BY DON LANCASTER

Solving Linear Equations, Induction Heating, and More

THERE SURE WAS A LOT OF EMAIL OVER OUR SIMPLIFIED TRISAMP DIGITAL-FILTER STORY FROM LAST MONTH. THOSE DIGITAL FILTERS CONTINUE TO AMAZE ME. PROPERLY USED, DIGITAL FILTERS CAN COMPLETELY BLOW AWAY ALL OLDER analog designs. With digital technology, it is trivially easy to make a "gentle" filter with a slope of, say, two-decibels-per-octave for high-end audio enthusiasts. Or a "violent" filter that easily provides stop-band slopes of hundreds of decibels-per-octave, which, to the signal, gives the effect of hitting a brick wall. And the filters will provide both "perfect" tuning and "distortionless" phasing.

At any rate, a lot of you asked for extra details on a "real" digital-filter design. I guess we can attack this in a future column. But first, we will need to explore certain math topics.

Linear Equations

The key to any digital filter design is finding coefficients. Hopefully, you find what you want in a book or an applications note. If not, you start with a pile of equations that describe the amplitudes and frequencies you desire. Then you solve the equations to find your coefficients. The tricky part is that you will typically be solving for lots of frequencies and amplitudes. The math usually involves linear equations. Such as:

$$x - 3y = 9$$
$$x + 2y = -1$$

That is one example of a pair of linear algebraic equations. The idea here is to find the value or values of x and y that makes both equations true. The solution in this relatively simple example is $x = 3$ and $y = -2$. It can be found in a number of different ways. You could subtract the second equation from the first, leaving one equation in y. Or solve the first equation for x and substitute its value into the second.

A pile of numbers is called a *matrix*. A matrix is *two dimensional* if it can be arranged into rows and columns. A matrix is *square* if the number of rows equal the number of columns. Math that takes a pile of numbers and creates a new number or pile of numbers is called a *matrix operator*.

One popular matrix operator is called a *determinant*. A determinant takes a pile of numbers and calculates *one* new number from that pile.

The determinant for a 2X2 matrix is the difference of the cross product of its diagonals...

$$\begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc$$

Higher order determinants are found by *reducing* them. A selected row and column is crossed out, leaving a *subdeterminant*. The value at the crossout is multiplied by the subdeterminant. Note that signs alternate across the row as the products are summed. Here is how a 3X3 is reduced...

$$\begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = a\begin{vmatrix} e & f \\ h & i \end{vmatrix} - b\begin{vmatrix} d & f \\ g & i \end{vmatrix} + c\begin{vmatrix} d & e \\ g & h \end{vmatrix}$$

The process continues for higher orders. Such as this 4X4...

$$\begin{vmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{vmatrix} = a\begin{vmatrix} f & g & h \\ j & k & l \\ n & o & p \end{vmatrix} - b\begin{vmatrix} e & g & h \\ i & k & l \\ m & o & p \end{vmatrix} + c\begin{vmatrix} e & f & h \\ i & j & l \\ m & n & p \end{vmatrix} - d\begin{vmatrix} e & f & g \\ i & j & k \\ m & n & o \end{vmatrix}$$

FIG. 1—DETERMINANTS ARE A POWERFUL method for solving complex linear equations such as those needed for digital-filter designs.

The system is linear because the only power of x or y involved is the first. When the number of equations equals the number of unknowns, you can usually find all the unknowns.

Often, you'd expect one solution for x and y, but in special cases, there can be zero or many solutions.

You could evaluate these oddball cases by graphing your equation as a pair of straight lines. If the lines cross only one time, you have one solution. If the lines are parallel, you have no solution. And if the lines extend into one longer

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Consider this set of four linear equations in four unknowns...

$$3w - 2x + 1y + 4z = -9$$
$$4w + 4x - 6y + 9z = 1$$
$$2w - 2x + 1y + 4z = 6$$
$$5w + 4x - 3y - 7z = -3$$

Make a 4x4 *system determinant* out of the numbers in front of the variables. Then make four *variable determinants* by selectively *substituting* the right side result in each *w, x, y,* or *z* column. Then divide variable by system...

$$w = \frac{\begin{vmatrix} -9 & -2 & 1 & 4 \\ 1 & 4 & -6 & 9 \\ 6 & -2 & 1 & 4 \\ -3 & 4 & -3 & -7 \end{vmatrix}}{\begin{vmatrix} 3 & -2 & 1 & 4 \\ 4 & 4 & -6 & 9 \\ 2 & -2 & 1 & 4 \\ 5 & 4 & -3 & -7 \end{vmatrix}} \qquad x = \frac{\begin{vmatrix} 3 & -9 & 1 & 4 \\ 4 & 1 & -6 & 9 \\ 2 & 6 & 1 & 4 \\ 5 & -3 & -3 & -7 \end{vmatrix}}{\begin{vmatrix} 3 & -2 & 1 & 4 \\ 4 & 4 & -6 & 9 \\ 2 & -2 & 1 & 4 \\ 5 & 4 & -3 & -7 \end{vmatrix}}$$

$$y = \frac{\begin{vmatrix} 3 & -2 & -9 & 4 \\ 4 & 4 & 1 & 9 \\ 2 & -2 & 6 & 4 \\ 5 & 4 & -3 & -7 \end{vmatrix}}{\begin{vmatrix} 3 & -2 & 1 & 4 \\ 4 & 4 & -6 & 9 \\ 2 & -2 & 1 & 4 \\ 5 & 4 & -3 & -7 \end{vmatrix}} \qquad z = \frac{\begin{vmatrix} 3 & -2 & 1 & -9 \\ 4 & 4 & -6 & 1 \\ 2 & -2 & 1 & 6 \\ 5 & 4 & -3 & -3 \end{vmatrix}}{\begin{vmatrix} 3 & -2 & 1 & 4 \\ 4 & 4 & -6 & 9 \\ 2 & -2 & 1 & 4 \\ 5 & 4 & -3 & -7 \end{vmatrix}}$$

FIG. 2—THIS EXAMPLE SHOWS how determinants are used to solve a system of four linear equations with four unknowns.

line, you will have an infinite number of solutions.

In a digital filter, you might want to solve ten linear equations for ten amplitudes at ten frequencies. While you can still solve your first equation for one variable, plug that into the second, plug that solution into the third, and so on, that "Gausian" elimination gets ugly in a hurry. Instead, we can turn to a super elegant (though obscure and awful-sounding) process. Let's look at that next.

Determinants

When mathematicians face a messy number problem, often they'll start working with entire piles of numbers instead. A pile of numbers is called a matrix. A matrix arranged into rows and columns is two dimensional. And those having an identical number of rows and columns are square.

A matrix operator takes one pile of numbers and generates a new pile of numbers from it following some rule or set of rules. Matrix operators are often dumb-witted, orderly, and very repetitive.

One extremely important matrix operator is known as a determinant. Determinants excel at ridiculously simplifying the solution of high-order linear equations. Consider the following 2 × 2 square matrix:

$$\begin{vmatrix} a & b \\ c & d \end{vmatrix}$$

Its determinant is found when you multiply the diagonals together and subtract them

$$D = ad - bc$$

A determinant for a larger square matrix is found per all the details in Fig. 1. For example, a 3 × 3 determinant:

$$\begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix}$$

will evaluate as follows:

$$D = a(ei-fh) - b(di-fg) + c(dh-eg)$$

The game can continue for larger

1. Avoid long floating point multiply times. Use a newer microprocessor, a DSP chip, or consider adding a math coprocessor.
2. Brute force your 4X4 code. This can reduce the overhead on your critical innermost timing loop.
3. Force zeros in all but one top row entry by using an obscure rule that says "*A determinant remains unchanged if any row is added to another row multiplied by a constant*". There is no need to evaluate a subdeterminant if it is only going to get multiplied by zero in the next step. Like so...

$$\begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = \begin{vmatrix} a+Kg & b+Kh & c+Ki \\ d & e & f \\ g & h & i \end{vmatrix}$$

   First, let constant K1 = $-b/h$ so that $b+Kh = 0$. Substitute these new values into your determinant. Then let a new constant K2 = $-c/i$. Substitute again. This leaves you with zeros in the "b" and "c" column positions. Thus, only the "a" subdeterminant needs evaluated. Speedup is substantial.

4. Solve the highest order equations for only *one* variable. Then substitute this into a lesser solution. For instance, suppose we want to solve...

$$\begin{aligned} aw + bx + cy + dz &= J \\ ew + fx + gy + hz &= K \\ iw + jx + ky + lz &= L \\ mw + nx + oy + pz &= M \end{aligned}$$

   Solve this 4X4 linear equation *only* for w. Since variable w is now known, we can call it *constant* W. And combine it with constants J through M. Leaving this much faster solving set of 3X3 equations...

$$\begin{aligned} fx + gy + hz &= K - We \\ jx + ky + lz &= L - Wi \\ nx + oy + pz &= M - Wm \end{aligned}$$

FIG. 3—TO KEEP COMPUTATION TIMES from getting out of hand, these speed-up tricks are used in the author's LINAREQ.PS utility.

determinants. Find a value in some row and column. Find the subdeterminant that is left when you strike out the row and the column of that value. Evaluate your subdeterminant and multiply by that value. Be sure to alternate the sign when you continue across (or down) your chosen row or column.

A determinant is just a series of multiplications and additions that accept a square matrix and determine a single numeric from its rows and columns.

Now for the neat part. Figure 2 shows us how determinants can solve linear equations. Such as:

$$\begin{aligned} Ax + By + Cz &= J \\ Dx + Ey + Fz &= K \\ Gx + Hy + Iz &= L \end{aligned}$$

Assume we know constants A through L and want to find unknowns x, y, and z. The system determinant is found using elements A through I. Your x determinant can be found by substituting for J, K, and L in the x column positions. Your y determinant is similarly found by substituting J, K, and L in the y column. And the same is done for z.

Our messy linear equations then simply becomes:

$$\begin{aligned} x &= (\text{xdet})/(\text{sysdet}) \\ y &= (\text{ydet})/(\text{sysdet}) \\ z &= (\text{zdet})/(\text{sysdet}) \end{aligned}$$

All you are doing here is simple multiplications and additions, followed by a single division for each variable. Note that whenever the system determinant is zero, the equations blow up, and you have no solutions at all. In other words, an indeterminate determinate.

Additional details on determinants can be found in almost any advanced algebra textbook.

Faster! Faster!

With PostScript, you can easily do an 8 × 8 determinant in 70 milliseconds or less. Directly solving an 8 × 8 linear equation will take nine times as long. One determinant is used as the system denominator; eight for the variables.

Call the 8 × 8 determinant time t. If you blindly go to a 9 × 9 solution, you will need 9t for the determinant. And 10 × 9 = 90t for the full solution. Thus, solving the raw 9 × 9 would take 10 times as long. A 10 × 10 would take 10 × 11 = 110 times as long, and so on. As you can see, things quickly can get way out of hand.

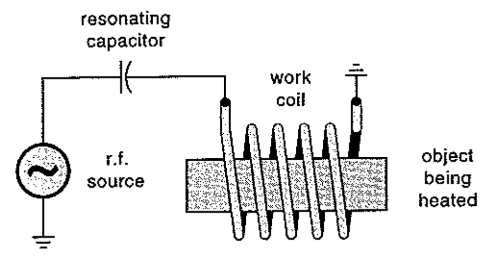
So, we'll think smarter instead of harder. Figure 3 shows us some handy speedup tricks. Those get real important when dealing with anything above 8 × 8.

First and foremost, use a computer system that does not take forever to do some floating-point multiplications. Any newer microprocessor, any DSP, or a math coprocessor should help bunches. Second, brute-force linear code your 4 × 4. Instead of using four 3 × 3s that call 12 2 × 2s. That reduces the overhead on your innermost (and most often called) service loop.

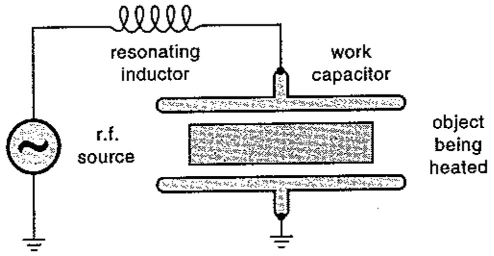
Third is the real biggie. There's a sneaky and off-the-wall rule that tells us: A determinant stays unchanged if you replace the value in a row with itself added to a constant multiplied by the value. Use that rule to force zeros as there is no need to solve any subdeterminant if you are just going to multiply it by zero in the next step. Therefore, if you force zeros first, an 8 × 8 determinant only has to calculate one 7 × 7, not eight of them.

Similarly, we know a full 9 × 9 is going to take much longer than an 8 × 8. So why not use the 9 × 9 to solve for only one variable? Then substitute that one variable value back into the eight remaining equations and solve a faster 8 × 8. That last trick lets you find a 9 × 9 in 1.2 times that of an 8 × 8. You can do a PostScript 10 × 10 determinant in 2.1 seconds.

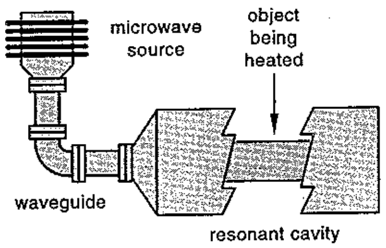
The speedup details can be a tad system specific. You have to take into account system overhead versus multiplication times and so on. And a few new divisions may be needed. Thus, linear coding a 5 × 5 or zero forcing a 6 × 6 may or may not help you much, and could actually slow you down. But those speedup tricks certainly help a lot for larger matrices. I've posted my PostScript code for all this as file LINEAREQ.PS to my www.tinaja.com.



(A) With an induction heater, energy is inductively coupled to a fairly conductive load. Energy is linked by the magnetic "H" field.



(B) With a dielectric heater, energy is electrically coupled to a fairly non-conductive load. Energy is linked by the electric "E" field.



(C) In a microwave oven, energy is coupled by both the "E" and the "H" fields. Depending upon load conductivity and position.

FIG. 4—HERE ARE THREE approaches that could be used for induction heating using radio frequencies.

Induction Heating

Considering that this topic is something of an arcane backwater, I've sure gotten a lot of calls about it. In brief, most induction heaters are really nothing more than a transformer with a shorted turn. A long time ago, someone noticed that transformer and coil cores sometimes got painfully warm. They then decided to try and do that on purpose, and the rest is history.

An induction heater places a fairly conductive object inside a resonant coil. Radio-frequency energy routed through the coil gets transferred by induction to the conductive object, heating it.

A non-magnetic conductor heats by way of the eddy effect. Magnetic conductors heat through an additional hysteresis loss. Either way, energy is mostly transferred by the magnetic, or the "H" field.

Induction heating is most popular with iron or steel objects. But nearly any lossy but otherwise fairly strong conductor can work.

Somewhat related are dielectric heaters. A dielectric heater places an object that is only somewhat lossy between the plates of a resonating capacitor. Radio-frequency energy is transferred by dielectric coupling to the object. Energy is transferred by the electric or "E" field.

Dielectric heating works best with glues, or similar lossy but otherwise fairly good insulators. Those conductive capacitor plates can also optionally apply pressure.

A microwave oven can be both an induction heater and dielectric heater. The target is put inside a waveguide or cavity. Energy can be transferred using either or both fields. Unfortunately, due to mismatch and reflected power, the magnetron in the oven blows up when you try actually using the induction part of the field by putting any metal inside.

I've shown three radio-frequency heating approaches in Fig. 4. The advantages of induction or dielectric heating are that you'll heat only the object, not the environment. You exactly control the temperature and its rate of heating or cooling, as well as the heating-depth profile and the total energy transferred. The (usually) contactless process also avoids contamination, and can even be done inside a vacuum.

A few important uses for induction heaters include heat treating of metals, brazing or soldering, and for shrink-fit assembling. Thanks to the frequency-sensitive skin effect, you can carefully control the depth of heat penetration. Therefore, induction is ideally suited for surface hardening of running parts such as crankshafts or CV universal joints.

Some of the new "cool-top" stove designs also use induction heating. In addition to warming your lunch, dielectric heating is used to make plywood, for materials research, and in various medical treatments.

Since they emit RF, the FCC regulates all induction and dielectric heaters. The applicable regulations can be found in Part 15, which covers virtually every type of emission and device, and in the short and obscure Part 18, which covers industrial electronics. One source for those regs are the US Government Bookstores in many cities. I was unable to find any of the less common FCC regs on line.

A popular operating frequency for those devices used to be 27.12 MHz, with a tolerance of 326 kHz. However, at that frequency the harmonics of an improperly shielded induction heater might totally trash TV-Channel 2, and much of the FM band.

Newer induction heaters often oper-

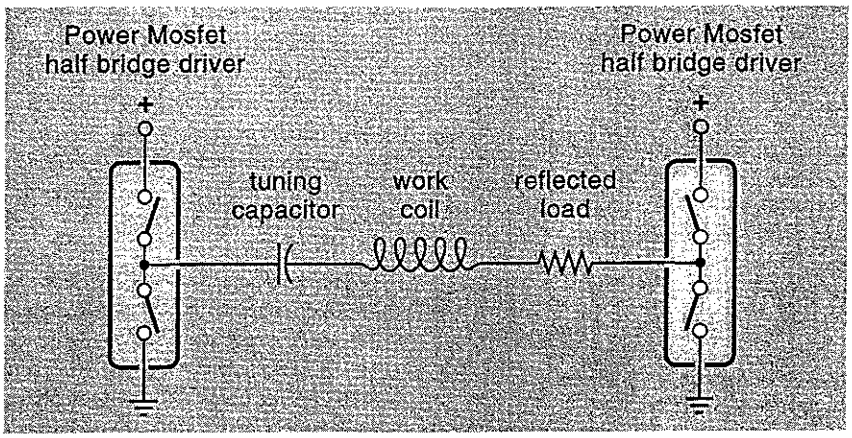


FIG. 5—HERE IS A SIMPLIFIED SCHEMATIC for an induction heater. In it, diagonally opposite switches are alternately closed, creating a squarewave drive at the heater's resonant frequency.

ate in the 50—200 kHz range. The frequency chosen is carefully optimized for the size of the load and the depth of penetration desired, but even raw 60-Hz AC power can be used to heat massive objects such as aluminum billets.

Earlier induction heaters required humongous vacuum-tube transmitters or motor-generator sets. These days, an induction heater is a variation on a switching-mode power supply, where power FETs or whatever squarewave drive a lossy but series-resonant load. Parallel-current modes are also possible. Figure 5 shows a simplified induction heater schematic.

Way back in high school, I worked with an early induction heater. It was just a tube-style 11-meter transmitter with an output of a few hundred watts driving a largish load coil. Inside the coil was a highly temperature-resistant glass tube. If a large nail was placed in the tube, it would light up to a bright cherry red within a few seconds.

You could also cook hot dogs in the thing, but you had to roll the hot dogs in iron filings first. We finally opted for a central coat-hanger wire through the hot dog. Even then, it usually burned the middle and left the outside cold.

While all this might sound like fun, the dangers inherent in home-lab induction-heat experiments are too numerous to mention here. As such, if you decide you want to pursue this topic further, be very careful, and make sure you do your homework first.

Getting Info

Induction-heating system design is tricky. Your frequency, power level, and coils have to be carefully matched to the objects being heated, and to the reasons for the heating in the first place. For one thing, tuning is critical.

It is fairly easy to find useful info on induction heating, but you'll have to dig around in some pretty obscure places.

A good place to start is the Web. I've just added a link for a super searching service to www.tinaja.com that simultaneously lets you access many dozens of the more popular search engines.

I've also gathered some resources for you into this month's sidebar. The best books seem to be the two volumes of the oldie but goodie *Basics of Induction Heating* by Chester Tudbury. The only source for this text I have been able to find is through InductoHeat. The better Volume One concerns itself with coil and load fundamentals and heating calculations. Volume Two is on 1960 transmitter-circuit designs, tuning, and matching.

A 1988 book is titled *Elements of Induction Heating*.It is available from ASM Press. I also found a Franklin reprint about the 1969 *Industrial Applications of Induction Heating* text.

There is also the specialized *High Frequency Plasma Heating* from the American Institute of Physics. I have not seen this one, though.

I was unable to find any specific trade journal or association. However, you could try the IEEE *Transactions on Industrial Applications* or their *Transactions on Industrial Electronics*. For heating apps in general, check into *Industrial Heating* or *Process Heating*. For the new cool stovetops, check into *Appliance* and *Appliance Manufacturer*. For power electronics, try *PCIM*.

Information from seminars on the topic are also available. InductoHeat is one source for that. In particular, check out their two-volume proceedings from the Sixth Annual Induction Heating Seminar. That consists of two thick, self-published volumes that cover heat treating and mass heating, with lots of solid design details. Dozens of free app notes are also newly offered. The ASM also promotes induction heating seminars and courses.

One high-profile induction-heating supplier already mentioned is InductoHeat. Competitors include Tocco, Fuji, Huttinger, and American Induction Heating.

Useful sources for coils and flux concentrators include Alphaform and Lepel. Lepel is part of InductoHeat. Raychem is big on induction-heated shrink tubing.

One used induction-heater buy/sell service is Tocco, but more brands are found in the *Used Equipment Digest* or *Surplus World*.

On your own, you could probably pick up a re-workable ham or military

Names and Numbers

Batelle Pacific Northwest
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(509) 372-4274

Leonard's Distributors
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Carmichael CA 95608
(916) 967-6401

Maher Messinger
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Planax North America
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New York NY 10010
(212) 532-1988

Power Engineering
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Tulsa OK 74112
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Thatcher AZ 85552
(520) 428-4073

Thomson Industries
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Port Washington NY 11050
(800) 554-8466

Wood Machining News
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Berkeley CA 94701
(510) 943-5240

Induction Heating Resources

Alphaform
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(614) 253-8900

Am Induction Heating
33842 James Pompo Dr.
Frazer MI 48026
(810) 294-1700

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Oak Brook IL 60522
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Solon OH 44139
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Elkins Park PA 19117
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(201) 712-0555

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Piscataway NJ 08855
(908) 981-0060

InductoHeat
32251 N Avis Drive
Madison Heights MI 48071
(800) 624-6297

Inductotherm
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Rancocas NJ 08073
(609) 267-9000

Industrial Heating
Box 2600
Troy MI 48007
(313) 362-3700

PCIM
2472 Eastman Ave. #33-34
Ventura CA 93003
(805) 658-0933

Process Heating
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Suite 101
Des Plaines IL 60018
(708) 297-3450

Raychem
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Menlo Park CA 94025
(800) 227-7040

Surplus Record
20 N Wacker Drive #2500
Chicago IL 60606
(800) 622-5449

Tocco
1506 Industrial Blvd.
Boaz AL 35957
(205) 593-7770

US Government Bookstore
720 N Main St.
Pueblo CO 81003
(719) 544-3142

Used Equipment Digest
1100 Superior Ave.
Cleveland OH 44144
(216) 696-7000

surplus transmitter at Fair Radio Sales. Better still, modify a high level switching-mode power supply or PWM motor driver.

Book-on-Demand Binding

The Unibind people just came up with an interesting new home-binding solution. It's called the Binding Spine, and is basically a "U"-shaped plastic channel with some hot glue in it and a temporary positioning tag.

You pop your text and your front and back covers in it and drop it in a Unibind "toaster." The results look fairly sharp and the cost is under a dollar each.

There are three gotchas with this: You have to adjust your content to fit one of the fixed sizes (they are available in 1/8-inch increments). Second, you can not easily letter your spine. And, third, it looks much different than a "real" binding from a "real" printer.

Nonetheless, a new home-binding option is certainly welcome. I still like Unibind's Pentabind best of all. But all we really need is a sanely priced, prescored sheet of self-stick hot glue on a carrier. Planax comes close, except for its high price.

There is no reason such a product cannot be offered at seven cents per binding (user retail). And as the new Hewlett Packard 5SiMX makes full wraparound covers trivial, there are some great new opportunities out there. Contact Ron Leonard at Unibind for more details.

New Tech Lit

Electric-power generators reaching a stunning 60 percent efficiency are described in the July, 1966 issue of **Power Engineering**. The big trick, it seems, is to start off with a gas turbine, put a steam generator in the middle, and bottom out with an ammonia cycle.

Wood Machining News is a pricey newsletter on precision sawing for cabinet makers and such. *Maher Messenger* is a ventriloquism catalog and newsletter.

Free samples of Nyliner polymer bearings are offered by Thomson. Inventor-assistance source lists are available from R.L. Conger of Battelle Pacific Northwest. One is intended for non-commercial help, and a second for commercial services. But these days, only a total idiot would purposely call themselves an inventor. To do so is precisely the same as wearing a big animated neon talking sign that says "Please rip me off". Much more on this in my *Case Against Patents* package.

More on BOD binding options and opportunities in my book-on-demand publishing kit, which can be obtained per my nearby Synergetics ad. And don't forget to visit my new Web site, www.tinaja.com

As usual, most of the mentioned items appear either in the Names and Numbers or the Induction Heating Resources sidebars. Be sure to check there before calling our no charge technical helpline listed in the Need Help? box. EN

NEED HELP?

Phone or write all your US Tech Musings questions to:

Don Lancaster
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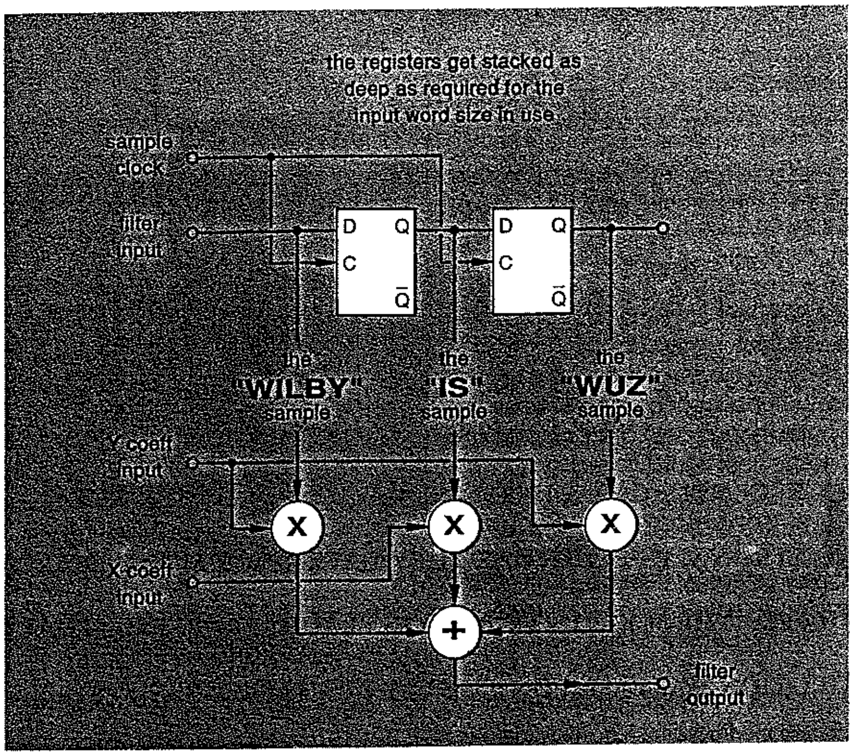

FIG. 2—DIGITAL FILTERS can be much more powerful than analog ones because they can look both forward and backward in time. The need for a "time machine" is avoided by using the shift-register scheme shown here.

robotics to gobble up all sorts of time and resources. And my magic sinewave development is currently using as much as twenty hours a day of my time. But, as hard as it is to do, you must focus on stuff that is technically challenging and still marketable by a small scale start-up if you are to be successful. Asking the fundamental questions outlined above ahead of time can save you lots of hours and grief and lets you focus your time and energy in better directions.

For much more on all this, see my *Case Against Patents* package, WHEN2PAT.PDF on www.tinaja.com, and, of course, my *Incredible Secret Money Machine*.

Digital Filters

Most books on digital filters seem excessively and unnecessarily arcane to me. This month, let's instead try a totally different and off-the-wall approach.

A filter is just some frequency-selective network that is designed to favor certain frequencies over others. It is usually used to isolate a desired signal or to improve the signal-to-noise ratio of a system. For example, the treble control on your hi-fi is a low-pass filter, the bass control is a high-pass filter, and AM radio tuning uses a bandpass filter.

Traditional filters were originally built with capacitors and inductors. Many of those were replaced long ago by active filters—combinations of resistors, capacitors, and op-amps that exactly fake inductors. You can find more details on that in my *Active Filter Cookbook*.

In contrast, a digital filter takes an existing pile of numbers and runs multiply-and-add calculations upon them to create a new pile of numbers whose behavior will, we hope, be "better" in some way or another than the original. For instance, a stream of digital video can become digitally high-pass filtered to improve its sharpness, or low-pass filtered for softening or to eliminate slanted "jaggies".

Plus and Minus

There are bunches of advantages to digital filters. First and foremost, a well designed digital filter is always "correct" and never needs "tuning". A digital filter could easily be adjusted over an incredibly wide range using software. Digital filters can often be swept without any nasty transients.

Special circuitry could be totally eliminated if the digital filtering gets done inside a stock microprocessor or a DSP digital signal processor.

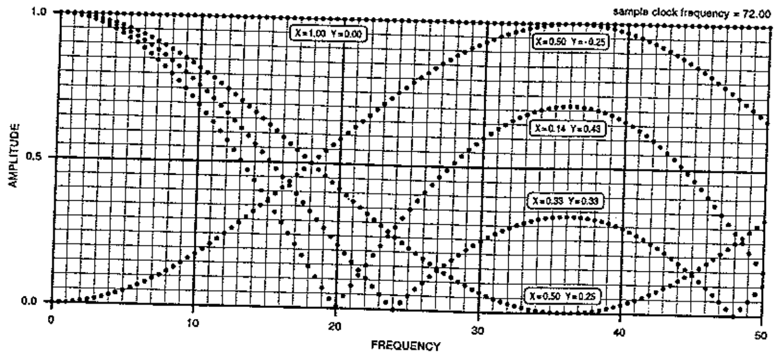

FIG. 3—HOW A TRISAMP'S FREQUENCY RESPONSE varies when its X and Y coefficients are changed.

Best of all, a digital filter can do certain tasks that end up being difficult or impossible when using classic analog designs. For one thing, in a sense, they can look forward and backward in time. That is, unlike capacitors and inductors, they can react to currents and voltages that are yet to happen; classic analog components can only react to things that have already occurred.

Examples here include "brick-wall" filters with extremely sharp cutoffs and linear-phase filters that attenuate a waveform's harmonics without any time-shifting distortion.

There are also disadvantages and limitations to digital filters. While they are a lot simpler than some may have you believe, they still are rather hard to understand.

You do already have to have your pile of numbers before you can filter them. Thus, A/D and D/A conversion might be needed in your system.

There is a really ugly property of digital filters called aliasing. If you sample any waveform less than twice per cycle, you might "fold over" and generate lower-frequency noise and artifacts. Very rarely, aliasing can be a valuable tool, one that lets you do digital mixing, downsampling, or a downconversion. But far more often, aliasing is a major nuisance that must be dealt with by prefiltering.

Here's a rule to follow when working with digital filters: Input signals to a digital filter must get prefiltered so that zero energy exists above one-half of your sample frequency. That is, unless you have some really good reason to be doing otherwise!

The dynamic range of any digital filter is limited by several factors. Those include your input and output word sizes, truncation errors, and any round-off errors.

Because you are often adding up very small differences between large values, the internal word size usually has to be much larger than that of the input or output. Thus, digital filters are much more suited to larger input signals than to very small ones.

Simpler digital filters apply integer math or fixed-point arithmetic. Such filters are faster and easier to implement, but have reduced dynamic range.

Exotic digital filters can use a full floating-point processing for all their math. While more accurate, floating-point filters often run much slower, either restricting the maximum input frequency or forcing you to move to non-real-time applications.

Finally, if your filter only works with a small number of samples, you might get into some ugly windowing problems. Softening the edges of a window or making sure that the edges happen where they don't cause problems are two possible cures. Watch out for that windowing detail, or it will nail you every time.

Trisamp Building Blocks

My approach in the *Active Filter Cookbook* was to use a basic analog building block called a second-order section. No matter how exotic your filter response, all you really ended up with was a pile of those cascaded sections. And each section only had two possible adjustments—the cutoff frequency and its damping.

Let's try something similar here. I'll call our basic building block a "trisamp," and it is shown in Fig. 1. Just as you can use and cascade second order analog sections, you can use and cascade trisamps.

A trisamp gathers in three samples of a waveform. Which I will call "wuz," "is," and "wilby." It then scales them and adds them all together by using this fairly simple rule:

output = Y(was) + X(is) + Y(wilby)

Since a digital filter is a linear type of "thingy," it should not matter what frequency or what phase we use for our analysis. Thus, we can apply just one frequency at a time to determine our overall response and arbitrarily pick an "is" phase of 90 degrees.

For a single-frequency sinewave input, your output should be a scaled amplitude clone of your input. The output will be larger or smaller than the input, depending on the values and signs of X and Y, and upon the ratio of your input frequency to the sample-rate clock.

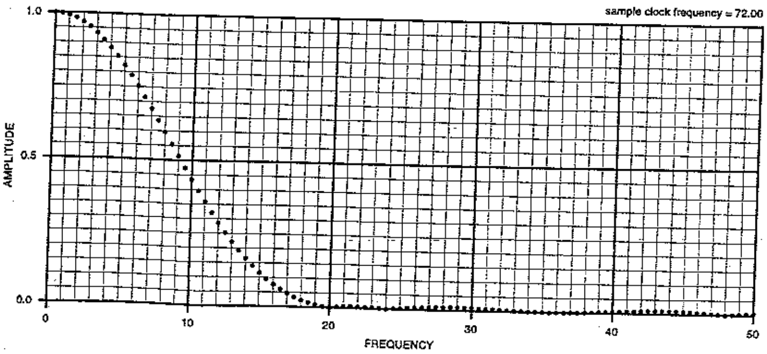

FIG. 4—A LOW-PASS FILTER built by cascading three trisamps. This is a "distortionless" or linear-phase filter that is extremely difficult to build using older analog techniques. To simplify your final design, using ordinary algebra easily reduces three cascaded trisamps into a single, seven-sample "septsamp." Additional samples improve response shape.

```
% PostScript triple cascaded trisamp digital filter designer v 2.04

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% draw a graph:
110 350 translate 8 dup scale 0.03 setlinewidth 1 setlinecap gsave 0 0 moveto 51
{0 0 moveto 0 20 rlineto 1 0 translate} repeat stroke grestore gsave 0 0 moveto 21
{0 0 moveto 50 0 rlineto 0 1 translate} repeat stroke grestore 0.12 setlinewidth
gsave 3 { -0.5 0 moveto 50.5 0 rlineto 0 10 translate} repeat stroke grestore gsave
6 { 0 -0.5 moveto 0 20.5 rlineto 10 0 translate} repeat stroke grestore

/dot { newpath 0.150 0 360 arc fill } def % dot utility

/tripletrisamp {0 0.5 50 {/freq exch store 180 freq mul sampfreq 2 div div cos
coeffB mul 2 mul coeffA add /firsthold exch store firsthold abs 20 mul freq exch
dot 180 freq mul sampfreq 2 div div cos coeffD mul 2 mul coeffC add /secondhold
exch store secondhold abs 20 mul freq exch dot 180 freq mul sampfreq 2 div div
cos coeffF mul 2 mul coeffE add coeffC coeffD 2 mul add div /thirdhold exch store
thirdhold abs 20 mul freq exch dot firsthold secondhold mul thirdhold mul abs 20
mul freq exch dot} for} def

% ///// demo - remove or alter before reuse /////

/sampfreq 72 def                    % set sample clock frequency

/coeffA 2.0 4 div def               % center of first trisamp
/coeffB 1.0 4 div def               % pair
/coeffC 1.0 3 div def               % center of second trisamp
/coeffD 1.0 3 div def               % pair
/coeffE 1.0 7 div def               % center of third trisamp
/coeffF 3.0 7 div def               % pair

tripletrisamp showpage quit         % do it and flaunt it
```

FIG. 5—THIS POSTSCRIPT TRIPLE TRISAMP exploration utility could make you an instant digital-filter-design expert. The code shown here can be easily expanded.

The X and Y values are known as coefficients. And while you could select different coefficients for "was" and "wilby," that change would add or remove time delay to your response.

Forcing the coefficients for "was" and "wilby" to always be identical can give you the class of "distortionless" filters known as linear-phase filters. Those are especially significant for data communications applications, and can be extremely difficult to do when using the older and more traditional analog design methods.

Which leaves dealing with . . . .

Negative Time?

So how *do* you find out who "wilby" is without a time-travel machine?

Simply look one stage previous in the shift register scheme of Fig. 2, or access one sample address earlier in a memory data bank. This is sort of the same way any vertically delayed scope lets you look at the waveform edge you have just triggered on.

Let's look at the responses we can expect from a trisamp as we vary its coefficients and the input frequency. Naturally, I prefer to use the superb PostScript general purpose computer language for this. I will use 72 clock samples per fundamental cycle.

Figure 3 shows you several trisamp responses. Positive Y values result in low-pass shapes and negative Y values result in band-pass shapes. Also, in general, the overall peak gain is set by the absolute value of the sum of X and Y. Gains near unity are often used to keep the results from getting too large or disappearing entirely.

For instance, a Y value of zero and an X value of one simply copies the peak value to the output for a flat or an all pass response. Next, consider Y = 0.25 and X = 0.50. At low frequencies, "wuz," "is," and "wilby" are nearly on top of each other, so they pretty much sum to 1.0 and give us nearly unity gain.

But at the frequency whose time period equals exactly 36 clock cycles, an interesting result happens. "Wuz" and "wilby" end up on negative cycle peaks, and "is" sits on a positive cycle peak. In other words, they sum to zero!

Other X and Y coefficients create the shapes shown. By themselves, those shapes may be interesting. But they aren't all that useful. So, to get useful response shapes, you must cascade your trisamps.

Figure 4 shows a highly desirable linear-phase, low-pass filter made by cascading the three trisamps shown. Note the excellent stopband response. And the modest droop in the passband is fairly typical of linear-phase filters. Most important, there is zero excess phase shift to higher frequency harmonics. That property is very important in telecomm filters and for wave analysis.

Yes, you can easily re-graph this result in semi-log frequency-vs.-decibels for a more traditional-appearing, classic response plot. Among other features, that re-plot would make the stopband zeros more obvious.

Actually, nobody really cascades trisamps. Go through some simple algebra and you can quickly prove that any two cascaded trisamps are the same as a five-coefficient filter. And three cascaded trisamps are the same as a seven-coefficient filter. So you apply a pentsamp or a septsamp instead. All digital filtering amounts to is finding the right coefficients to use for the result you are after.

PostScript code to do a seven-coefficient filter made from three cascaded trisamps is shown in Fig. 5. You could easily use that routine to explore fancier digital-filter response shapes on your own. Just modify the coefficients with your favorite word processor or editor. Then send it to GhostScript or route it to almost any PostScript printer.

Lots more PostScript-as-language details are found on www.tinaja.com For an amazing range of applications, PostScript can completely blow away the more traditional general purpose computer languages.

Incidentally, more coefficients are normally chosen for fancier shapes.

Names and Numbers

American Institute of Organbuilders
PO Box 130982
Houston, TX 77219
(713) 529-2212

Clement Engineering
PO Box 1086
Severna Park, MD 21146
(410) 268-6736

Compu-Mart
899 Presidential, Ste. 110
Richardson, TX 75081
(800) 864-1155

Dukane Ultrasonics
2900 Dukane Drive
St Charles, IL 60174
(708) 584-2300

Genesis Microchip
2111 Landings Drive
Mountain View, CA 94043
(415) 428-4277

Harris Semiconductor
Box 883
Melbourne, FL 32902
(407) 724-7000

ICT
2123 Ringwood Avenue
San Jose, CA 95131
(408) 434-0678

Mitel
2321 Morena Blvd., #M
San Diego, CA 92110
(619) 276-3421

Qualcomm Inc
6455 Lusk Blvd.
San Diego, CA 92121
(619) 587-1121

Redmond Cable
15331 NE 90th Street
Redmond, WA 98052
(206) 882-2009

Schott
3 Odell Plaza
Yonkers, NY 10701
(914) 968-8900

Seagate
920 Disc Drive
Scotts Valley, CA 95066
(408) 438-6550

Synergetics
Box 809
Thatcher, AZ 85552
(520) 428-4073

Thomson CFS
40G Commerce Way
Totowa, NJ 07511
(201) 812-9000

Wale Apparatus
400 Front Street
Hellertown, PA 18055
(800) 334-WALE

Western Reserve Games
21651 Tungsten Road
Euclid, OH 44117
(800) 531-1230

Typical hardware building-block chips offer four coefficients each. Those can get cascaded "wide" to handle twelve to sixteen or more coefficients. Or, they can be cascaded "deep" to handle the number of bits in a fixed-point word. Harris and Qualcomm are two big sources for these dedicated chips, but you can easily do the same thing with a PIC microprocessor.

I've been using digital filters as an important part of my magic-sinewave research. Magic sinewaves are my brand new way for simplifying and dramatically improving the efficiency of such products as variable-speed induction-motor drives, solar panels, and electric cars. You can find a lot more about them and all the new research opportunities they present on my Magic Sinewave shelf, which is in the www.tinaja.com reference library.

5SiMX Hard Drives

As we saw a couple of months or so ago, the Hewlett-Packard *5SiMX* is an ideal mid-range PostScript laser printer, one well suited to book-on-demand publishing. Its many features include genuine Adobe PostScript Level II , 24 pages-per-minute print speed, a page-flipping duplexer, 11 × 17 capability, refillable toner cartridges (offering excellent economics), 600 DPI resolution, and photo halftone enhancements; and all the service manuals and parts are readily available.

It also has, at least in theory, a hard disk.

Scant few printer users appreciate how absolutely crucial a local hard disk is for a PostScript printer (though Apple and QMS have had them for years). First, your hard disk lets you store lots of fonts. Second, it lets you stash all of your book-on-demand files so you'll never have to tie up a network resending them. That same storage lets you do a run unattended for overnight BOD publishing.

The same goes in spades for often-used forms or patterns. When a diskless PostScript printer is first turned on, all of those needed font bitmaps have to be laboriously built up into a font cache. Your first few printouts (and anything "new" after that) will always be very slow.

A local hard disk instead saves a font cache for you. There is normally not any speed-difference slowdown on your first few files.

Hard disks are also real useful for PostScript-as-language apps where they can serve as your primary I/O. They are also quite handy to log what is coming into your printer, to solve interface hassles, to convert formats, or to grab otherwise inaccessible data or commands. Once you have used a PostScript printer that offers a hard disk, it is unthinkable to ever again so much as walk through a room housing a printer that lacks one.

The only tiny 5SiMX problem is that the HP disk drive has been undeliverable—and it appears permanently so now as HP has gone completely out of the hard-drive business. Well, it turns out you can easily substitute your own hard drive—for as little as $35—after you know and understand a few simple things.

Let's excerpt some key info from the HPs *LaserJet 5SiMX Developer's Quick Reference Guide:*

"The standard 2½-inch ATA IDE disk drive interface is supported. (ATA stands for 'AT Attachment,' as in the IBM PC-AT bus. And IDE stands for Intelligent Drive Electronics.) This printer is designed to allow these drives to be mounted directly to the formatter board.

"The disk drive attaches to four standoffs. It is electrically connected via a ribbon cable.

"The Seagate ST9420AG is the disk that has been qualified to work in the LaserJet 5SiMx printer."

The developer's guide is available through HP Developers. My favorite source for custom cables is Redmond Cable. The oddball 2-millimeter bulk ribbon cable and connectors are sold by Digi-Key or Mouser (this is sometimes called a mini-IDE or "European" cable).

Bargain drives often show up in *Compu-Mart*, *Computer Hot Line*, and similar publications. Note that non-Seagate drives may be larger and have different mounting holes. Older and larger 3½-inch drives are most likely not worth the hassle. Besides needing excess supply current, their larger pinouts take a special adaptor.

```
% PostScript triple cascaded trisamp digital filter designer v.2.04

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