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ANALOG WITHOUT FEAR

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ORDNANCE SYSTEMS DEVELOPMENT DEPARTMENT

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Analog circuitry, also referred to as "Linear", has been nearly run over by the digital/computer bandwagon. This is unfortunate because tremendous advances are being made in the field of analog integrated circuitry. Each year's progress raises the state-of-the-art, bringing achievements not possible even the year before. Many of the traditional prejudices against analog circuitry are no longer valid.

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This report attempts to summarize what is available now and what can (and can't) be done with analog integrated circuitry.

SUMMARY

This report is a general paper concerning analog (linear) integrated circuitry. It is an outgrowth of a seminar presented in the Signal and Digital Processing Branch of the Naval Surface Weapons Center. It will be of interest to anyone concerned with the field of analog integrated circuits. The work was done under several projects, primarily the BEARTRAP program, Task No. A5335 330/004D/6WAS47.

J A Faulkner
J. A. FAULKNER
By direction

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ANALOG WITHOUT FEAR

WHAT IS ANALOG?

Analog is best defined as all circuitry not clearly digital (2-level logic). "Analog" has become sort of a dirty word, so now analog is often referred to as "Linear". However, analog includes much more that is not linear, for example, hybrid digital-analog system, digital-analog converters, sampled linear signals, regulators, and oscillators. Therefore, this paper will stick to the term "Analog". The word "analog" is a shortened form of "analogue". Analog computers were first used to solve other problems in other types of systems (e.g., mechanical) by working with an electrical "analogue" governed by similar equations. Large general-purpose analog computers have been replaced by digital, but smaller subsystems often do perform calculations in the analog domain.

Today's world of electronics is pretty much a digital world. Analog is usually ignored until it becomes a problem, sort of like plumbing. However, the real world is usually analog. Sensors or transducers that convert real-world parameters to electrical signals usually have analog outputs. A digital system which must interface with the real world often requires to Analog-to-Digital-Converter (ADC) to get in from the real world and/or a Digital-to-Analog Converter (DAC) to get back out to it. Because of the practical limits on the performance of the converters, analog pre-conditioning and/or post-conditioning of the signals is often necessary.

This leaves us with several paradoxes. Although most of the articles in the trade magazines are on digital system, the majority of existing systems are still analog. (I realize this statement depends on what system one chooses to count.) Also, in new system design the bulk of engineering time is spent on the digital aspects, in spite of the likelihood (and perhaps contributing to the likelihood) that the analog portion of the system may cause the most trouble in actual operation.

Like digital circuitry, or almost anything for that matter, analog really isn't bad once you understand it. There isn't too much black magic left in analog design; new devices are much nearer to ideal functional blocks than the older ones, and what is left that is not ideal is mostly well understood and well defined.

The purpose of this report is to summarize what can (and can't) be done with analog circuitry today, the most common types of analog integrated circuits, the most common uses, and the most common problems. The report will be primarily restricted to monolithic types, as these tend to be the most cost-effective.

SHOULD YOU USE ANALOG OR DIGITAL?

Whichever (analog or digital) is more cost-effective should be used. This usually implies figuring out how to do a particular job in both domains and then making some sort of cost/performance decision. There is no general rule which can give the answer without going through this procedure, but there are many particular situations where the answer is immediately obvious. Sometimes there is no choice. Here are some guidelines.

Consider first the nature of the input(s) and output(s). If both are digital, a digital system would normally be logical (no pun). If the input is digital and the output analog, computations would probably be digital with conversion near the end. If the input is analog and the output digital, considerable analog preconditioning may be necessary before digital can be used; for example the case where the input is a low-level signal from a transducer. If input and output are both analog, the size (complexity) of the system must be considered. For a large system it is often desirable to convert to digital, compute, and convert back to analog. For small systems the expense of two converters, additional power supply, clock, etc., usually makes it easier to have the entire system analog.

Another consideration is accuracy: for accuracy better than about 0.1%, equivalent to 10 binary bits, it is usually necessary to use digital. In a digital system errors are more precisely known and can be accounted for; with analog, error is subject to drift and mismatch between channels.

There are some tasks analog is well suited to. For example, a modest low-pass digital filter for analog data not only requires analog-to-digital and digital-to-analog conversion, but usually also a modest low-pass analog filter at the input to prevent aliasing due to sampling; so the analog filter might as well be designed to do the whole job at once. In some applications available bandwidth is not adequate for digital. An example is television, where complete digitazation would require far more bandwidth per channel than is available. Other areas where analog is good will be readily appreciated (as they say in the patent office) in the examples of analog integrated circuits.

RELIABILITY

Most engineers consider analog integrated circuits less reliable than digital. This was certainly true in the early days of integrated circuits. Digital circuits would usually survive any input voltage between supply voltages or an output short to ground, whereas analog circuits usually would not. Also, digital circuits were lower impedance, requiring larger current drive to cause failure.

The situation has now changed significantly; in fact, to a certain extent it has reversed. Most new analog ICs will tolerate any input voltage between supply voltages, and some will even tolerate input voltages beyond that. Outputs are usually protected against indefinite shorting to ground or supply voltage. On the other hand, digital circuitry has changed little. Outputs will often not survive an indefinite short to positive supply, and sometimes not even to ground. Some are very sensitive to input voltages slightly above supply voltage.

It is not completely clear just what consitutes failure. Because of the nature of digital circuitry, a specific IC may have considerable degradation and still cause no change in system operation. This is true only to a lesser extent with analog circuitry. Often system performance will degrade gradually as a given IC degrades. On the other hand, if a digital IC degrades beyond the allowable threshold, the system may fail catastrophically. Also, a digital system usually has a larger number of ICs, so individual reliability must be higher to achieve the same system reliability.

This author has experienced a higher failure rate for digital ICs than analog. This of course constitutes a very limited sample and does not necessarily indicate any general trend. But it does prove that it is a mistake to reject analog on the basis of reliability without careful analysis.

OPERATIONAL AMPLIFIERS

The mainstay of the analog world is the operational amplifier, abbreviated op-amp or simply OA, named thusly because the device originally was used for performing operations such as summation, integration, inversion etc., in analog-computers. The device is basically the best practical approximation to an ideal amplifier--high impedance, high gain, low output impedance, feedback-stable, etc. Designers have discovered that, because of these properties, op-amps are useful in many applications besides computation.

Many books and articles have been written on op-amps; most dwell at great length on irrelevancies. For example, most treatises speak of DC error as of great importance, but circuits can often be arranged so this error is irrelevant, for example by AC coupling.

Reference (1) is a good manual for readers knowing little electronics. Reference (2) is a good general book, but more detailed than necessary for most applications. Reference (3) is a compromise, aimed at the majority of applications. Any further references are generally unnecessary except for the enthusiast.

Op-amps are so much fun that other types of analog integrated circuits have been largely ignored in the literature. That is partly the impetus for this report. Hence, little time willbe spent on them here; for more detail the reader should consult the above references. Op-amps are useful in many amplifier, buffer, and oscillator circuits (references (3) and (4). They are also often used in impedance transformation circuits and low--power voltage/current controlled voltage/current sources; they are the basis for precision rectifier and peak-detector circuits.[2] Things to watch out for are the following:

a. In a linear application, the op-amp must have negative feedback to set the gain and insure linearity. This means the device usually needs frequency compensation, either internal or external, to be stable (i.e., not oscillate). This is considered in the design of the op-amp, and manufacturer's data sheets provide the necessary information for almost all applications.

b. The op-amp is basically a low-power device, roughly + 15V ± 10 ma, 500 mw, although specialized devices are available with considerably higher ratings. For high-power applications, such as power supplies, op-amps are normally used in conjunction with external transistors.

c. Op-amps are basically medium-frequency devices. General purpose ones can give problems at frequencies as low as 1 kHz; special purpose ones work well to 1 MHz. Applications above 1 MHz usually require devices other than op-amps.

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[1] Smith, John I, "Modern Operational Circuit Design," Wiley, 1971.

[2] Tobey, Graeme, and Huelsman: Operational Amplifiers; Design and Applications, McGraw-Hill, 1971.

[3] Delagrange, A. D., "An Operational Amplifier Primer," NOLTR 72-166, 1972.

[4] Delagrange, A. D., "A Useful Filter Family," NSWC/WOL TR 75-170, 1975.

d. If the response must include DC, imput current and voltages and offsets must be considered. These contribute minimum error of a few millivolts, which on one hand limits the minimum DC that can accurately be handled, but on the other hand is insignificant in many applications. Noise is a problem only if signals are low-level (in the millivolt range). This type of application often requires special devices, but new op-amp designs are much improved and well-specified for noise.

In general op-amps are general-purpose compromises and not suited for highly specialized applications such as the examples given of very high impedance or very low noise, although specifications are continually being improved. Inputs and outputs will usually endure application of any voltage up to the power supplies, making them relatively damage-proof.

A list of all op amps is very long.[5] Here is a quick summary of some popular types. (For details see the manufactuer's data; note that most are second-sourced). The μA 709 (Fiarchild, reference (6)) was the original general purpose; it is good but has problems and is obsolete for most applications. The μA 741 (Fairchild, reference (6)) is the standard general-purpose. It is compensated, well-protected, good to about 10 kHz, and inexpensive. The LM 118[7] is the standard high-speed, good to about 1 MHz. It is compensated, is good, but has some potential problems; however, the data sheet tells how to avoid these. The LM 101[7] was the first "low input current" op-amp; it is superseded by the LM 108, which reduces the input current another order of magnitude. The μA 740[6] was the first monolithic with an FET (Field-Effect-Transistor) input for high input impedance, but never became very popular. The new LF 155-156-157 family[7] is much better, reasonably priced and may become the standard. The CA 3130--3140--3160 family (RCA, reference (8)) is unique in having a MOSFET (Metal-Oxide-Semiconductor FET; equivalent to Insulated-Gate FET) input stage, having near zero input current and near infinite input impedance at the expense of some increase in offset voltage, noise, and drift. Also, they are inexpensive. The μA 776[6] and nearly equivalent LM 4250 National, (reference (7)) "programmable" op-amps have externally controlled bias currents. Performance can be tailored to a certain extent to the application, or the device can be turned completely off to save power or allow multiplexing. There are a number of pin-compatible "quads" (4 op-amps in one package) with performance roughly comparable to a 741: for example the

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[5] Linear Integrated Circuits, D.A.T.A., Inc.

[6] Linear Integrated Circuits Data Book, Fairchild Semiconductor.

[7] Linear Data Book, National Semiconductor Corp.

[8] RCA Integrated Circuits, RCA Corp.

MC 4741 (Motorola (reference (9)) is just what it says--four 741's. The first quads - the 1900 (National) were "Norton" amplifiers, not true op-amps, intended specifically for single-supply use such as automotive and not general purpose use. Note that any op-amp may be used with a single power supply, but the older ones have some problems; newer designs are better for single-supply use.

This list is necessarily very sketchy and leaves out some excellent devices. Most any specification can be improved by going to a specialized device, but often at the expense of some other specifications. Some of the descriptions given here are subjective or relative, and of course may change or be obsoleted by new devices.

WIDEBAND, IF-RF, DIFFERENTIAL AMPLIFIERS

So-called "wideband", "IF-RF" or "differential" amplifiers generally fill the need for amplification at high frequencies where op-amps are not applicable. They are usually fixed-gain, not intended for feedback use. They are often crude (sometimes consisting of little more than a differential transistor pair) having few or none of the nice features of op-amps, such as good power supply rejection, low output impedance, etc. There are exceptions, such as the MC 1545 (Motorola,[9]) which is a complete two-channel, gate selectable wideband amplifier. It has biasing circuitry and output buffering, but has no power-supply rejection of the positive supply for single-ended output and will not tolerate the usualy ± 15 V analog supply voltage. There is nothing approaching a standard among amplifiers of this type, and little interchangeability.

AUDIO AMPLIFIERS; POWER AMPLIFIERS

The chief problem in desigining IC audio/power amplifiers is that conventional IC packages are capable of little power dissipation. Numerous special designs in special packages having virtually no interchangeability have sprung up. The closest thing is a number of power op-amps in modified TO-3 packages, but even here the pinout (and even the number of pins) is not standard. An example is the μA791 (Fairchild, reference (6)) which has the front end characteristics of a 741, but the output is capable of up to 15W, ± 22V, ± 1.25A (not necessarily simultaneously or continuously). It is good to about 10 kHz, and makes a handy low-power audio amplifier. It is monolithic, but most designs are hybrid.

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[9] "Linear Integrated Circuits, Semiconductor Data Library," Motorola Semiconductor Products, Inc.

COMPARATORS

A comparator is really a limited-purpose op-amp. The output indicates only the polarity of the input signal; it can be considered a clipper or a 1-bit analog-to-digital converter. It is not a linear device and needs no feedback or compensation. Hence, it can be made much faster.

Although faster than op-amps, comparators are generally slower than digital circuitry. If high accuracy is required, the input considerations mentioned under op-amps apply. The high-speed devices require careful layout and power supply bypassing, or oscillations can occur. (This also holds for the special high-speed op amps.)

The original IC comparator the µA710[6] has problems and is obsolete, and normally should not be used. The LM111[7] is now the standard and is good, although not as fast as the 710. There are many higher-speed comparators available, but most have wierd supply voltages and/or pinout and are not interchangeable; none of the high-speed types has become a standard. The LM 139 (National, reference 7), equivalent to MC 3302 (Motorola, reference 9), is a quad with characteristics comparable to the LM 111; however, the pinout is not compatible with the quad op-amps, and in fact does not resemble anything else at all.

MULTIPLIERS

In electronic computation it is often necessary to find the product of two signals. This is a relatively difficult problem in both digital and analog, at least at least at high speed. In analog, the invention a few years ago of the "transconductance multiplier" or "Gilbert Cell" made multiplication far more practical (easier and faster) than before. This invention uses the logarithmic voltage-current relationship of a semiconductor junction to convert the signals to logs, add, and convert back to antilog. Moreover, all signals are handled differentially, so either input may be either positive or negative, otherwise a problem when using logarithms.

The Motorola MC 1595 (reference (9)) equivalent to Fairchild µA795 (reference (6)), was the first generally available version. The MC 1594 is an improved version, with more of the necessary circuitry on the chip itself. (Don't ask me to explain the reverse numbering.) These do require three potentiometer adjustments in most applications; accuracy is on the order of 1% (be sure to read the fine print). 3 dB down bandwidth is as high as 80 MHz, but 1% additional error due to phase shift occurs at 30 KHz, so frequency response is a very strong function of required accuracy. Some newer devices, such as the AD 532 from Analog Devices[10] are laser-

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[10] Product Guide, Analog Device, Inc.

trimmed so the pots are unnecessary. It also includes the output amplifier so nothing at all need be added. These units are usually well worth the additional cost. All units perform the computation $V_{OUT} = (V_{X_1} - V_{X_2})(V_{Y_1} - V_{Y_2})/10$. The quantities in bracket simply indicate differential inputs. The 1/10 is a scale factor included so that when both inputs are 10 V (full scale), the output is also 10 V. Multipliers can also be used with an op-amp and feedback to perform division and extract square roots.

The so-called multifunction module such as the Burr-Brown 4301[11] extends the computation to

$$V_{OUT} = V_y \left(\frac{V_z}{V_x}\right)^m ,$$

but these are not yet available in monolithic form and are relatively expensive.

BALANCED MODULATORS

A common task in analog circuitry is modulation, or frequency shifting, which requires multiplication. In place of a linear multiplier there is a simpler and faster device to use, the balanced modulator, or more properly the doubly-balanced modulator-demodulator, such as the Motorola MC 1596[9] equivalent to the Fairchild µA796[6]. The balanced modulator can be thought of as a multiplier where one input is linear and the other input is clipped; it multiplies one signal by the polarity of the other. As a modulator it performs the function of a multiplier but generates spurious bands at odd harmonics of the carrier freuuency; however, these often are irrelevant or at least can be filtered out by a simple low-pass filter.

The balanced modulator is simpler than a linear multiplier, requiring at most one balance pot and often none. It is faster, the 1596 having a bandwidth of 80 MHz at the signal input and 300 MHz at the carrier input. Parasitic oscillations at very high frequency can occur for certain input conditions, primarily long leads on the signal input. The data sheets give simple circuits to prevent this, for example a 1K resistor in series with the input right at the pin, and one of these should always be used. (Although less likely, this problem can also occur with the linear multipliers.) If carrier feedthrough is a problem a balance adjust is required; otherwise not.

The outputs are taken across resistors connected to the positive supply; this causes some potential problems. Any hum, drift, or noise on the positive supply is transmitted directly to the next

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[11] *1976 Catalog*, Burr-Brown Research Corp.

stage. It also invites oscillation if there is much gain in the succeeding stages. In most applications the supply is regulated well enough that this is not a problem; if it is, an op-amp differential amplifier can be added to reject common-mode noise. The amplifier can then also be used to shift the level back to ground potential, as the circuit requires three levels of DC bias and the output is usually well above ground. It will also provide a buffer, as the output impedance of the balanced modulator is equal to the value of the load resistor used, not low-impedance like the output of an op-amp.

GAIN CONTROL ELEMENTS

A specific problem that arises often in analog processing is varying the amplitude of an AC signal according to a DC control voltage. This may be done with a linear multiplier, but the reliable dynamic range is limited to about 40 dB because at the low end a small DC error causes a large relative change in AC signal amplitude. Also, an error giving a shift through zero causes the signal to simply reappear with opposite polarity, which may be unacceptable, for example in feedback systems. It is usually preferable to have an antilogarithmic control characteristic, i.e., a given change in control voltage in volts produces a given change in signal level in dB. This can be done by adding the AC signal and the DC control voltage in an antilog element and removing the DC from the output by AC coupling, but the AC amplitude must be kept very small compared to the DC control or significant distortion occurs. A better arrangement is used in the MC3340 "electronic attenuator" from Motorola[9]. This circuit achieves a range of attenuation of 90 dB, and the characteristic is more-or-less antilog.

Sort of the opposite function is Automatic Gain Control (AGC), which maintains a constant output AC signal level for a wide range of input levels. There are a number of integrated circuits available which are adaptable to AGC; some are rather crude and require a lot of additional circuitry, but some are rather sophisticated. There are a number of variables to be considered with AGC circuits, and some designs have features which may prove undesirable. Some exhibit a large change in output DC voltage when the AGC level changes. Some are capable of much gain but little attenuation, and some are the opposite. LM 170 (National[7]) was one of the first general-purpose designs.

LOG-ANTILOG CONVERTERS

Logarithms are often used in electronic engineering. Decibels are directly related to logarithms. Logarithms can be used to multiply, divide, exponentiate, root, etc. As pointed out, a logarithmic control characteristic is often desirable because logarithms simplify handling of wide dynamic ranges.

A silicon semiconductor junction exhibits basically a logarithmic voltage-current relationship, but there are problems utilizing it, chiefly the temperature dependence of the characteristic. However, these problems are taken care of in integrated devices such as the Intersil 8048/8049 pair.[12] These are fairly easy to use and work well if the data sheets are followed. Note, however that they are not linear devices, and the effect of errors must be carefully thought out. For example input DC offset voltage does not produce an equivalent DC offset at the output; the output error depends on the signal applied. Nor is the effect the same for log and antilog circuits. Also grounding the input (0 volt in) will not necessarily produce a meaningful output. Two op-amps are used in both circuits and offset adjustment terminals provided, but for many applications one or both adjustments may be unnecessary. Note that on the inside the two devices are very similar. This is true of many other analog device pairs. In general one device of a pair may be made to serve as the other by use of op-amps and negative feedback. Hence, accuracy, speed, etc., are usually comparable for a device pair.

PHASE-LOCK LOOPS

A phase-lock loop (PLL) is a common device used to "lock" a reference oscillator to another periodic signal in frequency and perhaps also in phase. In many cases, this is possible when the original signal is contaminated by or even obscured by noise; a PLL is thus used to produce a relatively noise-free replica of a noisy signal. The Signetics SE 560 series[13] were the first monolithics, but there are now many PLL IC's available. The CD 4046 from RCA[8] is a good general-purpose device. It is made with CMOS (Complementary Metal-Oxide-Semiconductor) technology for low power consumption, requires few external components and offers a choice of the two most common phase detectors.

The various designs differ widely because there are many variables involved in designing a PLL; most are designed for specific applications such as radio receivers or frequency synthesizers. One must find a type designed for applications similar to the one at hand; it may well be that none are satisfactory. The first consideration is the range of frequencies that the PLL must cover--wide or narrow; high or low. Some PLL's can track a noisy input signal while others require a noise-free signal; this depends primarily on the type of phase detector used. It may be of importance what the PLL does when the input signal becomes small or vanishes; does the frequency remain stable, drift badly, head for zero? How noisy is the Voltage-Controlled-Oscillator (VCO)? In some applications it is important that the VCO have a linear control characteristic; in others it does not matter.

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[12] Intersil Semiconductor Products Catalog, Intersil, Inc.
[13] Data Manual, Signetics Corp.

Most designs provide for either first-order or second-order loops. Second-order is almost always advantageous. Third-order or higher is possible with additional components, but is rarely necessary. Reference (14) gives a thorough analysis of PLL's and is worth reviewing before designing a PLL.

FUNCTION GENERATOR; OSCILLATORS

The function generator IC has been described as a "WAVETEK* on a chip". With the addition of capacitors, potentiometers, and switches it does indeed perform much the same as the simpler WAVETEK* - type function generators. It typically provides a square triangle or "sine" wave of good amplitude stability and medium frequency stability, where the frequency is easily variable. It may provide a symmetry control, in which case pulse, sawtooth and "half-sine" waves are also available. It may provide control of both frequency and amplitude by DC voltages.

The function generator is very handy as a signal source but does have its limits. The square and triangle waves are accurate, as the circuit is basically an integrator and hysteresis switch in a loop, but the sine wave is not generated as such but is synthesized from the triangle wave by nonlinear (e.g., diode)shaping networks. The distortion or harmonic content is relatively high, and is usually quite sensitive to an amplitude adjustment. If a very pure sine wave is necessary, a different type of oscillator should be used.

Variable frequency and high stability are generally incompatible. The output frequency of a function generator may be varied by a control voltage over a wide range, generally at least 10:1 and perhaps as much as 1000:1. The price is that the frequency will vary on its own (noise and drift), especially at the low end of the range. If high frequency stability, low phase noise or exceptional symmetry are required the function generator IC will probably not be acceptable. Performance deteriorates above about 1 MHz, and lower if an asymmetrical waveform is generated.

The XR-205 from Exar[15] is an early design. It is fairly versatile, but newer designs are fancier and probably more accurate.

If a very stable, fixed-frequency oscillator is required, a crystal-controlled oscillator should be used. These are now available in IC form from several manufactuers. Because of the infinite number of possible frequencies these are custom units with high prices and long lead times, unless by chance one of the manufacturers makes a "standard" frequency which is acceptable.

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[14] F. M. Gardner, Phaselock Techniques, Wiley, 1966.

[15] Product Guide, EXAR Integrated Systems.

*registered trademark

This is one case where it is still usually easier to just order the crystal and build the circuit.[3]

VOLTAGE REGULATORS AND REFERENCES

Nearly all electronic systems have at least one power supply and nearly all power supplies have at least one regulator. Engineers tend to take these for granted, but power supply failure is one of the most frequent causes of system failure, and often the problem is the regulator. Regulators have to operate at relatively high power, and consequently high temperature, which tends to induce failure. To make matters worse, failure may well cause the output voltage to rise, which may damage the rest of the system. Besides the possibility of catastrophic-type failure, simple lack of adequate power-supply regulation may cause a system to malfunction.

It is usually more cost effective to buy a regulated power supply than to design and build one, as there are many good manufacturers who have spent years solving the many inherent problems. Sometimes the designer must be concerned directly with regulators, however; for instance when regulation must be done at each board because of noise picked up in the cabling or connectors between the power supply and circuitry. Integrated circuit regulators have been around for years, but newer versions are much improved. The original was the Fairchild µA723 (reference (6)), which is still used. The simplest version is the fixed 3-terminal regulator, for example, the Motorola MC7800 and MC7900 series.[9]
Of these, simply choose the device having the proper polarity, voltage, and power capability, provide it with a reasonable input voltage and ground reference, and the rest is done for you. Capacitors to ground are often recommended on the input and/or output. Most new designs are protected against thermal (power) and current overloads, and are difficult (but not impossible) to damage. Note that to obtain maximum output, heat sinking as specified by the manufacturer must be provided.

If the voltage is not accurate enough or must be adjustable, there are methods of controlling the voltage. However, these often adversely affect the regulation, and it is better to use a 4-terminal regulator such as the Fairchild µA78G - µA79G family[6] or 3-terminal designed to be adjusted such as the National LM117.[7] These are similr to the fixed 3-terminal regulators and are almost as simple to use.

A special type of regulator is the voltage reference, which does not have high power capability but provides a voltage which is extremely accurate. Again, the simplest is the fixed voltage reference, such as the Analog Devices AD 2700 series[10] which supply 10.000 volts, accurate to within a few millivolts for reasonable conditions. Some references are adjustable over a limited range with minimal effect on termperature stability, such as the Precision Monolithics REF-01[16] which gives 10 volts adjustable to ±3%, allowing adjustment to 10.24 volts for binary-weighted ladders.

ANALOG SWITCHES; MULTIPLEXERS; SAMPLE-AND-HOLD

Switching of digital signals is easy, since digital circuits are themselves switches. Switching of analog signals, for example in time multiplexing and demultiplexing, is more tricky. The most common type of analog switch employs field-effect transistors as solid state switches. Newer integrated designs include the driving circuits so the switch can be controlled directly by most types of digital logic. Probably the best general purpose types are the CMOS (Complementary-Metal-Oxide-Silicon) switches such as the Siliconix DG200[17] which employ a P-channel, N-channel complementary FET pair. Probably the most common unit is the CD4016[8], which is part of the RCA COSMOS digital series, but which also can be used to switch analog signals. Present units are not buffered and do have a significant channel resistance, on the order of 100 ohms, in the "on" state. This varies somewhat with input voltage so the load should not be low impedance . Feedthrough or crosstalk may be a problem at higher frequency where leakage capacitance becomes significant. Switching time and switching transients should be considered for switching rates higher than 1 KHz. The maximum analog input voltage must be observed.

Obviously, these switches can be used to build analog multiplexers or demultiplexers. In fact this has already been done by the IC manufactuers. The problems listed for the switches also apply here; in addition the number of channels required must be considered. Because of this additional variable no particular device is likely to become a standard.

A sample-and-hold (S&H) is an analog switch with memory. A better name is track-and-hold. When the switch is on, the output follows the input. When the switch is turned off, the output remains at the value of the input at the time of turnoff. An S&H is typically used with a demultiplexer to preserve the value in one channel while the other channels are being sampled. It consists of an analog switch followed by a memory capacitor with output buffer and feedback. These are now available in monolithic form (except for the capacitor), e.g., Harris HA2420[18], which can be

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[16] Linear and Conversion I.C. Products, Precision Monolithics Inc.
[17] Siliconix Semiconductor Devices, Siliconix Incorporated.
[18] Integrated Circuits Data Book, Harris Semiconductor.

switched directly from most types of digital logic. The size of the memory capacitor must be chosen according to the application; a larger capacitor increases memory time but lengthens acquisition time and reduces tracking rate, and vice versa. Note also that a high-quality capacitor must be used or the capacitor itself may introduce error. Again, maximum input voltage range must be observed.

ANALOG SHIFT REGISTERS, MEMORIES

Memory is one of the outstanding features of digital systems. Many types of memory systems are available, offering a wide range of capacity, speed, and volatility. On the other hand, the search for a good analog memory system has been virtually unproductive. There is no mass memory system except tape recording, which works better when digitally coded anyway. The only random access memory is some experimental cathod-ray-tube systems similar to a memory scope.

However, analog shift registers have recently shown great promise. There are two types. The "bucket-brigade" uses older MOS technology, and shows little promise of significant improvement. Charge coupled-device (CCD) technology, is newer but promises continual refinement. The problem is charge loss or alteration. For a large number of stages, say 100 or 1000, each transfer must be considerably better than 99% efficient, or the cumulative error from input to output is terrible. Devices are now available for specialized applications such as ghost-cancellation in TV. General purpose devices may become available as the technology improves and new systems utilize more exotic techniques such as correlation and transversal filtering.

ACTIVE FILTERS

One of the classic quests of electrical engineering has been to find the ideal filter, defined generally as a device which passes one part of the frequency spectrum without alteration while totally rejecting the rest of the frequency spectrum. It can be shown that such a device exists only as a theoretical limit. Digital computers can come close, but are complex and require A-D and D-A converters, and cannot perform in real time at higher frequencies. A general complete digital-filter integrated circuit is not yet available.

A single, general analog filter circuit does not exist either. However, a large number of circuits have been thoroughly developed (references (3), (4), and (19)), and for most practical applications there is at least one type that will perform adequately. Many of these use op-amps which, again, are not ideal but are usually adequate.

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[19] Blinchikoff and Zverev, Filtering in the Time and Frequency Domains, Wiley, 1976.

One rather general type that lends itself to integration is the so-called "state-variable" filter, (e.g., National AF100, reference (7)), which appears in several variations with several different names. It is basically a resonator consisting of two op-amp integrators and an op-amp inverter in a feedback loop. (The circuit looks somewhat like an oscillator, and indeed with minor modifications can be made to oscillate.) By placing input and output at appropriate places, the circuit can be made to function either as a single pole-pair high-pass, low-pass or band-pass filter. With the addition of a fourth op-amp as a summing/difference amplifier, band-reject and all-pass functions are also available. The center frequency and "Q" or damping can be readily adjusted. Theoretically any realizable filter function may be achieved by placing enough of these having the proper pole frequencies in tandem, with a single pole (simple RC) added for odd-order filters.

Obviously a state-variable filter can be made by adding appropriated resistors and capacitors to a quad op-amp. The integrated circuit versions provide the quad op-amp plus some of the necessary good-quality resistors and/or capacitors. This is especially useful if band-reject is required. They also provide handy charts and tables, allowing the inexperienced designer to build a working filter with a minimum of thought. The sensitivity of the state-variable filter to component tolerance is relatively low(good). However, some multiple-pole filter types (for example Chebyshev) require high-Q pole-pairs, and these become critical.

ANALOG-DIGITAL-ANALOG CONVERTERS

It has already been stated that an analog-digital converter (ADC) and/or a digital-analog converter (DAC) is often the limiting factor in a "digital" system. These devices are small systems in themselves, and only recently have been built in integrated circuit form. However, integrated devices have progressed rapidly from good to very good, and 12-bit or 13-bit devices are available (e.g., the AD 562 12-bit DAC and AD7550 13-bit ADC from Analog Devices, (reference (10)). These figures should be approached cautiously, as a 13-bit device often will not give 13-bit accuracy under all conditions, perhaps never under realistic conditions. At this level of accuracy care must always be exercised in system design and layout.

There are no "standard" devices; early widely-used units have been obsoleted by newer devices. Emphasis has been primarily on increasing accuracy; for high speed applications hybrid or discrete units are generally necessary. Eventually, high-speed monolithic devices will surely become available, though.

VOLTAGE-FREQUENCY-VOLTAGE CONVERTERS

A sort of specialized analog-digital conversion circuit is the voltage-frequency (VF) converter and its counterpart, the frequency-voltage converter (FV). The VF converts an analog voltage (or possibly current) to a square wave or pulse train having a proportional frequency. It is useful as a wideband FM (Frequency-Modulation) generator which may be used to transmit analog data over a channel of insufficient quality, such as noisy telephone lines. It may also be used to make a long-time-constant integrator. Conventional op-amp integrators are limited to integration times of a few seconds. If the signal is converted to a frequency, the integration may be done by a digital counter chain, and the integration time may be increased almost without limit by adding more counter stages. Note, however, that the low-order bits are not necessarily accurate; accuracy is still limited by the accuracy of the VF converter, usually 10 bits or so.

The units are least accurate at the high and low ends of the range; in particular the circuit cannot be expected to work precisely down to zero. The frequency range is usually determined by an external capacitor; accuracy decreases at higher frequencies (less capacitance). When used as a transmitter, the maximum input frequency is limited by the Nyguist sampling theorem. Since the frequency is proportional to the voltage, the effective bandwidth goes down at lower input (DC) voltage. Some units operate as high as 1 MHz, however, giving considerable bandwidth at the upper end. An example is the Raytheon 4151.[20]

TIMERS

The 555 timer (Signetics)[13] has been called the most popular analog circuit ever produced. If this is true, the reason is not obvious. It does not do some things a timer should do, and what it does can be done by op-amps or comparators with a few extra parts. Nevertheless, with the addition of a few components the 555 provides either a monostable or an astable multivibrator, both of which always seem to fascinate engineers. Accuracy of the device is good, but note that the timing resistors and capacitance must be of high quality to maintain the accuracy. Newer desings provide more features; also quads are now available.

GENERAL PRECAUTIONS FOR ALL CIRCUITS

The newer circuits are pretty much damage-resistant, but no circuit is completely idiot-proof. It is always wise to connect the circuit correctly; mistakes seldom improve performance. With analog circuits a split supply (equal positive and negative voltages) is usually used. If so, both should be turned on and off together, as having only one turned on may result in biasing conditions the circuit was never intended for; using a dual supply makes this

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[20] Linear IC's, Raytheon Semiconductor.

makes this precaution automatic. Most circuits will withstand any voltage up to either supply voltage being applied to any input or output. However, there are exceptions and these should be noted. Also, extra terminals such as compensation or offset terminals are usually not protected and signals should not be applied to these. Do not connect anything to "unused" pins, as these may actually be used internally. Also, turning the power off is usually equivalent to having zero volt supplies; the circuit is then not guaranteed to withstand any signal at all even applied to the input. This is usually not a problem, but if a circuit has no current-limiting impedance at the input applying a signal from a low-impedance source such as a 50-ohm signal generator or charged capacitor may cause damage.

Except when switching, a digital circuit is saturated and there is no gain to be had. Analog circuits usually have high gain and are operating in the linear region, so the possibility of oscillation always exists. A good ground is a necessity. At least a low-impedance ground bus is required; a ground plane is recommended. Power supplies should be well regulated and the printed-circuit leads bypassed to ground with good capacitors every few inches. Output leads should not be laid alongside input leads. Observe that an oscillating circuit cares not at all what the input frequency is; your 1 Hz amplifier may well oscillate at 1 MHz or conversely your 1 MHz amplifier may motorboat at 1 Hz. On the otherhand, be not upset if your circuit begins to oscillate when the input is disconnected; a perfectly legitimate circuit may become unstable when the driving impedance is removed.

High-impedance circuits present special problems especially in troubleshooting. Normally a 10 Megohm, 10 picofarad oscilloscope probe should be used, but even that may be too much load for a circuit using impedances near a Megohm. If an FET input probe is not available, a simple buffer may be made by connecting a CA3140 op-amp[8] as a voltage follower, giving an input impedance of around 10^{12} ohms and a few picofarads capacitance. The only effect at low frequency is a DC offset error of a few millivolts; at high frequencies(above 100 KHz) it may be necessary to use a faster op amp, possibly at the expense of input impedance. Note that circuitry should always be clean and free of soldering flux, manufacturers' claims notwithstanding.

The question always arise s "how do you breadboard a circuit?" For simple circuits, breadboarding strips having a 0.1 inch grid where components imply push in, such as the AP products 923252 or the E&L Instruments SK-10 work well. For complex or sensitive circuits a printed-circuit layout is necessary. The circuit board should have all the wiring on one side, with the other side being devoted to ground plane. The digital type boards having wiring on both sides often give problems because the component side cannot be easily cleaned. Similarly, general-purpose wire-wrap boards are undesirable because analog circuitry will not tolerate long leads laid together to the extent that digital circuitry will.

Because of the wide variety of analog circuits there is no really general procedure for debugging a circuit that doesn't work. However, there are some guidelines; most can be traced to common sense. The first impulse is to assume the IC is bad and replace it; this usually does not solve the problem. The first step should instead be to double-check the circuit layout and components to make sure it is assembled correctly. Next, using an oscilloscope, check all nodes for correct signal and DC bias voltage, beginning at the input of the circuit and working toward the output. It may become necessary to separate the circuit into smaller parts to eliminate interactions and isolate the problem, but it is also possible for the parts to work separately but not together. It may be necessary to break feedback loops, for the same reason, but the expected performance is usually quite different without the feedback.

When developing a new circuit it is best to build two units at once. This sounds expensive, but often pays for itself in time saved. Having two units to compare will quickly pinpoint a bad part or single wiring mistake, or conversely indicate a more basic problem if the two units exhibit the same misoperation. Also, any change should be made to one board only and "before" and "after" performance compared directly. Furthermore, if the circuit works, it is nice to know that it is not so touchy that it cannot be duplicated if necessary.

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