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SERVO DESIGN

Would it be feasible to use Daniel Ferguson's servo system (Sept. '04 *aX*) with a high-quality "plate" amp designed for subwoofers? I own a Kiega amp with high- and low-level inputs and 250W (probably a realistic figure) of power into an 8Ω load, and am currently driving an Adire Audio Shiva DVC 12″ driver in a large transmission line enclosure. I'd love to switch to a compact enclosure and utilize one of Mr. Ferguson's servo controllers if he thinks that would work.

Neil Walker
Elgin, Ill.

Dan Ferguson responds:

It should be more than feasible to build a good-performing servo with these components, both of which have excellent specifications. The Adire woofer seems particularly well suited with low f_s and very high excursion capability. The trade-off will be a somewhat lower SPL output capability than your current setup. If your application is high-accuracy music reproduction, then I think you will be quite pleased with the result.

However, I have some reservations about using a single 12″ servo driver for home theater. You could try it and see. If you find that the headroom is insufficient, you could simply turn off the feedback system when watching movies. If you take this approach, make the enclosure large enough for closed-box Q to be around 0.9 to 1.0, which should give you the best of both worlds.

Good luck with your servo design. Readers would be interested in hearing how it turns out.

I found Dan Ferguson's two articles in *audioXpress* about a servo dual voice coil subwoofer (Nov. '03 and Sept. '04) very interesting. I always wondered why no one had done this before, but your articles and a little digging told me that someone has. I think you're on the right track and would like to offer a few observations.

Analog Devices makes a series ADXL xxx of very small, light, and relatively inexpensive accelerometers. I recognize that this is not what you set out to do, but thought you might be interested. In addition, they (www.analog.com) have a rather naïve student paper "Using an accelerometer to make an active subwoofer" that you might find interesting, because it is full of obvious mistakes.

In your project you first tried and then abandoned your attempt to cancel the magnetic coupling between the driving and pickup coils by using a 0.1Ω shunt and differential amplifier A. This didn't work, because the mutual inductance coupling causes the picked up voltage to be shifted 90° from the current.

If I = A sin wt, then V = M(dI/dt) = MAw cos wt, and no amount of sine wave will cancel the cosine wave. If you add A sin wt and B cos wt, you get $\sqrt{(A^2 + B^2)}$ sin (wt + Ang), where Ang = arc tan (B/A); this is always bigger than A and B.

The choices are to differentiate the current signal before subtracting it or use a mutual inductor instead of a shunt to generate the canceling signal. You know how to make a differentiator, so I'll talk about the mutual inductor idea.

You can make a simple mutual inductor by slipping a high permeability magnetic core on one speaker lead and winding a bunch of turns on the core. The "unloaded" output voltage from the winding will be M (di/dt), just like the pickup in the second voice coil which is causing your problem. You then use this signal instead of the output from differential amplifier A.

P.S. If you put a low impedance load across the secondary (burden), this is called a current transformer, which then produces an output voltage in phase with the current. You don't want a current transformer for this application.

Walter Schillinger
(waschil@attglobal.net)

Daniel Ferguson responds:

Your observation that the current derivative should be taken before the summer is correct, and I tried a number of times to make that work. If the passive voice coil voltage is V = dx/dt + M(di/dt), then the cone velocity dx/dt = V – M(di/dt), and the cone acceleration (a) = d/dt[V – M(di/dt)], or a = dV/dt – M(d^2i/dt^2). Thus the current term must eventually pass through a differentiator twice.

Every time I tried to do this, the servo wailed like a banshee. As you pointed out, the problem is due to phasing. The phase angle difference between the reference signal and the output is called the "phase margin." When the phase angle reaches 180°, the phase margin is zero and the system becomes completely unstable.

The feedback loop has a built-in 90° phase lead after the differentiator, which uses up half of the available phase margin, so there's little room left for error. When you introduce a second derivative term, it must be *precisely* cancelled out or the result is instability. I was never able to do that with sufficient accuracy to get complete cancellation.

The approach I presented in my first article was based on empirical results—after the theoretical paths led to failure. Over time, I was eventually able to generate some spectacular waveforms—but not at high output levels.

Then came your thoughtful letter. I thought about using the iron core-based pickup on the speaker lead that you suggested but had reservations about introducing another phase shift due to the unknowns. After several days of mulling this over, I was convinced that you were onto something and then it hit me—what was needed was to exactly replicate a dual voice-coil.

The published voice-coil inductance for the driver I'm using is 0.18mH. I had a spare 0.30mH air-core inductor on hand, so I stripped off the windings, doubled them in half, and carefully hand-wound a bifilar 0.15mH inductor. I connected one winding in series with the driven voice-coil and used the other as a sensor to pick up the cross-talk component. It worked!

I was able, for the first time, to get the electronic "accelerometer" to duplicate the complex waveforms generated by the condenser mike at every frequency within the subwoofer's passband. What a thrill! And after a few more days of fiddling, I was finally able to close the loop and reproduce music at about the same levels as without the current term.

There's still more work to do, but thanks to your help, I now have hope for success. Thanks very much for your assistance.

I was very pleased to read Daniel Ferguson's "A Servo Dual Voice Coil Subwoofer" and "12″ Dual Voice Coil Servo Subwoofer System," in the November 2003 and September 2004 issues. These are the kinds of articles that should be published more often in *audioXpress*, because they offer valuable research and development by amateurs that have enough will and faith to follow, clarify, and experiment with their own ideas.

I would like to make the following remarks and comments on Mr. Ferguson's work.

1. Is the SPL driven by velocity or acceleration?

The best answer to this question was given by Lord Rayleigh when calculating the mechanical impedance of a piston of radius a, radiating acoustic power in a half-space. His results were:

If $a \le \lambda/\pi$, the acoustic power radiated by the piston is proportional to the square of the piston acceleration. So to keep the power constant, the piston acceleration must stay constant. In this frequency domain, it is the piston acceleration not the piston velocity that drives the SPL.

If $a > \lambda/\pi$ the acoustic power radiated from the piston is proportional to the square of the piston velocity. So to keep the power constant, the piston velocity must stay constant. In this frequency domain, it is the piston velocity not the piston acceleration that drives the SPL.

These statements are similar to those made by J.F. Novak, but they apply to the radius not on the loudspeaker cone diameter.

2. True loudspeaker cone velocity

Because passive and driven voice coils are tightly wound together, it is evident that the measured voltage across the passive voice coil is, using notations defined in the articles, $v_s = c(dx/dt) + M(di_1/dt)$. There is no mystery in this relationship—simply the Ampere and the Lenz or Faraday laws. The strategy proposed by Mr. Ferguson is to remove the coupling term $M(di_1/dt)$ to obtain the true loudspeaker cone velocity. But doing this requires a current-sensing device to measure i_1, then a differentiator to get di_1/dt, then an adjustable voltage gain to scale the signal as $-M(di_1/dt)$, prior to summing it to v_s. I was surprised to find no mention of this current differentiator and scaling voltage gain.

The test setup described in the first article is a simple and clever one having the enormous advantage of giving the true loudspeaker cone velocity. So, I suggest using it as a reference to verify objectively that the passive voice coil signal processing system is effectively working properly.

3. Servo-regulator concept

I am not surprised that Mr. Ferguson faced great instability problems when using his preliminary proposed concept. All designers who have tried to develop such a regulator know that it is a highly difficult question. Today, the knowledge on closed loop circuits is more elaborate and many efficient strategies are available with a high probability of success. Consequently, I suggest Mr. Ferguson look at these modern concepts. He will probably take great advantage from this effort and find the suitable solution, giving him the capability to complete his job successfully.

I hope these remarks and comments will be of some help to author Ferguson.

Pierre Touzelet
Velizy France

Dan Ferguson responds:

At the beginning of my second article, I explained in some detail why the current term was left off the prototype subwoofer design—namely, that I could not get the phasing relationships exactly matched to avoid instability at high output levels. The details are given in my reply to Walter Schillinger (previous letter).

In summary, two differentiations are required to accurately model the current-to-voltage and velocity-to-acceleration relationships, and the second differentiation exacerbates things considerably. The second-order term must be modeled exactly to obtain cancellation. Any "leakage" results in instability.

The approach I used in my first article, using a single differentiator, was arrived at empirically and was another compromise. It provided a visible waveform improvement at lower volume levels and was, in fact, stable at those levels. After adding a phase shift circuit later on, I was eventually able to obtain exceptional square-wave tracking, but could not overcome all of the volume limitations.

I like your idea about using the drone woofer as a waveform reference. I had used it primarily as a frequency-response reference in the past, but used a microphone as the waveform reference. Using your approach should provide purer visual representation of the crosstalk component. The one drawback is that gain settings would be unique to the test woofer and not transferable to the 12″ woofer I'm currently using.

Regarding stability, the system is inherently stable except for the 90° phase lead introduced by the differentiator, which consumes half of the available phase margin. In fact, there is quite a bit more gain margin available than I am using. The reason I chose to use lower gains is that the differentiator phase shift causes less accuracy at higher gains, not more.

In my opinion, stability will not be improved significantly by a more sophisticated controller algorithm. The 90° phase lead is inherent in the mathematical derivative function and places the use of a velocity sensor at a distinct disadvantage compared to other approaches such as installing an accelerometer on the driver's moving mass. In spite of the limitations and theoretical compromises in the prototype's design, let's not lose sight of the fact that I was able to attain an overall loop gain of 5.65 and a response that tracks the input within 1dB. This is because the current term represents only approximately 10% of the feedback signal content.

Thanks for your suggestions. Input like yours and others will enable me to continue to work to refine this approach to servo subwoofer design.

CATHODE STRIPPING

In response to Edwin Pettis' article ("Why Power Tubes Arc," Nov. '04), I can state as a first-hand witness that oxide cathodes can indeed be damaged by applying anode B+ with the cathode cold—because I managed to observe the effect when I worked at Svetlana. I put a Svetlana 300B on a test jig and repeatedly hit the anode with 450V with the filament cold. This caused the filament to "snap" due to the electrostatic attraction of the filament to the cathode (no, it was not caused by mechanical vibration; I was careful). Flakes of oxide were seen to fall off the filament. When I tested the tube afterward, its bias point had changed significantly—I needed to change the negative grid bias from −103V to −122V to obtain the same 60mA plate current.

Mind you, this is a directly heated oxide filament. Indirectly heated tubes (of modern design, anyway) are less prone to the effect. I tried the same abuse on a 6550C and saw no noticeable effect. Older indirectly heated tube designs, however, might be susceptible to it.

This is more of a question of being conservative versus taking risks. If I were designing a large audio power amp, regardless of which tubes I used for output, I'd consider it prudent to time-delay the plate voltage. It isn't done in lower-cost amps for simple cost reasons.

Admittedly very few textbooks talk about cathode stripping. This is because in the old days tube rectifiers applied plate voltage slowly, so it was rarely seen.

Today's big radio transmitters, with silicon plate rectifiers, usually apply plate voltage with a time delay, even if it isn't likely to damage the tubes. This is considered good design. A big transmitter can run plate voltages of 12kV or more at several amps, and it's a good idea to warm the tube filaments before hitting them with that much power—especially if there is stray gas in a tube. It doesn't make itself known until you put on the B+, whereupon the tube can arc, discharging and destroying itself and the power supply. Radio stations have been burned down by a transmitting tube that became slightly gassy. Better safe than sorry.

And I frequently see low-cost Chinese tube hi-fi amps that were damaged by a single gassy tube. Sometimes it just happens, even if the customer was very careful and bought well-tested NOS tubes. Gas in a tube is difficult, if not impossible, to detect sometimes. And the average tube hi-fi owner usually does *not* own a tube tester.

Reference Help

You can start with: http://www.vaxxine.com/phil/scopes/arnoud/weyer.txt and http://www.john-a-harper.com/tubes201/.

Power Vacuum Tubes Handbook by Jerry Whittaker (CRC Press, 1999) states on page 118 that oxide emitters are more easily damaged when subjected to bombardment from high-energy particles.

My copy of *Electron Tubes in Industry* by Henney and Fahnestock (3rd edition, McGraw-Hill, 1952) warns against applying anode voltage to a cold cathode (page 177). Unfortunately, this section deals with mercury-vapor thyratrons, not vacuum tubes. Both *Electronic Designer's Handbook* by Landee, Davis, and Albrecht (McGraw-Hill, 1957) and *Electronic Engineering Principles* by John D. Ryder (Prentice-Hall, 1952) state that oxide cathode coatings are susceptible to oxygen poisoning and damage by gas ion bombardment. So they are usually seen only in tubes for use below 1000V.

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Edward T. Dell responds:

Mr. Pettis' views of the relative importance of possible cathode stripping do not agree with others of some repute, as evident from the correspondence from Regular Contributor Eric Barbour. Eric was a regular staff member in Svetlana's California research facility for a number of years and is a Senior Editor at *Vacuum Tube Valley* magazine.

I am on record since 1966, when my article "The Brute" was published in *Stereophile*. It advocates delayed B+ plate voltage as an attempt to prolong output tube life. I used multiple capacitor bypassed diodes to rectify the delayed B+ plate voltage by using a separate heater supply for the amplifier's tubes.

Although I no longer have the reference that advocated this technique, I am quite certain that the early claims of Mullard for the use of the GZ34 tube rectifier were the source for my choice. The GZ34 was said to have a heating time of 11 seconds, which matched that of the EL34 and the KT types from Genalex. This meant that the cathodes were fully heated, or nearly so, before the B+ was applied to the plates, presumably avoiding any stress to the cathode coatings. The heating time of 5U4G rectifiers was supposedly only 5.5 seconds, if my memory is correct, although the tube manuals do not give data on the heating times, except for mercury vapor types.

Amperex, the US sales organization for the Dutch Philips tubes, ran a series of ads for the various types in *Audiocraft* magazine. The GZ34 was featured in several of these in 1958. The ad lists five characteristics of this rectifier, the fifth one being, "protection of costly power output tubes through delayed warm-up."

Amperex was the US subsidiary of Philips, whose libraries exhibit the thorough and painstaking research which went into their tube designs. The GZ34 is obviously a smaller, more rugged rectifier with evident quality features.

I think one of the advantages of amateur construction practice is to build in as many operational features as possible since the design is not a candidate for mass production with limiting competitive cost factors. Stock-car enthusiasts will understand this motivation. In the case of output tube cathodes, even a small longevity advantage seems reasonable.—**E.T.D.** *aX*