Design of an Electronic Muffler - A DSP Based Capstone Design Project

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Abstract

Active control of noise has been an emerging technology for the past two decades. Active noise control (ANC) is an attractive means to achieve large amounts of noise reduction in a small package, particularly at low frequencies, where passive noise control may be impractical. While the concept of ANC has long been established, the technological means for implementing ANC have only recently become available. With the advent of high-speed digital signal processors (DSPs) and modern signal processing methods, ANC is now becoming a reality.

This paper presents an interesting undergraduate design project involving ANC. In their capstone engineering design course students designed and built a prototype ANC system that successfully demonstrated the concepts of an electronic muffler. The heart of the project centered on the popular Analog Devices' SHARC DSP evaluation module (EVM). In this paper we will discuss ANC concepts and the electronic muffler, the students design project, and the pedagogical outcome.

1.0 Introduction

The Systems Engineering curriculum at the U.S. Naval Academy is a four-year, undergraduate, ABET accredited, program, where students specialize in the interaction between mechanical, electrical, and computer systems. The curriculum focuses mainly on linear systems theory, feedback control, and mechatronics. An integral component of the Systems Engineering curriculum is its capstone design course. This course provides students with a comprehensive design experience bridging the gap between textbook problems and real life applications. Students work in teams to complete a semester-long design project. Each team must propose a project, prepare schedules and reports of their activities, and design, build, and test a prototype. One of the many challenges facing students in this course is the selection of a project that is meaningful and representative of their engineering discipline.

For nearly a decade automotive manufacturers have been experimenting with electronic mufflers for automobile exhaust systems [4] and their realization is near production. Some current electronic muffler concepts are based on active noise control (ANC) that uses destructive interference of sound waves to reduce unwanted noise. An additional advantage of an electronic muffler is the reduction of backpressure associated with conventional mufflers. Reduction of backpressure provides improved fuel economy in most gasoline engines.

A relevant on-going project in the Systems Engineering Dept has been the design of an interference-based electronic muffler. The Systems Engineering Department has had several teams of students over the past three years working on electronic muffler designs. Students find the design of an electronic muffler project intriguing because draws upon previous course work

in systems engineering and challenges them with advanced topics in active noise control and in digital signal processing.

The design and construction of a fully functional electronic muffler is impractical for a one-term design project. However, students do not need to solve every aspect of a complex, real-world project to make it a meaningful design experience. Rather, students can identify one or two key design issues, whose resolution would contribute to the overall objective of the project [1]. The key issue in the design of an electronic muffler is the design of the active noise controller. Therefore the focus of the electronic muffler project is for students to design a prototype ANC system that simulates the behavior of an electric muffler.

In the sections that follow, we will discuss the ANC and DSP aspects of this project, the student's electronic muffler design, and the pedagogical outcome of this project.

2.0 The Electronic Muffler Concept and Active Noise Control

An electronic muffler is a practical example of ANC technology. Noise radiating from the outlet of an automobile exhaust system is reduced by transmitting "anti-noise" from a loud speaker located near the end of the exhaust pipe. The acoustic output of the loud speaker is controlled so that it destructively interferes with the automotive noise. The concept of an electronic muffler is shown in Figure 1.
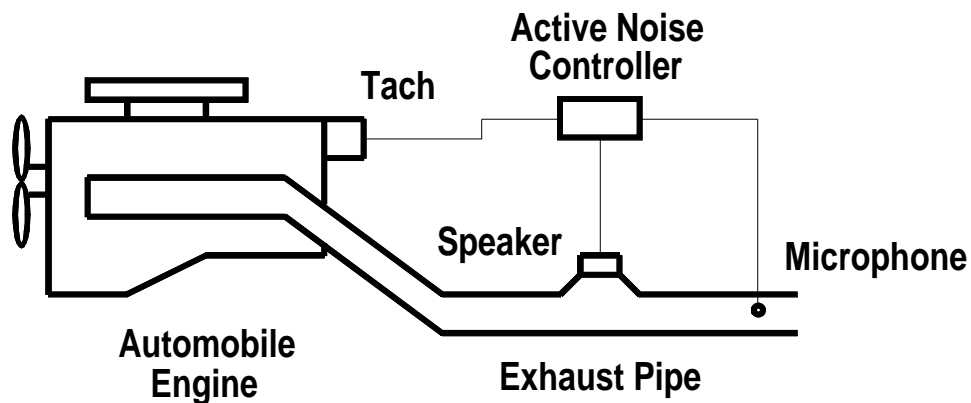

Figure 1. Electronic Muffler Concept

Much of the noise generated by an internal combustion engine is periodic and its frequency components vary as a function of engine rotation speed. An active noise controller uses a tachometer to synthesize a reference signal that is coherent with engine rotation speed. The reference signal is then processed with an adaptive digital filter to produce a signal that is 180° out-of-phase with engine noise. This signal drives a loud speaker to generate anti-noise. An error microphone located at the outlet of the exhaust system measures residue engine noise. This error microphone signal is used to automatically adjust the digital filter's coefficients such that the residue noise is minimized [3][4]. The most common form of adaptive algorithm used in ANC is the least mean squares (LMS) algorithm developed by Widrow [5].

While the concept of ANC has long been established, the technological means for implementing ANC has only recently become available. With the advent of high speed digital signal processors (DSPs) and modern signal processing methods, ANC is now becoming a reality.

3.0 A DSP Based Capstone Design Project

As mentioned earlier, the objective of the electronic muffler project is to have students design a prototype ANC system that simulates an electronic muffler. The project is ideal for a team of two Systems Engineering students. Students who have worked on this project in the past were familiar with linear systems theory, digital control systems, basic electronics, and elementary physics of waves. Prior to the project, these students had no exposure to active noise control or to adaptive signal processing. These new concepts were introduced to the students by the project's faculty advisor. Also, as part of the project, the students did extensive research on these topics.

Over the years, there have been several iterations of the electronic muffler design in this project. They have ranged from trombone-like devices to simple speaker and pipe arrangements. However, the most recent and most successful design is depicted in Figure 2.
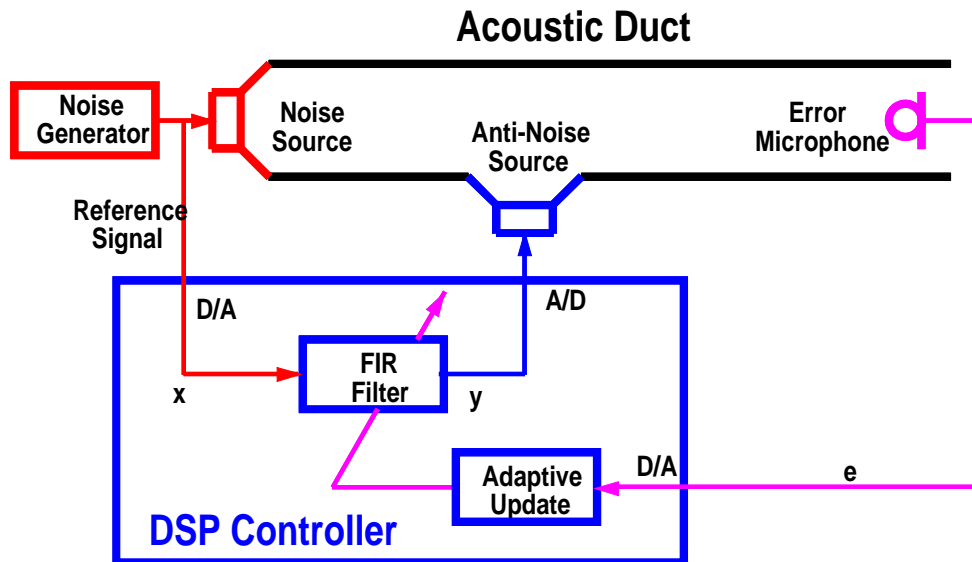

Figure 2. Project System Diagram

For their design, the students proposed to build a prototype ANC system that would demonstrate narrow band noise attenuation in the 200 to 800 Hz frequency range. The ANC system that materialized consisted of two speaker enclosures connected by a length of $1 \frac{1}{2}$" diameter PVC pipe, a microphone, a digital signal processor, signal conditioning circuitry, and power amplifiers to drive the speakers. A photograph of the student's project is shown in Figure 3. One speaker acted as the noise source simulating the noise generated by an internal combustion engine. The other speaker acted as the anti-noise source. The PVC pipe represented the automobile exhaust pipe. A signal generator was used to drive the noise source speaker. An Analog Devices SHARC DSP was programmed as an active noise controller that generated the anti-noise signal.
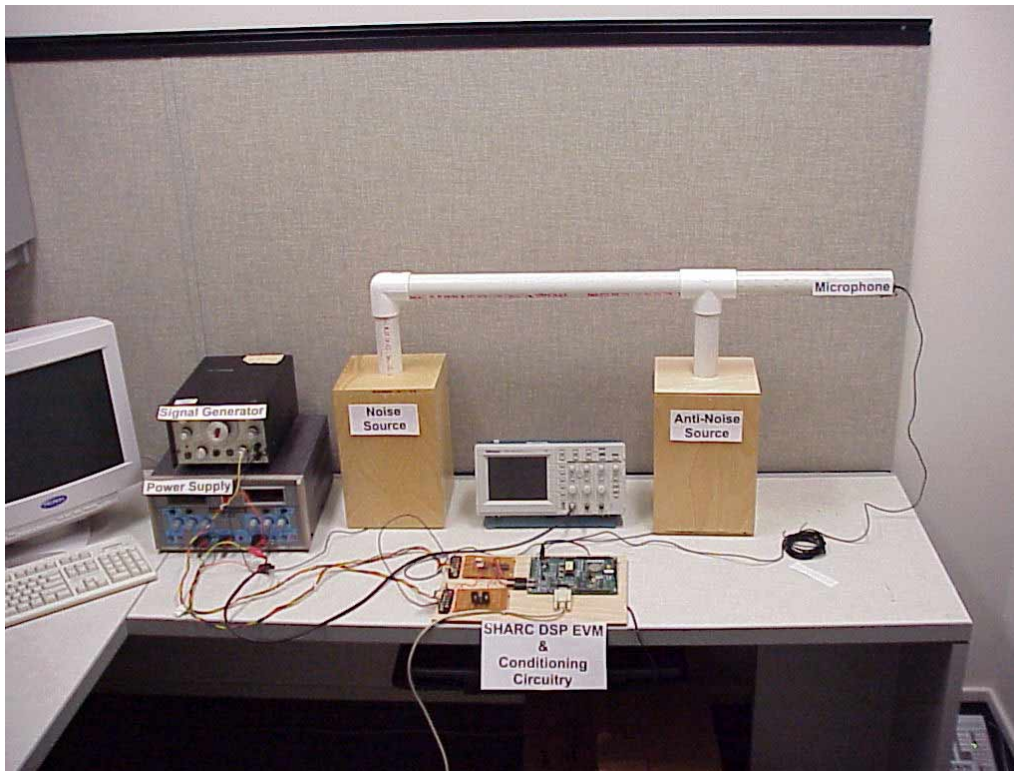
Figure 3. Electronic Muffler Project

The heart of the project centered on the implementation of an adaptive digital filter for the active noise controller. The adaptive filter used in this project consisted of two distinct parts as shown in Figure 2: a digital filter to modify the amplitude and phase of the reference signal $x(k)$, and an adaptive algorithm for adjusting the filter's coefficients. The digital filter was implemented as a finite impulse response (FIR) filter. Because a FIR filter has only zeros and no poles it is always stable. The output of the digital filter $y(k)$ at time k is computed as

$$y(k) = \mathbf{w}^T(k)\mathbf{x}(k)$$

where $\mathbf{x}$ is the input vector at time k

$$\mathbf{x}(k) = \begin{bmatrix} x(k) & x(k-1) & \ldots & x(k-N+1) \end{bmatrix}^T$$

and $\mathbf{w}$ is the time-varying coefficient vector at time k

$$\mathbf{w}(k) = \begin{bmatrix} w_0(k) & w_1(k) & \ldots & w_{N-1}(k) \end{bmatrix}^T$$

A least-mean-squares (LMS) adaptive algorithm [5] is used to adjust the filter coefficients such that the noise detected by the error microphone $e(k)$ is minimized. The filter coefficients are updated every control cycle according to

$$\mathbf{w}(k+1) = \mathbf{w}(k) + \mu \cdot \mathbf{w}(k) \cdot e(k)$$

where μ is the step size. By adjusting μ, the algorithm performance characteristics such as stability and convergence time of the coefficients can be changed.

The students implemented their filter on an Analog Devices ADSP-21061 SHARC EZ-KIT evaluation board. The SHARC evaluation board was recommended for the project by the faculty because it is an affordable and effective tool for developing DSP applications. Students used the (locally generated) SHARCByte user interface [6] to write a C program to implement the adaptive filter algorithm on the SHARC processor.

The students examined the ANC system's performance for tonal noise reduction over the frequency range of interest (200 - 800 Hz). They measured noise attenuation by comparing the error microphone output when the active noise controller was operating against when the active noise controller was not operating. They found that the active noise controller performed well over certain frequency bands. Outside these frequency bands the adaptive digital filter would not converge and the system would become unstable. The students concluded that this anomaly was caused by the adaptive filter's inability to make large changes in phase shift. They recommended adding predetermined time delays for different frequency bands to introduce the needed phase shift. The student's recommended fix is similar to filtered-x LMS algorithms found in the literature [3].

4.0 Conclusions
In this paper a DSP based project for a capstone design course was discussed. The objective of the project was to design a prototype ANC system that demonstrates the concept of an electronic muffler. Experience has shown that this project provides the students with a meaningful comprehensive design experience that bridges the gap between textbook problems and real life applications. The project not only draws on students previous course work in systems engineering, but it also introduces students to advanced topics in digital signal processing and active noise control.

5.0 References
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6.0 Biographical Information
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