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Using an Accelerometer to Make an Active Subwoofer

— Douglas Doucet, Rob Fasani, Peter Hasenkamp, Matthew Senesky

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Problem Statement:

Determine the feasibility of incorporating low-cost accelerometers and a feedback loop into subwoofer speaker design to achieve a 10% reduction in total harmonic distortion.

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Timetable:

Because the circuit required a great deal of revision, prototype construction took approximately a week longer than originally estimated. Additionally, the mathematical modeling was conducted at the end of th term, instead of at the beginning. This was primarily because experimental speaker and accelerometer were required for an accurate model. The properties of these parts were impossible to anticipate, so dat was taken once the prototype existed in order to create the model. Constant contact throughout the term was maintained with the sponsor regarding the project's progress and some of the technical specificatio the accelerometer.

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Work Accomplished:

Specifications

To review, there are four major specifications for our project. The feedback system must reduce, by at le 10%, the Total Harmonic Distortion (THD) of the uncorrected response. To clarify, the 10% reduction is relative to the THD measurement without the feedback system in effect. The project must remain within $500 budget. The accelerometer must be able to handle accelerations of up to 50g. In addition, the subwoofer must be able to handle frequencies between 20Hz and 500Hz. Since subwoofers most commonly handle only frequencies between 20Hz and 120Hz, it is hoped that our best results would be this frequency range, but this is not a direct specification.

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Proposed Solutions

Some design options presented themselves after examination of the problem statement. Options under consideration included the use of digital or analog circuitry, car or home speaker systems, and retrofittin existing production system or building our own system from a kit or from scratch. Our group decided to u analog circuitry because our group has more experience in that area. Car speaker components were us because they are cheaper and easier to use. In addition, we decided to build our own system so the des could be incorporated as the system was built . While car components were used, the system and its application are designed for use in all audio markets.

In addition to the considerations above, junctures were encountered during the creation of the system th required certain decisions. Standard production amplifiers could not be used because the pole placemer the amplifier transfer function was not suitable for our feedback system. This means that the final produc would include an integrated amplifier with subwoofer using the feedback system. These self-powered subwoofers are common today in the home stereo market.

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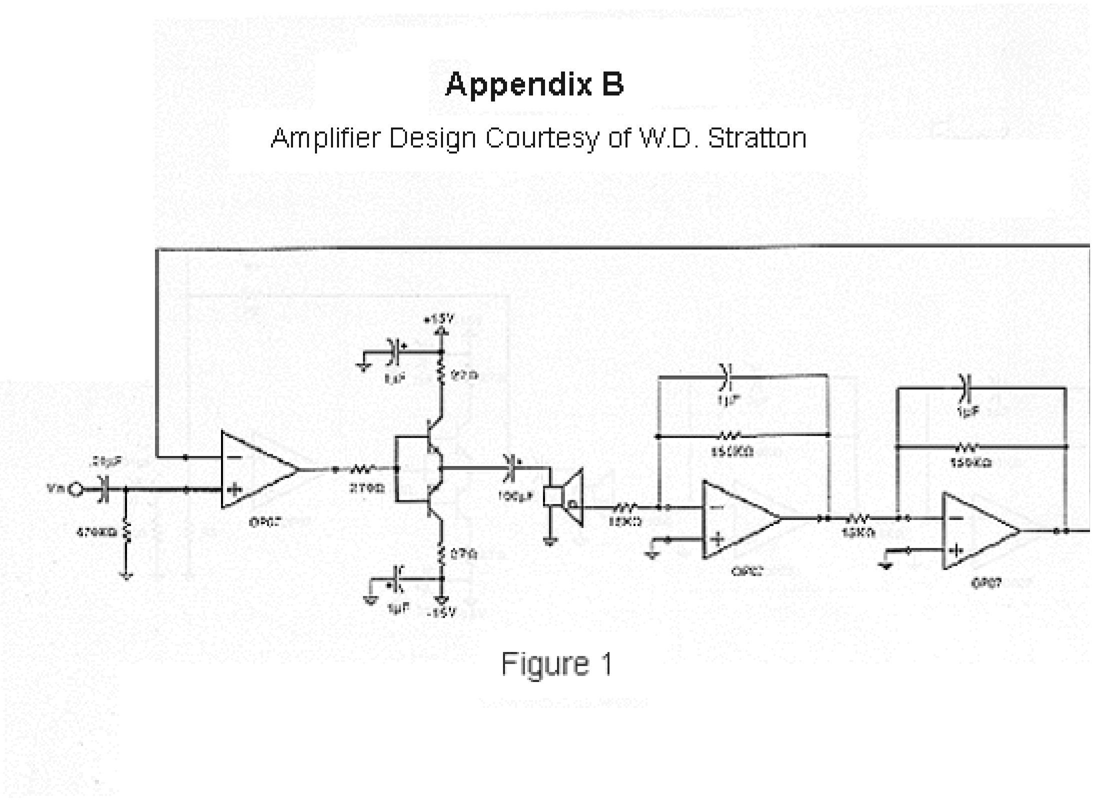
Circuit Design

Our design originated from a simple concept based on amplifying the sum of an input signal and a feedt signal to produce an error signal that would correct for the nonlinearities inherent in audio speakers. An accelerometer mounted on the speaker would give an acceleration signal, and this signal would then be integrated twice to obtain a "position" signal, which would be fed back to the input. Our initial decision to feed back position rather than acceleration or velocity was based on the assumption that a speaker con position is proportional to the voltage across its inputs.

Our initial test setup consisted of a small dominant-pole amplifier powering a 20 watt woofer fitted with a accelerometer. The summing junction was implemented by feeding the input signal into the non-invertin input of an op-amp, and running the feedback to the inverting input. Integration was accomplished with t simple op-amp integrators (Figure 1):


Appendix B

Amplifier Design Courtesy of W.D. Stratton

Figure 1

This setup oscillated fiercely and painfully when the feedback loop was closed, and all attempts to alter gain and phase characteristics of the circuit failed to eliminate the oscillation.

It was suspected that the high open-loop gain of the input op-amp was contributing to oscillation. A seco approach involved two feedback loops, the weighted sum of which would be fed back to the op-amp (Fi 2).

Amplifier Courtesy of W.D. Stratton

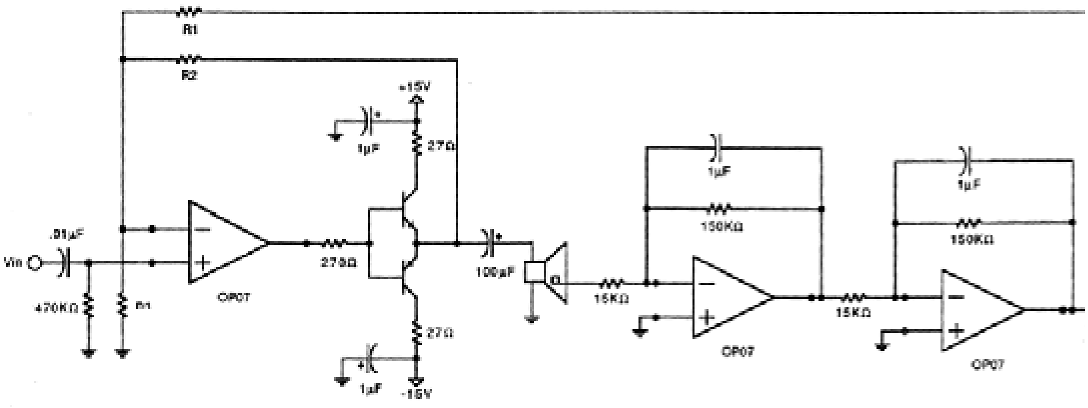


Figure 2

The thinking was that the inner loop could help keep the gain of the op-amp in check, while the outer loc provided the desired position feedback. This succeeded in eliminating oscillation, but it was soon determined that the "inner" feedback loop completely dominated the action of the feedback, so that the position signal went essentially unused. Heavily weighting the position signal when summing the two feedback loops again produced oscillation.

Returning to the idea of a single feedback loop and focusing on the problem of reducing the extremely h gain of the summing junction op-amp, another idea that seemed plausible was to replace the op-amp wi differential amplifier. This would maintain the desired differential operation, while allowing a choice of op loop gains. With the diff-amp in place, oscillation no longer occurred as long as gain was kept close to u

Originally, it was assumed that a microphone would be used to determine the speaker output for THD measurement. However, as our advisor pointed out, the accelerometer was already measuring speaker cone movement more accurately than a microphone could, so a microphone seemed somewhat redund Measuring input at the function generator, and output at the output of the double integrator, THD measurements were taken. According to the results, THD was worse with the feedback loop closed thar open.

It was observed that for a sinusoidal input, with the feedback loop open, and the speaker output distorte (by placing small weights on the speaker cone), output from the double-integrator was still a normal look sinusoid. That is, it was possible to feed a relatively distorted sine-wave acceleration signal into the doul integrator, and get a clean (to the naked eye) sine-wave position signal out. It was speculated that the double-integrator was "smoothing" the acceleration signal in addition to integrating, so that the circuit fai to correct the distortion detected by the accelerometer. Further support of this theory came from the fact integrators are, after all, low - pass filters, and the corner frequency for ours was down at 1 Hz. A small experiment was performed in which a signal with high frequency components was fed into the double integrator, and the output was observed. The high frequency components of the signal were severely attenuated. This explained the failure of the system with integration in place - the frequencies that we wished to detect with the accelerometer were being filtered out by the integrators.

Based on a suggestion given by our contact Jim Doscher early on in the project, the double integrator w removed from the feedback loop, so that the accelerometer output was fed directly into the diff-amp.

Justification for this comes from the fact that $\iint \sin\theta = -\sin\theta$, and from fourier theory, which states t any given wave form can be reproduced as the sum of a series of sine waves. If the double integration i distributed across the fourier sum, the result tells us that all we need to do to accomplish "integration" is invert the accelerometer signal.

Alternatively, lack of integration can be justified by the fact that the real purpose of the feedback loop is t detect and cancel out unwanted frequencies. For a given distorted signal, these frequencies are present both acceleration and position wave forms. Thus phase (the only real difference between position and acceleration in this case) is irrelevant.

With the integrators removed from the setup, measurements showed that THD was reduced when using feedback. Although THD, as well as the effectiveness of the feedback loop, varies widely with input frequency, THD was reduced by up to 50% at some frequencies.

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Design Evaluation

The main measurement used for evaluating the effectiveness of our system was total harmonic distortio As explained in our proposal, the percentage of total harmonic distortion is defined as the rms sum of th harmonic amplitudes divided by the amplitude of the fundamental frequency.

Figure 1 of Appendix C is a plot of the total harmonic distortion vs. the input frequency for the subwoofer speaker with and without feedback from the accelerometer. Zooming in for a closer look (Figure 2), it becomes clear that the total harmonic distortion is better with feedback. The total harmonic distortion is improved by an average of 36.4% of the uncorrected measurement. The spike at 76 Hz is due to some property of the subwoofer bandpass enclosure. It disappears when the speaker is removed from the enclosure.

Appendix C

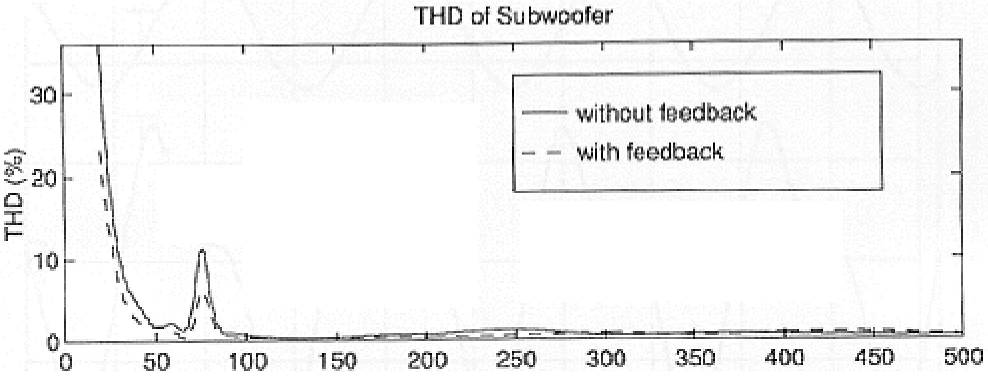

Figure 1

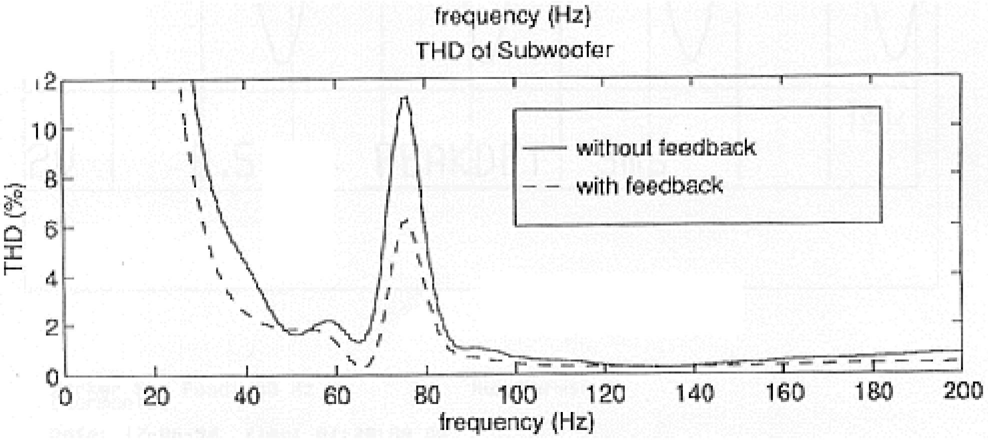

Figure 2

For large enough values of total harmonic distortion, the improvement with feedback can be seen on an oscilloscope. The upper waveform is the input signal, the lower waveform is the output. As the total harmonic distortion drops from 43% to 13%, there is a marked improvement in the waveform's shape. W also calculated the typical accelerations, using the oscilloscope to look at the accelerometer's output. Th output signal ranged from -2.2 V to +2.3 V. The accelerometer puts out 38 mV/g, so the accelerations ra from approximately -58g to 60g.

In an effort to model the system, we also looked at the system's frequency response, as seen in Figure Appendix C. The effect of the speaker enclosure can again be seen at 490 rad/sec, where the response dips suddenly. Using techniques from ENGS 52, we found that the system can best be approximated wi the transfer function:

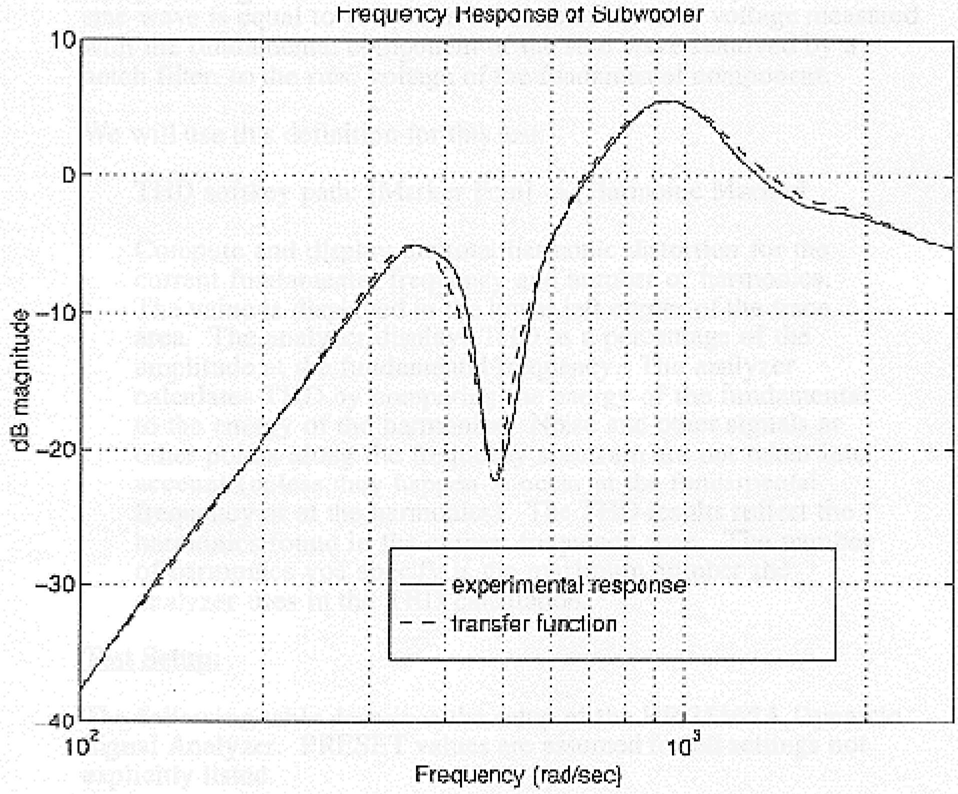

Figure 5

The slope of the frequency response for low frequencies is 60 dB per decade, which corresponds to an term in the numerator. We then estimated the gain K for which $20 \cdot \log(K) + 120 = -37.7$, leading t = 1.3x10-8. The peak at 345 rad/sec and the dip at 490 rad/sec correspond to second order terms in the denominator and numerator, respectively. Some tweaking with the damping factors resulted in a nice fit our experimental data. For the second half of the curve (w > 600 rad/sec), we at first assumed another second order term in the denominator for the peak at 900 rad/sec, followed by another in the denominat for the slight downturn at 1450 rad/sec. This didn't work very well. A closer look at the response curve revealed that there was a slight change in slope at 600 rad/sec. By adding a first order term in the denominator, we improved the curve's shape, but we were still unable to find the correct damping factor the peaks at 900 rad/sec and 1450 rad/sec. We then decided to try squaring the second order term for 9 rad/sec. This resulted in the desired shape of the curve, and we tinkered with the damping factors until obtaining the final curve shown in Figure 5.

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Resources:

People:

Contact at Analog Devices: James Doscher

Faculty Advisor: Professor David Stratton

Equipment:

From sponsor: several ADLX250 micro-accelerometers

From Thayer School:

HP 35665A Dynamic Signal Analyzer
oscilloscope
frequency generator
2 36-watt power amps
various tools, LES, wire, etc.

Purchased:

10" Rockford Fosgate subwoofer speaker
6" trial subwoofer speaker
subwoofer enclosure
various electronics, connectors, glue, etc.

Project Budget:

Enclosure	$80.00
2 Speakers	$100.00
Parts	$150.00
TOTAL:	**$330.00**

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Conclusion:

The primary deliverables that the sponsor desired were: a working prototype of the subwoofer with feedl loop, a theoretical analysis of the system, typical accelerations encountered in normal operation, and an economic analysis, if time allowed. A working prototype has been constructed, the mathematical modeli complete and some experimental readings of typical accelerations encountered in the speaker have bee recorded. As anticipated, there was insufficient time for the economic analysis, but since this was not a required deliverable, the goals of the project have been met.

Had this been a two-term project, the next goal would have been to assess the economic feasibility of ou project for commercial production. This would include evaluating different sensors and feedback methoc addition, the problem of oscillation at high gain would need to be addressed. One possible solution to th problem might be to increase the gain of the inputted signal to the amplifier and use unity gain within the system itself.

In conclusion, though additional work is possible on this project, the primary goals have been met and a working prototype exists. This is a feasible application of Analog Devices' accelerometers.

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