference signals could run on a quad C40 board, similar to the board used for the tests presented in this thesis.

4. Work should be directed towards making the controller, power amplifiers, signal conditioning much more compact and integrated with present vehicle system.