A Tribute to Jim Williams

Various Articles and Bibliography

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Electrophoresis with Continuous Scanning Densitometry: Separation of Cells in a Density Gradient

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An instrument and procedure for electrophoresis with continuous optical scanning densitometry, automated data processing, and related methodology are described for the continuous analysis of electrophoresis and unity gravity sedimentation of macromolecules or cells in a static density gradient system. The instrument consists of a dual-beam spectrophotometer, a scanning stage and scanner control unit, an electrophoresis cell cassette, a filling/purging/cooling module, an analog-to-digital converter, and a digital data-logger. The distribution of cells is monitored repetitively during migration by absorbance measurements at any wavelength in the 200–800-nm range. A computer program provides the statistical analysis of each peak (baseline correction, smoothing, area, mean, standard deviation, skewness, and kurtosis) which can be further utilized for computing additional parameters, such as resolution and heterogeneity. A mixture of human and rabbit erythrocytes were used as a model system to evaluate the performance of the instrument and demonstrate some of its capabilities.

A considerable body of knowledge about the electrokinetic behavior of cells has been acquired by the microscope electrophoresis technique (1,2). However, bulk separation and analysis of cell populations by electrophoretic methods has been limited primarily to flow methods, including free-flow electrophoresis (3,4), steady-flow (STAFLO) electrophoresis (5), and endless belt electrophoresis (6). The use of stationary vertical density gradients for the stabilization and preparative electrophoresis of viable mammalian cells was introduced only recently (7,8).

In the present study, fractionation of cells was carried out in an instrument capable of repetitive optical scanning during electrophoresis. The instrument is a modification, largely based on commercially available components, of previous designs (9) which are similar to devices used in gel filtration (10) and "free zone electrophoresis" (11). These devices, in turn, are descendants of the original Tiselius apparatus.

The application of the continuous scanning instrument to cell separation provides analysis of physical-chemical properties, such as average velocity, mobility, charge heterogeneity, and resolution in addition to cell separation. Human and rabbit erythrocytes were selected for fractionation because they exhibit a rather large electrophoretic mobility difference of at least 0.6×10^{-5} cm^2/sec/V (in 0.15 M saline, pH 7.2, at 25°C) by the microscope method (2). At its present state of development, the instrument described here must be considered analytical rather than preparative since it is capable of handling a maximum of 10^6–10^7 cells per experiment. However, collection of fractions for further analysis is possible.

APPARATUS

The principles of electrophoretic analysis with continuous scanning during electrophoresis have been reviewed previously (9). A schematic diagram of an improved apparatus and accessories is provided in Fig. 1. The dual-beam spectrophotometer is similar to that described previously (12) except for the following: A 200-W xenon–mercury arc lamp and associated power supply (Schoeffel) are used in conjunction with a tandem grating monochromator (Schoeffel GM100D) to produce monochromatic light in the 200–700-nm wavelength range of very low stray light characteristics (specified by the manufacturers, 1 : 10^4 at 220 nm) (Fig. 2). Slit widths available for each monochromator are 0.5, 1.0, 1.4, 2.0,

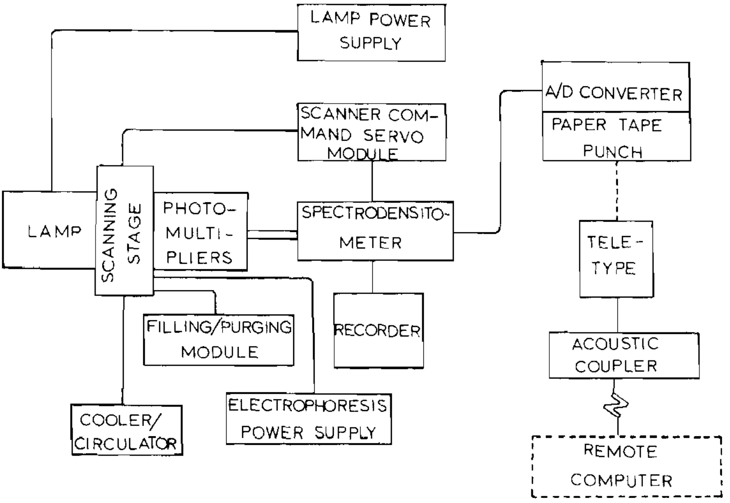

FIG. 1. Block diagram of the apparatus.

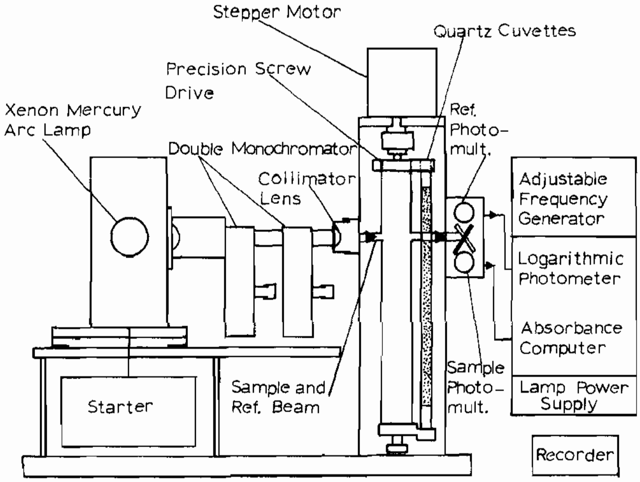

FIG. 2. Schematic diagram of the spectrophotometer scanning stage.

and 2.5 mm. The monochromatic light beam is subsequently collimated by a quartz lens, shaped by a variable horizontal slit (25–100 μm), and divided to illuminate the sample and reference electrophoresis cells simultaneously. Each beam is detected separately by its own photomultiplier tube, and the log of the ratio of the two signals, i.e., the linear optical density, is obtained electronically (Schoeffel model SD 3000 Spectrodensitometer). The use of a split-beam instrument eliminates errors due to fluctuations of the power supply, light intensity, and photomultiplier high voltage. A balance control and zero meter permit matching sensitivity levels of the photomultipliers at any desired wavelength. This adjustment equilizes the electrical outputs of the two channels, providing a reading of zero optical density (OD) at the beginning of the scan, with the sample beam in a "neutral" area of the media to be measured. The photometer supplies an analog output of 1 V per 1 OD unit and 100 mV full scale (corresponding to 0.1, 0.2, 0.4, 1, 2, 4, or 10 OD units) for operating a recorder. The output is processed by an analog-to-digital converter and recorded on perforated paper tape. An optional single channel mode of operation is also available in the instrument.

SCANNING STAGE

Linear transport:[1] This part of the instrument provides vertical linear transport of a stage for the removable electrophoresis cassette by means of a reversible stepping motor attached to a precision leadscrew (Fig. 3). The stepping motor and adjustable frequency generator provide six

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[1] Blueprints, engineering drawings, or sample output provided upon request.

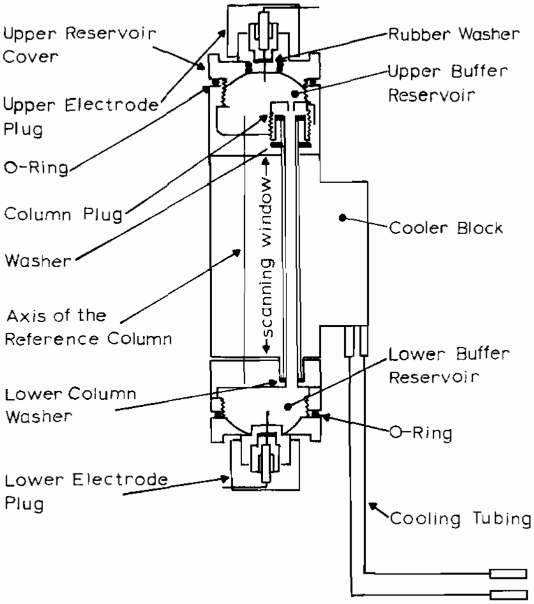

FIG. 3. Schematic diagram of the electrophoresis cassette.

reversible up or down scanning speeds of 5, 10, 20, 40, 80, and 160 sec/cm. This unit also provides dark housing.

Control unit:[1] The control unit regulates the movement of the scanning stage, the X–Y recorder, and the tape puncher. A 2.5-kohm "scanner pickoff" linear displacement potentiometer is mechanically fixed to the moving stage. The potentiometer is driven from an appropriately scaled dc voltage source such that the output voltage is equal to the position of the scanner (in centimeters) with 0.05% accuracy. This potential is displayed on a digital panel meter (Newport 2000) which provides a direct readout of the scanner position in centimeters. The signal is also supplied to two amplifiers which are in a double limit comparator configuration. Two 10-kohm ten-turn potentiometers permit setting up "high" and "low" scanner travel limit positions and are calibrated directly in centimeters with a 1% accuracy. The comparator continuously compares the limit potentiometer settings with the pickoff signal and issues motor-reversing commands to the memory/switching element which functions as a set–reset flip-flop, with versatile switching capability and high noise immunity. One set of relay contacts functions as a latch and provides the "memory" function. A second set of contacts transmits the reversing information to the motor. A third set of contacts automatically operates the "sweep" and "reset" functions of an X–Y recorder and signals the paper tape punch to issue a leader (blank space on tape) on the tape. A fourth set of contacts provides for the motor to run at higher speed in the "down" scan mode. All the functions of the control unit may be superseded by manually controlled panel switches.

The practical implications of the control unit are several. The scanning interval (in centimeters) can be selected digitally and be set at any part in the column by means of two controls. A digital display of column position with respect to the light beam is available at all times. The recorder and paper tape puncher are actuated automatically when desired. Finally, the scanner may have different speeds for the "scan" or "reset" mode of travel. This permits data collection either in both directions of travel (which is more difficult to analyze) or preferentially at normal speed in the "up" mode accompanied by fast reversal in the "down" mode without data collection. Without this control unit large-scale experiments with the apparatus are impractical.

Electrophoresis cassette.[1] This part of the assembly is removable and accommodates two quartz columns (Amersil, Hillside, N.J.; Suprasil T21) (Fig. 3), with dimensions of 6.0-mm i.d., 8.0-mm o.d., and 142-mm length. One column carries the sample for analysis, the other acts as reference background in balancing the photometer output. In density gradient experiments the bottom of the sample column is closed either with a semipermeable membrane or by a plug of polyacrylamide gel. The cassette also accommodates the upper and lower flow-through electrolyte reservoirs, with removable platinum electrodes, and a flow-through cooling block maintaining constant temperature by dissipating Joule heat. An additional outlet is provided at the top of the lower electrolyte reservoir to allow escape of any air pocket introduced during loading or gas bubbles generated by electrolysis. The cassette can be readily disassembled for cleaning.

Filling/purging/cooling pump accessories.[1] This unit consists of a multichannel Technicon proportioning pump, a vacuum pump, Hamilton chemically inert valves, a thermostatically regulated cooler/circulator, and associated tubing. The function of the assembly is to recirculate the buffers into the upper and lower electrolyte reservoirs during electrophoretic fractionations, purge and wash the electrolyte flow lines at the end of the run, and circulate temperature-controlled fluid through the cooling block of the electrophoresis cassette. The buffer reservoir bottles are equilibrated in a constant temperature bath. Recirculation of upper and lower buffers allows marked reduction in size of the chambers in the electrophoresis cassette. This allows the electrophoresis cell to fit in the available space for dark housing.

Monitoring accessory. Voltages, current, temperature inside the cooling block (on the inlet side) or of the water bath can be monitored at adjustable intervals (1–100 sec/channel), digitized, recorded on a teletype, and punched on paper tape.

Other accessories. A Beckman Duostat constant current or constant voltage regulated dc power supply was used for electrophoresis. The photometer output was recorded with an Esterline–Angus model 2417 TB X-Y and Y-time recorder connected to the scanner control unit.

Data logging accessory. This unit (ESP model No. DDS, II) consists of an analog-to-digital converter with visual display, two-channel analog multiplexer, variable speed sampler, and a Tally tape punch. Data can be punched at a switch-selectable rate of 1–20 readings per second. Other provisions include choice of three gain settings, single or double channel operation, and single or continuous sampling of the data. The acquired data punched on the paper tape are processed by a remote computer, accessed via a teletype and acoustic coupler. Programs were developed in FORTRAN for a CDC 3600 time-share computer service (MULTICOMP) using a considerable extension and refinement of methods previously used (13).

PROCEDURE

Liquid flow through the cooling block of the electrophoresis cell cassette is initiated at approximately 100 ml/min. The quartz column, covered at the lower end with a dialysis membrane sheet premoistened with the lower buffer, is placed in the cassette and the density gradient is generated *in situ*. Concurrently, buffer is pumped into the lower electrolyte reservoir which is tilted at a slight angle to prevent entrapment of air under the column. The sample solution is then applied above the gradient and carefully overlayered with upper buffer, which fills the remainder of the column. Subsequently, the upper buffer is pumped into the upper reservoir with the upper chamber cover (without electrode plug) in position. The upper electrode plug is then gently inserted to avoid applying pressure to the column. The electrophoresis power supply is turned on for a few seconds to verify the expected conductivity. The electrophoresis cassette is placed on the scanning stage and the dark housing lid is closed. The photometer is adjusted to zero at a “neutral” area of the column, and a preliminary scan is obtained to establish the baseline before the voltage is applied. During electrophoresis the buffers are circulated through the upper and lower electrode reservoirs at 1.4 ml/min to remove products of electrolysis. The column is repetitively scanned during the experiment providing both a graphical record on the chart recorder and digital output on the paper tape. If desired, microfractions can be collected sequentially from the top of the column with a micropipet. Then, the reservoirs and tubing are cleared of buffer by suction. The quartz column is removed, appropriate plugs are inserted, and the total buffer circulation system is washed with water and purged repetitively by means of the filling/purging accessories.

Quartz column. The column is made of clear fused quartz T21 Suprasil synthetically produced (Amersil). The dimensions of the column are as follows: 0.6 ± 0.01-cm i.d.; 0.8 ± 0.02-cm o.d.; 14-cm length; and 0.28 ± 0.01-cm^2 cross-sectional area. The volume of the column is approximately 4.0 ml.

Data processing. The photometer output is digitized at a preselected rate (usually 5/sec or 100/cm of scan) and punched on paper tape, which is subsequently entered into a computer accessed via teletype and acoustic coupler. The computer program developed for these studies plots the densitometry profile together with its first and second derivatives. This facilitates the recognition of the limits of each peak. Then the program subtracts the baseline from the peak, computes the area, centoid, standard deviation, variance, third and fourth moments around the mean as well as indices of skewness and kurtosis or "excess" (β_1 and β_2 cofficients) (13).

A second computer program plots the peak position versus duration of electrophoresis and calculates velocity of the peak by least-squares linear regression analysis.

Cell electrophoresis. The procedures of cell preparation and electrophoresis are given in Appendix I.

RESULTS

Scanning profiles. Typical optical scans of the electrophoresis of a mixture of human (M) and rabbit (R) erythrocytes are shown in Fig. 4. The absorbance distribution of the cells versus migration distance is shown for different periods of electrophoresis. The complete separation of the two cell populations is evident. The higher-mobility fraction (human) appeared as normal biconcave discs with a small admixture of

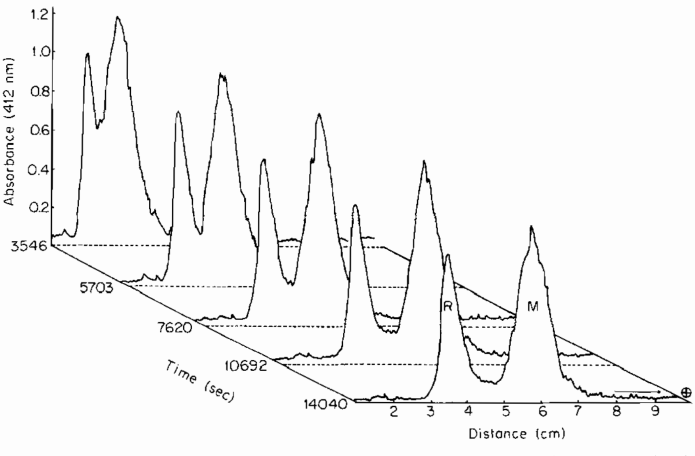

FIG. 4. Densitometric scan of human (M) and rabbit (R) erythrocytes obtained after various periods of electrophoresis.

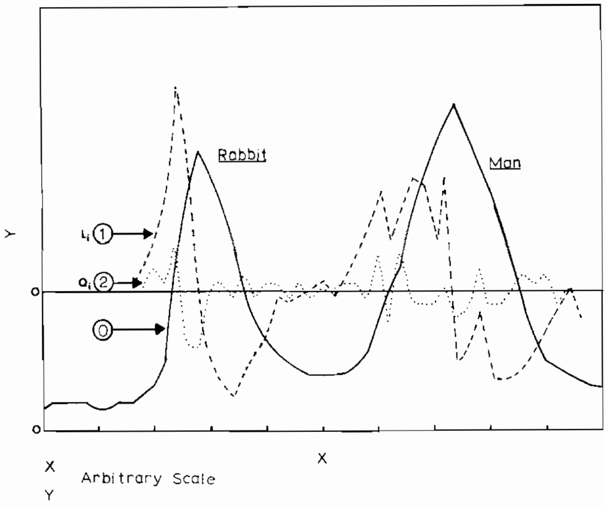

FIG. 5. First and second derivatives of the "smoothed" data superimposed on a typical scan of human (M) and rabbit (R) erythrocytes.

slightly crenated forms when examined by phase microscopy. The low-mobility cells (rabbit) appeared as spheroidal discs of smaller diameter than the high-mobility cells. These results are in agreement with previous studies (16), indicating that human and rabbit erythrocytes should be separable because human erythrocytes have a considerably higher mobility. Measurement of absolute or relative electrophoretic mobilities were not obtained in these studies, due to the changes in density, conductance, and viscosity during the course of fractionation. Graphical output of the computer analysis of a profile is shown in Fig. 5.

Estimation of average velocity. As discussed above, the instantaneous velocity of the cells in the system depends on a number of factors associated with both the nature of the cell (e.g., surface charge, radius, and density) and experimental parameters (e.g., conductance, voltage gradient, viscosity, cross-sectional area, density of the supporting medium, and electroendosmosis). The present apparatus and procedures allow for the estimation of the average cell velocity. This is accomplished by plotting peak position, $\bar{x}$ versus the duration of electrophoresis for data obtained from different scans. If the relationship is linear, average peak velocity can be estimated from the slope $d\bar{x}/dt$. A typical plot of position versus time is shown in Fig. 6. Linear regression analysis allowed for the estimation of the slope $d\bar{x}/dt$ with a coefficient of variation that ranged between 3 and 6%. The average velocity of human erythrocytes was 27.4×10^{-5} ($\pm 0.89 \times 10^{-5}$) cm/sec and that of the rabbit cells 14.8×10^{-5} ($\pm 8.89 \times 10^{-8}$) cm/sec.

Resolution. The dispersion, or variance, σ^2, of each distribution of

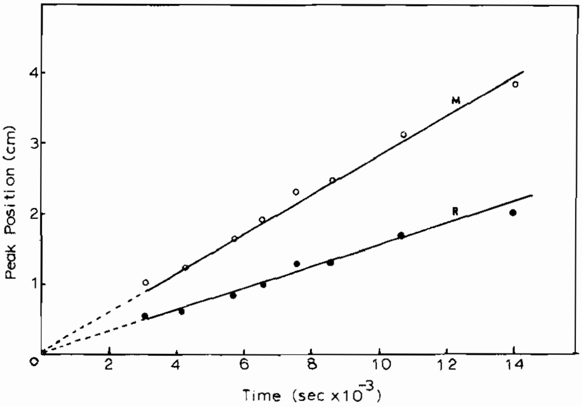

FIG. 6. Peak position versus electrophoresis time for estimation of mean velocity of the distribution of cells.

cells can be estimated as the second moment about the mean using well-known equations (13,15).

Since cells diffuse negligibly during electrophoresis (in contrast to macromolecules), resolution should improve continuously in the absence of charge or size (and hence mobility) microheterogeneity. Resolution was calculated by methods described previously (16,17).

The above relationships were used to establish the time of electrophoresis at which the resolution between human and rabbit erythrocytes was greater than unity. The populations were "completely" resolved ($Rs = 1.5$) at approximately 8000 sec. Thus, the present system provides data necessary for estimation of the degree of contamination of different cell populations (exhibiting different mobility) with each other assuming Gaussian distributions. Calculation of resolution also permits one to rationally decide on the optimal duration of electrophoresis in a fractionation experiment. Also, calculation of resolution provides a quantitative criterion for selecting among a wide variety of fractionation conditions (e.g., pH, buffer, ionic strength, voltage etc.)

DISCUSSION

The reported experiments represent a first attempt in applying electrophoresis with optical scanning for the separation of cells in density gradients and subsequent automated data processing for analysis of the distributions. The system is capable of measuring the average velocity of migrating cells, and providing information on polydispersity of the cell population.

Once methods are developed to measure field strength at any point in the tube, the system used will provide the electrophoretic mobility distribution of cells currently obtained by tedious microscopic procedures (2).

The most vulnerable aspect of the present technique involves the possible alteration of the cell mobility by interaction of the cell surface with the stabilization medium (e.g., Ficoll) which may also result in some cases in cell aggregation phenomena. Although disaggregation could be achieved by controlling the ionic strength of the medium (14), the problem of alteration of the zeta potential at the cell surface by polymer adsorption is more difficult to handle and may require additional corrections in standardized systems. However, the application of computer techniques may again offer a significant advantage over a simpler apparatus, provided the appropriate physical correction data are at hand. The separation system described here offers a new approach to cell separation and appears very promising in obtaining useful biological information involving cell surface charge.

It is planned that future modifications of the instrument will involve the addition of a fluorescent detection and laser small angle light scattering system. These features should expand considerably the information obtained on specific cell populations (18,19). A preparative method for separation of cells in a density gradient was reported recently (20).

ACKNOWLEDGMENTS

We acknowledge the custom design and construction of prototypes of the electrophoresis cell and scanning stage accessories and their integration with a commercially available spectrophotometer by Dr. V. M. Novacek and K. Lohse of Schoeffel Instrument Corporation, Westwood, N. J. We are most grateful to Dr. Paul Todd for helpful discussions on the static density gradient system and to Dr. G. V. F. Seaman, Dr. H. C. Mel, and Dr. L. Weiss for discussing with us some critical points in the electrophoresis of cells and preservation of their viability. J. R. Crowley generously provided us with human blood. D. M. Hutt of Standard Information Service, McLean, Va., provided valuable assistance with computer programming. This work was supported in part by National Cancer Institute Contract No. NO1-CB43928 and U.S. Army Research Office Contract No. DAHCO4-74C-0029.

APPENDIX I

Procedures Used for Cell Fractionation

Column coating procedure. The quartz column is coated before use to minimize electroendosmosis by a modification of the procedure described by Hjertén (11). Methyl cellulose (Methocel, viscosity 8000 cP, Dow Chemical Company) (0.4 g) is dispersed in 30 ml of boiling water and stirred until dissolved. An additional 70 ml of cold (4°C) water is added, and stirring is resumed in the cold room until the solution appears clear. Formic acid (7 ml) and then formaldehyde (35 ml) are added, with stirring. The final solution is clarified by filtration and can be stored at 4°C for at least 6 months. The quartz tube is rinsed thoroughly with a detergent solution, hot and cold tap water, distilled water, and dried. The methyl cellulose solution is introduced into the tube and after 5 min is drawn out slowly by placing the tube on a pad of paper towels. Subsequently, the tube is dried at 120°C for 40 min. The coating and drying procedures are repeated once more. Care should be exercised to avoid air bubble adherence to the tube wall and to keep the tube in the vertical position during coating.

Density gradient. Stabilization of cells during electrophoresis is achieved by a 2.5–10.0% Ficoll (400,000 MW, Pharmacia Fine Chemicals) gradient which is also an inverse 6.35–5.1% sucrose gradient (7,30). All solutions are in buffer. The gradient is formed from a "dense" solution containing 10% Ficoll plus 5.1% sucrose and a "light" solution containing 2.5% Ficoll plus 6.35% sucrose. The "bottom" solution is 10% Ficoll plus 5.1% sucrose, and the "top" solution consists of 6.8% sucrose. The cells are suspended in 2.0% Ficoll plus 6.44% sucrose. The density gradient is formed in the analytical column with a microdensity gradient maker (Buchler no. 2-5070A). The gradient covers the density range 1.032–1.060 g/cm^3 at 4°C. The gradient is isotonic throughout in the electrophoresis buffer.

Buffer. The buffer is a modification of that described by Boltz *et al.* (7) and has the following composition: 0.20 g of KCl, 1.15 g of Na_2HPO_4, 0.2 g of KH_2PO_4, 0.12 g of Na-acetate; 10.00 g of glucose, glass-distilled water to 1 liter. The pH of the buffer is 7.2 at 25°C, with a conductivity of 800×10^{-6} mho/cm.

Since only 10.5 cm of the quartz column length is available for the scanning window, the contents of the column are arranged as follows. The lowest 1.3 cm (0.46 ml) is filled with the dense solution which is thus brought up to the lower edge of the window. The next 8.9 cm (2.5 ml) are occupied by the gradient which is available to the scanning window in its entirety. An additional 1.9 cm (0.53 ml), are occupied by the sample (0.1 ml) and the light solution. The remainder of the tube, 1.9 cm (0.53 ml), is filled with the light solution. This particular arrangement standardizes the density at each point in the column and permits calculation of the viscosity at any point in the column.

Description of cell movement. Boltz *et al.* (7) proposed the following equation describing downward cell velocity in a density gradient and in the presence of the electric field.

$$\nu(x) = M \frac{i}{q\kappa(x)} + \frac{2}{9} \frac{a^2 g}{\eta(x)} [\rho_c - \rho(x)], \tag{1}$$

where $\nu(x)$ = instantaneous velocity of cells at any position x in the column (cm sec^{-1}); M = electrophoretic mobility (cm^2 V^{-1} sec^{-1}); i = current; q = cross-sectional area of the tube (cm^2); $\kappa(x)$ = conductivity at position x (ohm^{-1} cm^{-1}); g = acceleration of gravity (980.7 cm sec^{-2}); $\eta(x)$ = viscosity of the medium at position x (poises); ρ_c = cell density (g cm^{-3}); and $\rho(x)$ = density of the medium at position x (g cm^{-3}). Independent measurement of ρ_c, cell radius (a), assuming sphericity of the cell, and $\kappa(x)$, $\eta(x)$, and $\rho(x)$ should allow the calculation of the mobility (M) from Eq. (1). Equation (1) allows one to calculate any of the parameters (M, ρ_c, or a) if the other two are known from independent measurements.

Cell preparation and fractionation. Human blood was anticoagulated with citrate phosphate dextrose solution (Fenwal, Morton Grove, Ill.). Rabbit blood was collected by orbital venus plexus bleeding with a special micropipet and diluted immediately in 20 volumes of the sample buffer. Both human (blood type B) and rabbit erythrocytes were allowed to sediment at 1000*g* for 3 min and washed three times with 2.5% Ficoll plus 6.35% sucrose in portions of the "light" buffer solution. Each washing was followed by centrifugation.

Electrophoresis of a mixture of human and rabbit erythrocytes was carried out as described above with a constant current of 1.0 mA at 4°C for 250 min. After electrophoresis the separated cells were withdrawn from the quartz tube (under light scattering illumination) with a micropipet and analyzed by phase microscopy. In addition, the cells were washed once with 0.15 M NaCl, pH 7.2, and tested for hemagglutination with anti-B serum.

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Heavy-duty power supply regulates either voltage, current, or power

By combining switching and series-pass techniques, this high-voltage supply's designer achieved 0.01% regulation at power levels to 100W.

By Jim Williams, Teledyne Philbrick -- EDN, June 16, 2011

Regulated high-voltage power supplies, while common, generally offer only constant-current and constant-voltage modes of operation. This one adds a constant-power (EI product) mode.

Careful circuit design permitted fitting the unit's 100W capability into an unventilated rack-mount chassis measuring only 3-1/2x14x19 inches. Also, no high-voltage semiconductors (except diodes) are employed in it. Voltage output is 50 to 1000V at up to 100W, with better than 0.01% regulation. In the current mode, the unit delivers a maximum of 100 mA with 0.01% stability. Finally, when regulating power (EI), the output supplies up to 100W with 0.01% stability.

Regulator + converter = amplifier

Both switching and series-pass regulation techniques are used (**Fig. 1**). The instrument functions by controlling the input power to a toroidal do-to-dc inverter with a FET-input operational (servo) amplifier. One of the amplifier's inputs is referenced to a precision variable voltage. The other input is connected, through suitable circuitry, to the rectified and filtered output of the inverter.

About this article

Longtime EDN *contributor Jim Williams was a staff scientist at* ***Linear Technology Corp****, where he specialized in analog-circuit and instrumentation design. His first article for* EDN *was published on May 5, 1975, while Jim was with Teledyne Philbrick. The article, including the original graphics, is republished here.*

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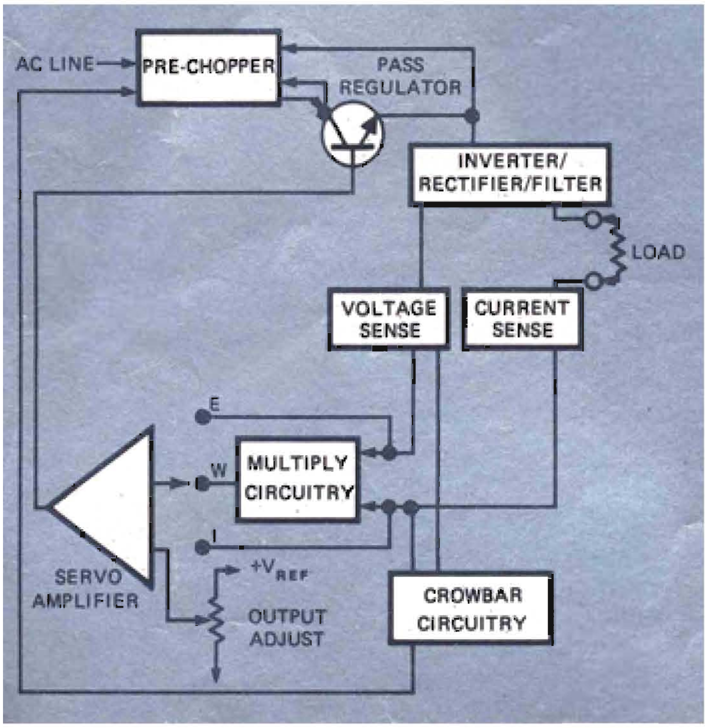


Fig. 1—Functional diagram of the 3-mode HV power supply.

Considered as a unit, the pass regulator and converter function as an amplifier within the servo amplifier's feedback loop. When feedback is taken from the "voltage sense" network, a constant-voltage output is produced. Taking it from the "current sense" network results in a constant current through the load. Lastly, when inputs from the voltage-sensing and current-sensing networks are multiplied by the multiplier circuitry, the load receives constant power.

The pre-chopper maintains a small fixed voltage across the pass regulator regardless of inverter output setting. It does this by synchronously chopping the 120-Hz peaks from a full-wave rectifier in a manner similar to a lamp dimmer. This limits the pass regulator dissipation to an acceptable level. Had it not been done, dissipation would have been excessive, especially at low-voltage output settings.

Crowbarring prevents overload by shutting down the supply when it senses either too much current flowing in the load or a load dropout.

A Cook's tour of the circuit

Details of the circuit will now be discussed with the aid of a detailed schematic (**Fig. 2**). Looking at the SERVO AMPLIFIER section, reference stability results from using a 1N944B temperature-compensated zener diode (D7) with its output scaled to 10.000V across the Kelvin-Varley potentiometer. The potentiometer's output biases the 1023 FET amplifier A1 which functions as a precision servo amplifier. Its 20-pA bias current insures negligible loading error on the potentiometer. A1's output drives the Q6/Q7 pair, a 2N2102-2N3442 Darlington pass regulator, via the 2N2102 pull-down transistor Q5. Q7's collector is supplied dc power from the output of the prechopper, which will be described later. Q7's emitter drives the toroid transformer, T1.

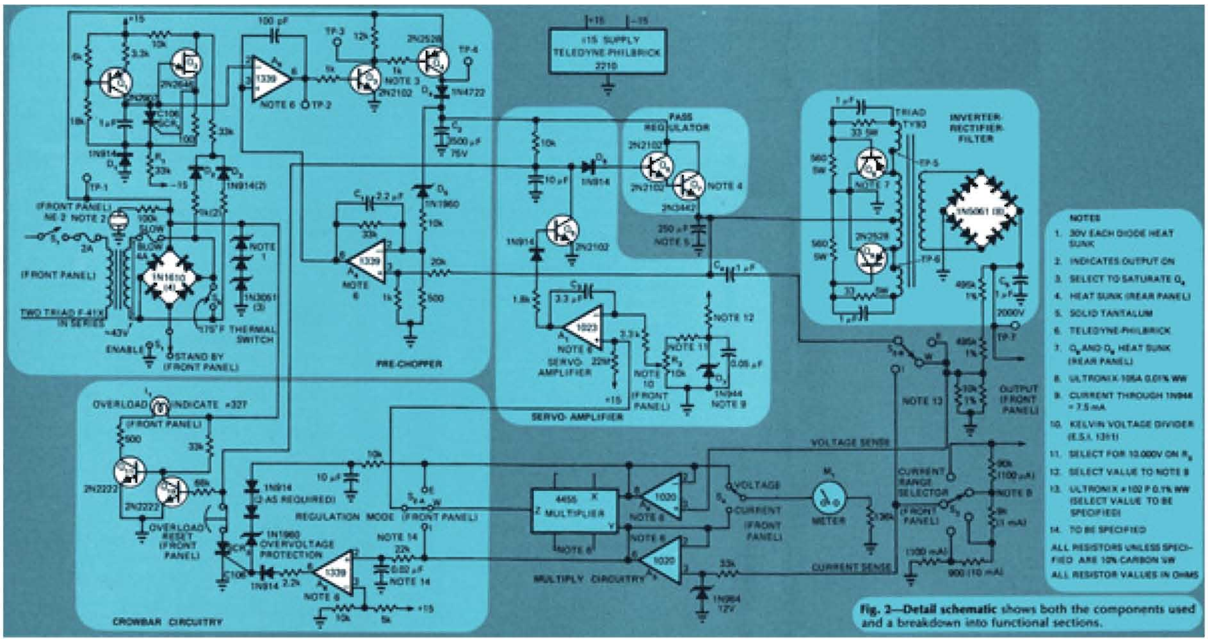


Fig. 2—Detail schematic shows both the components used and a breakdown into functional sections.

The wide dynamic range of the inverter is due to the 2N2528 transistors (Q8, Q9) that featured low saturation voltages, good beta linearity and reasonable speed. They permit the inverter to run at low output voltages with no resultant sacrifice in performance at high output potentials. Output of the transformer is rectified by a full-wave bridge employing two 1N5061,s in each leg. The stacking allows use of diodes rated at only 800V. Filtering, provided by the 1-vF capacitor, is adequate for the square-wave output.

Higher is better

Voltage feedback is derived by a 99 to 1 division of the filtered output. The current-feedback signal, on the other hand, is split into four separate switch-selectable ranges. This promotes ease of setting and keeps the current-feedback signal at high levels—and therefore easy to work with. The "shorting-switch" selection scheme insures feedback even during the switching operation.

Unity-gain followers, A2 and A3 convert the current and voltage signals to the low impedance needed to drive the 4455 multiplier. The impedance transformation also allows easy monitoring of the respective signals by a voltmeter or a multiplexing data-acquisition system. Switchable meter M1 provides a “ballpark” indication of the voltage or current at the load. A1 and A2 feed the multiplier, which provides the feedback signal for the power mode of operation. Regulation-mode switch S2 selects which feedback signal (E, W or I) is sent to servo amplifier A1, thereby determining the regulation mode of the instrument. R2, a 22 MO resistor, prevents the servo loop from running wild during the transient condition that exists when the mode switch is operated.

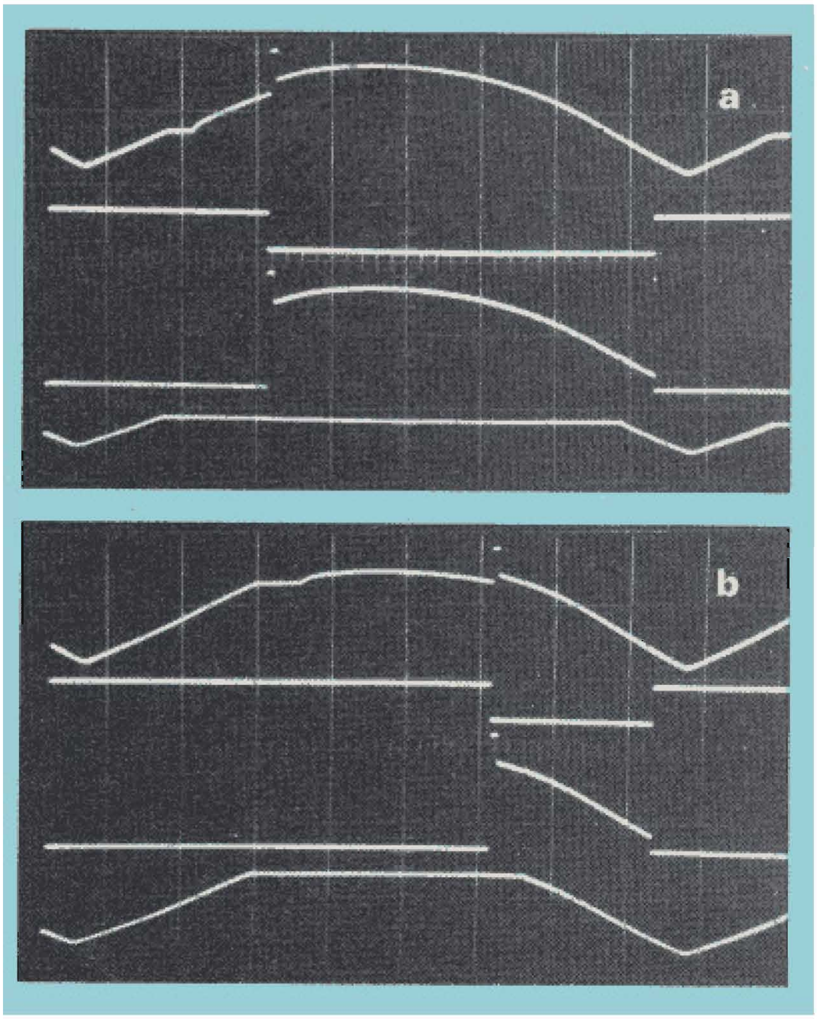


Fig. 3 —Pre-chopper waveforms at 4.2W output (a) and 42W output

(b) (taken with a 15 kO load on the supply output). Scope traces shown are at 50V/div. and 1 msec/div. In each picture the top waveform, taken at TP1, shows the 120-Hz output of the full-wave bridge. Note the spike created by flyback effect in the power transformer when the prechopper allows it to "let go." Spike amplitude would normally be about 150V, but the series string of three 30V zeners (1N3051) clips it to 90V. The second waveform, present at TP2, is that at the output of pulse-width modulator A5. The third waveform, taken at Q3's collector (TP3), shows how much of the 120-Hz waveform is not being utilized. At the bottom is the waveform present at TP4. The 1N4722 diode (D4) prevents Q4 from becoming reverse biased when the dc voltage on C2 is greater than that on Q4's emitter.

As might be suspected, the servo loop is very prone to oscillation. C3 and C4 were included to insure loop stability, but slow it down as well. Loop response is about 75 msec (no load to full load), so transient response clearly is not this circuit's forte.

Pre-chopper keeps a constant drop

The pre-chopper is essentially a servo that keeps the drop across pays transistor Q7 at a constant, low voltage, regardless of inverter demand conditions. This lowers dissipation and insures reliability. A4 looks differentially across the Q7 pass element. A4's negative input is biased through the 10V zener, D5, and its output voltage is compared to a 120-Hz line-synchronized ramp by amplifier, A5. This op amp functions as a pulsewidth modulator, and drives the Q3, Q4 combination that delivers phase-controlled power to C2 and the collector of Q7. Diode D4 insures that Q4 will not be reverse biased when the 120-Hz signal is below the dc across the capacitor.

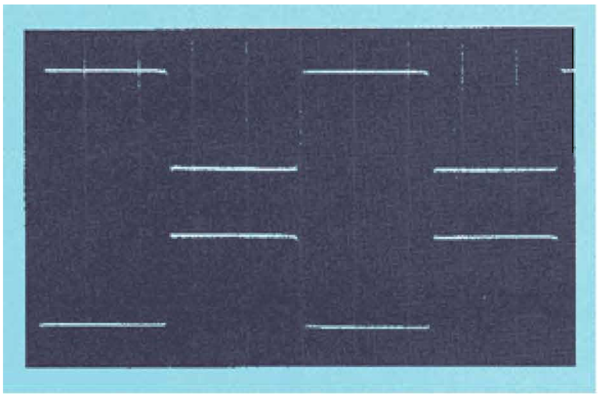


Fig. 4 —Inverter waveforms taken at TP5 and TP6 (the emitters of Q8 and Q9). Scope was set at 50V/div. Despite the high currents, the combination of suitable transistors and a well-designed transformer obviously yields clean waveforms containing a minimum of ringing or overshoot.

Since A4's negative input is routed through the 10V zener, Q7's emitter will always be 10V below the collector, despite the required inverter input power. This value, 10V, is low enough to keep dissipation down, yet high enough to insure good regulation characteristics.

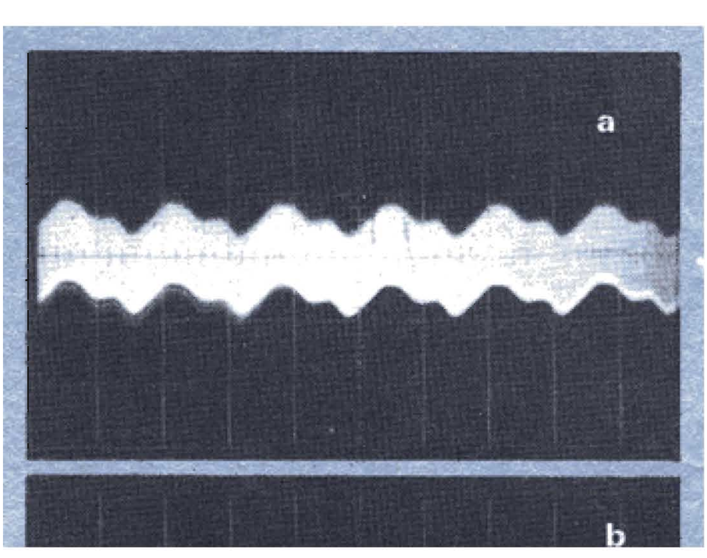
Loop inside a loop

The battle-scarred veterans among those reading this article will realize the unpleasant surprises that can be encountered by running a servo loop within a servo loop. Here, these embarrassments have been avoided by giving the pre-chopper slower response time than the main servo loop. C1, the 2.2-μF capacitor across A4, satisfies this condition.

The 120-Hz reference ramp arrives at A5 via the 2N2646 unijunction transistor Q2. Q2, in turn, is driven by Q1, the 2N2907 current source. SCR1, D1 and R1—which is connected to –15V—assure a true zero-volt reset for the ramp. D2 and D3 provide the synchronizing signal, which cannot be taken from the bridge rectifier because the bridge output waveform is heavily influenced by the phase angle at which Q8 and Q9 fire.

Carry a crowbar for protection

A 1339 amplifier (A6) helps protect the supply from excessive output current. The amplifier looks at the current-feedback signal and will swing its output to positive saturation if that signal exceeds 10V. In turn, SCR2 is triggered and grounds the inverter drive signal, resulting in a supply shutdown. The "overload indicate light (I1) will come on to alert the operator to the situation. To reset, the "overload reset" button is pressed, commutating the SCR and enabling the inverter to again receive bias. D6, a 1N914 in the base line of Q6, assures a clean turn-off when the SCR comes on.



Overvoltage protection is provided by D10, D9 and D8, the 10V zener diode and the 1N914's, which are connected between the "voltage" output signal and SCR2. This arrangement prevents the supply from running away in the event of a load dropout when in the "current°' or "power" regulation modes.

Preventing catastrophes

Physical layout of the supply is not critical except for the point grounding considerations common to any precision circuit. The inverter ground return (from Q8 and Q9 collectors) contains fast, high-current spikes and should be returned directly to supply common. Returns from the reference diode, its potentiometer and the amplifiers are also critical. They also should be connected directly to the supply ground.

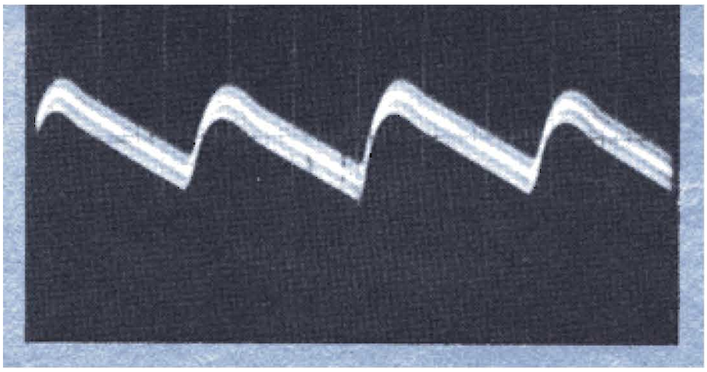


Fig. 5—Power-supply output noise is shown (at TP7) when the supply was delivering 750V into a 15 k? resistive load. In (a) the scope was calibrated to show the low-frequency residual pre-chopper noise (0.5V and 10 msec/div.), while in (b) the sweep speed was changed to 20 µsec/div. to clearly show the high-frequency noise (inverter frequency related).

Particularly insidious failures can result from a malfunction in the pre-chopper circuitry. As an example, assume an emitter-to-collector short in Q4. All of the 120-Hz waveform will then be supplied to the 3500-µF integrating capacitor, and the dc potential at Q7's collector will rise to maximum voltage. The power supply will, however, continue to function in an apparently normal fashion—that is, until Q7 achieves its molten state. This most unwelcome state of affairs is prevented by the 175°F thermal switch (S5) mounted next to Q7. Closing of the switch will blow the fuse at the transformer primary.

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A Highly Regulated, Recording Constant Power, Voltage, and Current Supply for Electrophoresis and Isoelectric Focusing

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A highly regulated (better than 0.01%) power supply of novel design is described for use in electrophoresis, isoelectric focusing, and isotachophoresis experiments. This new instrument provides constant voltage, current, and power output with recording capabilities at a low cost. The power supply has been used extensively in high precision scanning electrophoresis and isoelectric focusing procedures which require continuous monitoring of the applied electric field.

Recent experimental approaches to electrophoresis and isoelectric focusing (1–3) require a flexible, highly regulated power supply with recording capabilities. The instrument should be able to provide constant voltage, current, and power output with regulation better than 0.01%. Such a power supply built at a low cost (i.e., less than $500) could also find extensive applications in commonly practiced electrophoretic procedures.

Stable high voltage (500–1000 V) power supplies are available from several manufacturers. While these units feature good precision, they are unable to produce more than a few milliamperes of output current (usually 100–250 mA). These supplies are usually designed according to the series pass regulation scheme and utilize high voltage transistors or vacuum tubes as the pass element. As is well known, series pass configurations offer excellent regulation at the expense of efficiency due to their power dissipative nature. Conversely, switching regulation techniques yield efficiency at the cost of stability. Although *constant power* supplies are also commercially available (Ortec, Oak Ridge, Tenn.; Grainer, Milan, Italy; Isco, Lincoln, Nebraska; Medical Research Apparatus, Boston, Mass.; LKB, Rockville, Md.), these rely either on approximation methods such as pulse width control and time proportioning (pulsed power supplies) or on modifications of available circuitry (4,5) which results in compromises in performance. In addition, pulse-power supplies do not really provide constant power when operating at high load conditions such as those encountered in isoelectric focusing.

This paper describes a versatile high voltage power supply that combines the advantages of linear and switching technologies to produce a precision output at high current. This supply is adjustable from 50 to 1,000 V at up to 100 W output to better than 0.01% regulation. In addition, it will operate as a current source with up to 100 mA output with 0.01% stability. Finally, because this unit was also specifically designed for isoelectric focusing (which requires constant power dissipated in the load for optimum results) it will regulate power (EI product) to 0.01% stability at up to 100 W.

The combination of a hybrid circuitry approach and high performance circuit elements allow this precision 100-W supply to fit in a 3 × 14 × 19 in. unventilated rack mount chassis while using no high voltage semiconductors other than diodes. Recording output capabilities of current, voltage, and power have been incorporated.

Generalized Description

The instrument functions by controlling the input power to a toroidal dc–dc-converter with an operational amplifier (Fig. 1). One of the amplifier inputs is referenced to a precision variable voltage. The other input is connected, through suitable circuitry, to the output of the converter. The pass regulator and converter function as an amplifier within the op-amp's feedback loop. When the feedback is taken from the "voltage sense" network, a constant voltage output is produced. When the feedback comes from the "current sense" network, a constant current through the load results. When the "V" and "I" loops are multiplied

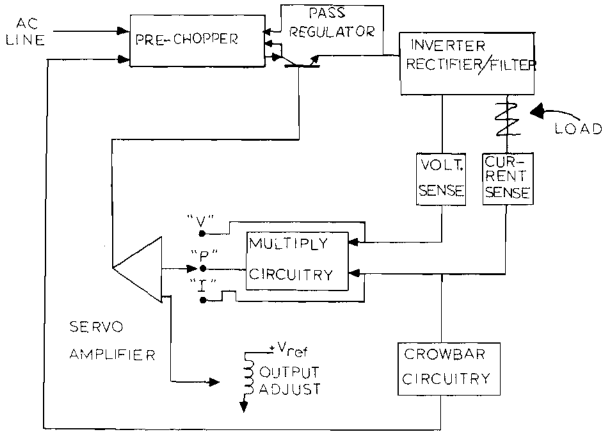


FIG. 1. Block diagram of the main power supply components.

by the multiplier module, the load receives constant power, especially at low voltage output settings.

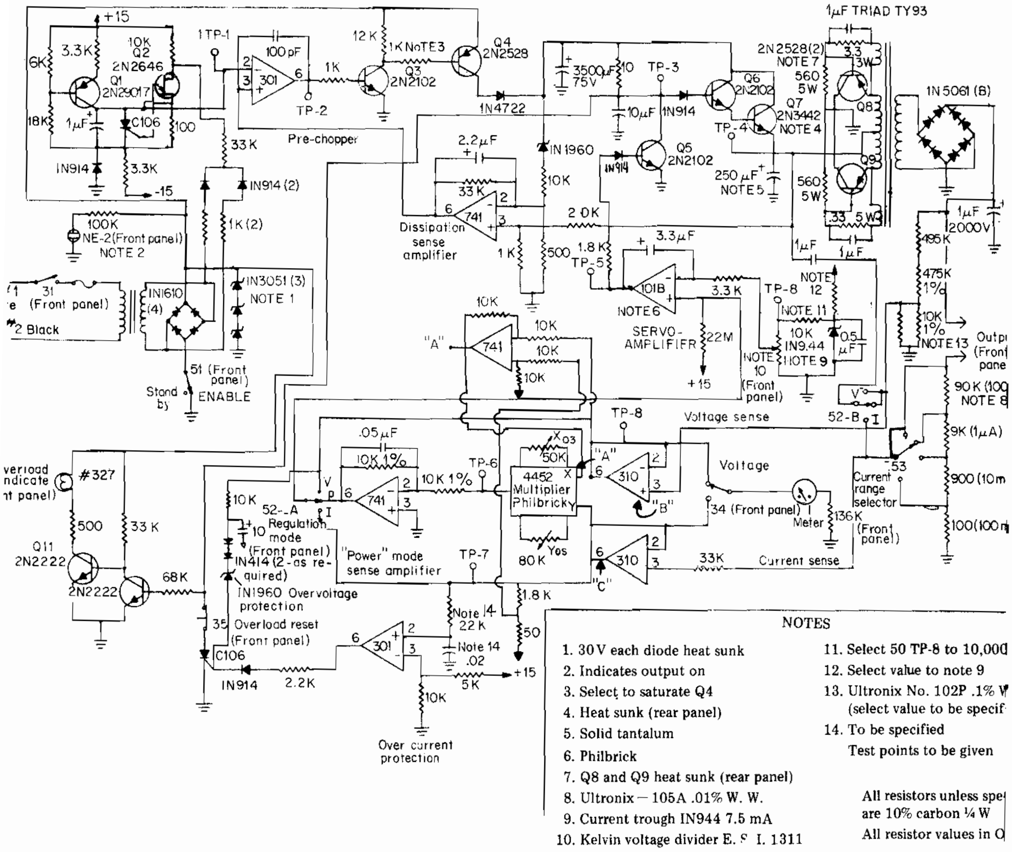
The overvoltage/overcurrent protection circuit prevents overload by shutting down the supply when it senses too much current flowing in the load. If the supply is either shorted or a load dropout occurs, the instrument will shut down nondestructively due to the overvoltage/overcurrent provisions.

Circuitry Discussion

The 1N944B temperature-compensated zener diode provides a stable reference voltage which is scaled to 10,000 V across the Kelvin–Varley potentiometer (Fig. 2). The 1018 amplifier is biased by the potentiometer's output and functions as a precision servo amplifier. Its 20 pA bias current ensures negligible loading error on the potentiometer. The 1018's output drives the 2N2102-2N3442 darlington pair via the 2N2102 pull down transistor. The 2N3442 collector is supplied dc power from the output of the prechopper which will be described. The transformer is driven from the 2N3442 emitter. The wide dynamic range of the inverter is due to the 2N2528 transistors which feature low saturation voltages, good beta linearity, and reasonable speed. These devices allow the inverter to run at low output voltages with no resultant sacrifice in performance at high output potentials.

The transformer output is rectified by the 1N5061's in a bridge. The diodes are stacked two to each leg because of their 800-V rating. Filtering is provided by the 1-μf capacitor which is adequate for the square wave output. The filtered output is divided by a 99 to 1 ratio to provide the voltage feedback signal. The current feedback signal is split into four separate panel switch-selectable ranges. This promotes ease of setting and keeps the current feedback signal at high levels making it easy to work with. The "shorting" switch-selection scheme is used to preclude a transient absence of feedback when the current range selector switch is operated.

The current and voltage signals are unity gain followed by the 310 amplifiers because the input resistance of the multiplier is low. The impedance transformation also allows easy monitoring of the respective signals by a voltmeter or (as is the case in the system this unit was designed for) a multiplexing data acquisition system. A switchable meter is provided to give a "ballpark" indication of the voltage or current at the load. The 310 followers feed the 4455 multiplier which provides the wattage feedback signal. The "regulation mode" switch selects which feedback signal, "E", "I", or "P", is sent to the 1018 servo amplifier, thereby determining the regulation mode of the instrument. The 22-Meg. resistor prevents the servo loop from "running wild" during the transient "no signal" condition which exists when the regulation mode switch is used.



NOTES

1. 30V each diode heat sunk
2. Indicates output on
3. Select to saturate Q4
4. Heat sunk (rear panel)
5. Solid tantalum
6. Philbrick
7. Q8 and Q9 heat sunk (rear panel)
8. Ultronix — 105A .01% W. W.
9. Current trough IN944 7.5 mA
10. Kelvin voltage divider E. S I. 1311
11. Select 50 TP-8 to 10,000
12. Select value to note 9
13. Ultronix No. 102P .1% W (select value to be specif
14. To be specified

Test points to be given

All resistors unless spe are 10% carbon ¼ W

All resistor values in O

FIG. 2. Schematic diagram of the power supply.

As might be suspected, the loop is very prone to oscillation. Stable loop compensation is effected by the 0.33-μf capacitor at the 1018 and the 1-μf capacitor that runs between the 2N3442 emitter to the switch-selected sense line. Loop response is about 75 msec (no load to full load); plainly transient response is not this circuit's forte.

The prechopper is essentially a servo which keeps the voltage across the 2N3442 pass transistor at a constant low voltage regardless of inverter demand conditions. This keeps dissipation down and ensures reliability. The 301A looks differentially across the 2N3442 pass element. The negative input is biased through a 10-V zener diode. The 301A output voltage is compared to a 120-Hz line synchronized ramp by another 301A amplifier. This 301A functions as a pulse-width modulator and drives the 2N2102-2N2528 switch which delivers phase-controlled power to the

3500-μf filter capacitor and the 2N3442 collector. The diode ensures that the 2N2528 will not be reverse biased when the 120 Hz signal is below the D.C. value across the capacitor. Since the 301A negative input is looking through the 10-V zener diode, the 2N3442 emitter will always be 10 V below the collector despite the required inverter input power. This voltage (10 V) is low enough to keep dissipation down but high enough to ensure good regulation characteristics. The unpleasant surprises that can be affected by running a servo loop within a servo loop can be avoided by giving the prechopper a slower response time than the main servo loop. This condition is satisfied by the 2.2-μf capacitor across the 301A. The 120-Hz reference ramp arrives via the 2N2646 unijunction transistor which is driven by the 2N2907 current source. The SCR, 1N914, and the 3.3K resistor to −15 assure a true zero-volt reset for the ramp. The 120-Hz synchronizing signal is derived through the 1N914 diodes. The synchronizing signal cannot be derived from the bridge rectifier because the bridge output waveform is heavily influenced by the phase angle the 2N2528 switch fires at.

The output of the supply is protected against excessive current drain by the 301A amplifier. This 301A looks at the current feedback signal and will swing its output to positive saturation if the current signal exceeds 10 V. This will trigger the C106 SCR which grounds the inverter drive signal, resulting in a supply shutdown. The "overload indicate" light will come on to alert the operator to the situation. When the "overload reset" button is pressed, the SCR is commutated and the inverter is again able to receive bias. The 1N914 in the 2N2102 base line assures a clean turn-off when the SCR comes on.

General Remarks

The physical construction of the supply is not critical except for the usual point grounding considerations in any precision circuit. The inverter ground return contains fast, high current spikes and should be returned directly to supply common. Returns from the reference diode and its potentiometer are also critical as are amplifier grounds.

A particularly insidious failure mode is possible with a malfunction in the prechopper circuitry. Assume that Q3 or Q4 shorts emitter to collector. All of the 120-Hz waveform will then be supplied to the 3500-μf integrating capacitor. This will cause the D.C. potential at Q7's collector or rise to maximum voltage. The instrument will, however, continue to function in an apparently normal fashion until Q7 achieves its molten state. This most unwelcome state of affairs is prevented from occuring by the 175°F thermal switch mounted next to Q7. When the switch closes, it will blow the fuse at the transformer.

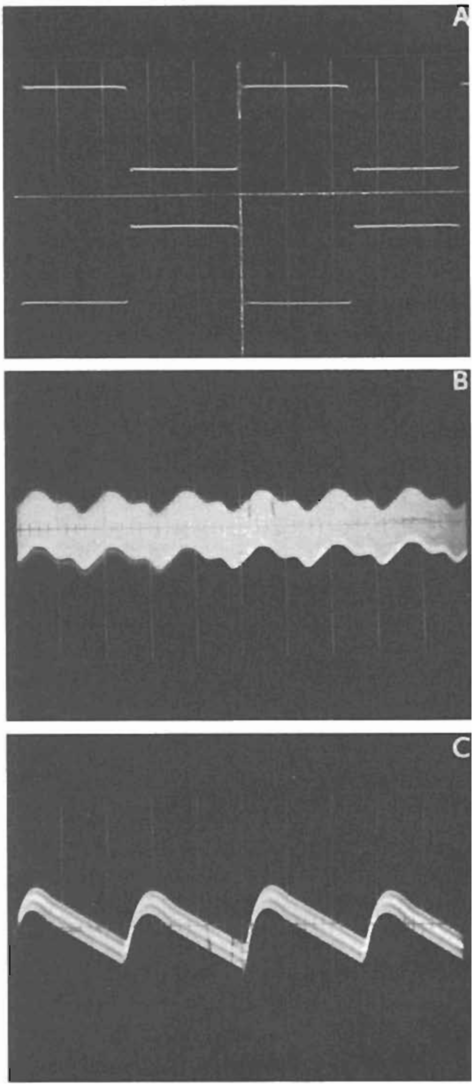


FIG. 3. Inverter and output noise waveforms: (a) 50 V/div; 50 μsec/div; (b) 0.5 V/div; 10 msec/div; (c) 0.5 V/div; 20 μsec/div. B and C were taken at 750 V output.

Instrument Performance

Figure 3A depicts typical patterns of inverter waveforms taken at the 2N2525 emitters. Despite the high current, the combination of good transistors and a well designed transformer yield clean waveforms with almost no overshoot or ringing. Figures 3B and 3C illustrate power supply output noise characteristics. The low frequency noise component (Fig. 3B) is residual prechopper noise, whereas the high frequency noise

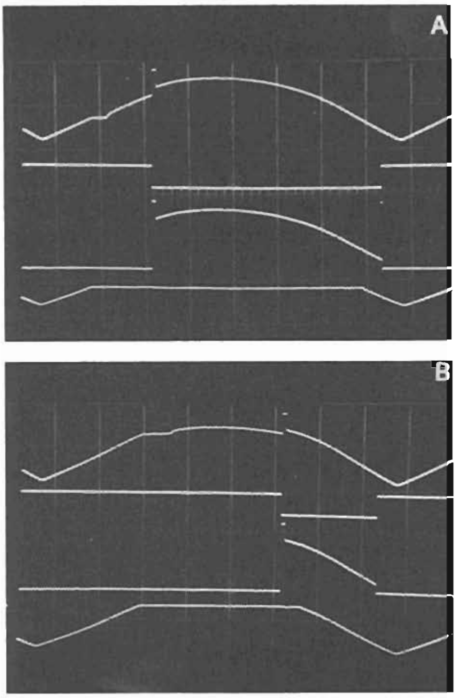


FIG. 4. Prechopped waveforms at two different supply outputs: (a) 4.2 W output; (b) 4.2 W output-scale: 50 V/div, 1 msec/div.

(Fig. 3C) is inverter-frequency related. The prechopper waveforms shown in Fig. 4 were obtained with a 15K load at the supply output. Top waveform is 120 Hz out of the full wave bridge. Note the spike created by flyback effect in the power transformer when the pre-chopper allows it to "let go". The spike would normally rise to 150 V, but it is chopped by the 90-V zener (three 30-V zeners in series) at the bridge output. The second waveform is the 301A pulse-width modulator output. The third waveform is taken at the Q3's collector and clearly shows how much of the 120-Hz waveform is being utilized. The last trace is taken at the 2N2528 collector (anode of the 1N4722 diode). The cathode of the diode is at a pure D.C. potential. The diode prevents the Q4 from becoming reverse biased when the charge on the 3500-μf capacitor is greater than the Q4's emitter voltage.

Table 1 shows typical teletype recorded outputs of voltage, current, and power as a function of time under different dummy loads and modes of operation. Note the exceptional stability over long periods of time of the voltage, current, and power outputs. It should be pointed out that despite the fact that the load changed by approximately a factor of 5 or 6, the power changed by an incredibly small one part in 2000. The power

TABLE 1

SAMPLE DIGITAL OUTPUT[a] OF CURRENT, VOLTAGE, AND POWER AS A FUNCTION OF TIME

Mode	Approximate load (ohm × 10^{-6})	Time (sec × 10^{-4})	Voltage (V)	Current (A × 10^{6})	Power[b] (W × 10^{3}) A	B	C	D
Constant voltage	3.30	1	191.0	55.9	8.3	10.6	11.4	−0.8
	3.30	2	191.0	55.8	7.8	10.6	10.9	−0.3
	2.20	3	191.0	86.6	13.0	16.5	16.1	+0.4
	2.20	4	191.0	86.3	13.4	16.4	16.6	−0.2
	1.50	5	191.0	124.2	19.9	23.7	23.3	+0.4
	1.50	6	191.0	122.8	19.5	23.4	22.8	+0.6
	1.00	7	191.0	197.5	33.8	37.7	37.5	+0.2
	1.00	8	191.0	203.3	35.0	38.8	38.7	+0.1
	0.68	9	191.0	321.1	57.5	61.3	61.8	−0.5
	0.68	10	191.0	319.2	56.6	60.9	60.8	+0.1
Constant current	3.30	1	558.3	191.0	104.2	106.6	106.3	+0.3
	3.30	2	558.4	191.0	104.2	106.6	106.3	+0.3
	2.20	3	374.4	190.9	68.9	71.4	71.9	−0.5
	2.20	4	375.1	191.0	68.8	71.5	71.8	−0.2
	1.50	5	264.2	191.0	47.4	50.4	50.9	−0.5
	1.50	6	264.6	190.9	47.6	50.5	51.0	−0.5
	1.00	7	178.7	190.9	30.6	34.3	34.5	−0.2
	1.00	8	179.9	190.9	30.6	34.3	34.5	−0.2
	0.68	9	122.6	190.9	19.4	23.4	23.5	−0.1
	0.68	10	124.5	190.9	19.5	23.7	23.6	+0.1
Constant power	3.30	1	733.4	263.6	191.0	193.3	193.1	+0.2
	3.30	2	733.5	263.7	191.0	193.4	193.1	+0.3
	2.20	3	595.4	325.3	191.0	193.6	193.1	+0.5
	2.20	4	596.0	325.0	191.0	193.7	193.1	+0.6
	1.50	5	498.8	389.0	191.0	194.0	193.1	+0.9
	1.50	6	499.4	387.7	191.0	193.6	193.1	+0.5
	1.00	7	397.4	487.8	191.0	193.8	193.1	+0.7
	1.00	8	396.0	487.0	191.0	192.8	193.1	−0.3
	0.68	9	322.3	594.5	191.0	191.6	193.1	−1.5
	0.68	10	321.3	596.6	191.1	191.6	193.1	−1.5

[a] Recorded on a 33 ASR teletype through an AD converter/multiplexer interface.

[b] Column A, recorded value; B, estimated from the product of the recorded voltage and current; C, corrected A values (see text); D = B − C.

can be read directly from its output channel (through the multiplier) with an error of approximately 3 to 5 mW, or it can be computed from data of the product of the recorded output of current and voltage to a precision better than 0.5 mW. The computations are performed as follows. For the constant voltage or current mode, linear regression analysis is carried out using the recorded power value (X_{obs}) and the computed (EI) power value (Y_{obs}) to obtain the corrected power values W_v and

W_i corresponding to constant voltage and constant current conditions, respectively. The regression equations are:

$$W_v = (1.024)\,X_{\text{obs}} + 2.868 \qquad (r = 0.9995)$$

$$W_i = (0.976)\,X_{\text{obs}} + 4.592 \qquad (r = 0.9998)$$

For constant power conditions, the mean value of the computed power (EI) is used.

This high-precision power supply has been used successfully for more than 6 months in this laboratory in various electrophoresis and isoelectric focusing experiments. The recorded output routinely filed with the protocol of each experiment has been extremely helpful in the interpretation of results and in experimental troubleshooting.

ACKNOWLEDGMENT

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Application Briefs

HIGH-RESOLUTION SCALE

Measures up to 250 lb ±0.01 lb

Detects a Single Bite of Food

by James Williams

At the M.I.T. Nutrition & Food Science Instrumentation Laboratory, a scheme that is straightforward in concept but exacting in execution has resulted in the development of a scale that is both accurate (needing no calibration long-term) and able to measure small increments of weight gain or loss (such as intake of food or loss of water through perspiration).

A carefully-designed nonlinear filter permits large changes of weight to be stably registered within 5 seconds, small changes within one second, and fast disturbances, such as body motions or the pulsation of blood with each heartbeat, to be rejected. (Interestingly, the raw measurement voltage can be filtered by a different scheme to provide a "ballistocardiographic" measure of pulse rate without any electrical connections to the subject*.)

As Figure 1 shows[1], the system consists of a high-linearity temperature-compensated bridge – excited by a floating 10.000V reference supply, a noninverting chopper-preamplifier, a level-controlled filter, and an AD2025† 4¾-digit panel meter that permits weight to be read directly up to the system maximum of 250.00 lb, with a resolution of 0.01 lb (4.5g).

The weighing platform is supported by four symmetrically-disposed bonded strain gages, in a bridge configuration. The linearized low-level output is 15mV full-scale; 600nV (600×10^{-9} V) corresponds to 0.01 lb. To eliminate calibrations after installation the excitation voltage is based on a selected 1N829A that has been aged for 2500 hours, running at a precisely maintained constant current, and buffered from the ~100Ω load by a boosted AD504† low-drift op amp.

The bridge output, amplified by a 261† non-inverting chopper amplifier, is applied to a nonlinear filter that combines rapid slewing for weights greater than 4 lb. with a 1s-time-constant filter applied to small noise signals.

Because of the low levels, attention to grounding, shielding, and careful component selection are essential in order to obtain the specified performance of absolute accuracy to within 0.02% (0.05 lb.), repeatability and sensitivity of 40 ppm (0.01 lb.), operating temperature range 20° – 30°C, and no field adjustments.

▶▶▶

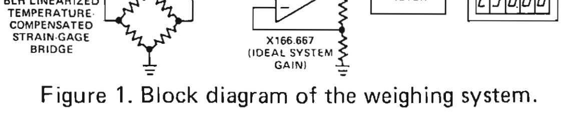

Figure 1. Block diagram of the weighing system.

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[1] The system is described in greater detail in an article appearing in EDN magazine (October 5, 1976, Vol. 21, No. 18).

*Patent applied for.

†For information on ADI products, use the reply card.

Application Briefs

HIGH-RESOLUTION SCALE

Measures up to 250 lb ±0.01 lb Detects a Single Bite of Food

by James Williams

At the M.I.T. Nutrition & Food Science Instrumentation Laboratory, a scheme that is straightforward in concept but exacting in execution has resulted in the development of a scale that is both accurate (needing no calibration long-term) and able to measure small increments of weight gain or loss (such as intake of food or loss of water through perspiration).

A carefully-designed nonlinear filter permits large changes of weight to be stably registered within 5 seconds, small changes within one second, and fast disturbances, such as body motions or the pulsation of blood with each heartbeat, to be rejected. (Interestingly, the raw measurement voltage can be filtered by a different scheme to provide a "ballistocardiographic" measure of pulse rate without any electrical connections to the subject*.)

As Figure 1 shows[1], the system consists of a high-linearity temperature-compensated bridge – excited by a floating 10.000V reference supply, a noninverting chopper-preamplifier, a level-controlled filter, and an AD2025† 4¾-digit panel meter that permits weight to be read directly up to the system maximum of 250.00 lb, with a resolution of 0.01 lb (4.5g).

The weighing platform is supported by four symmetrically-disposed bonded strain gages, in a bridge configuration. The linearized low-level output is 15mV full-scale; 600nV (600×10^{-9} V) corresponds to 0.01 lb. To eliminate calibrations after installation the excitation voltage is based on a selected 1N829A that has been aged for 2500 hours, running at a precisely maintained constant current, and buffered from the ~100Ω load by a boosted AD504† low-drift op amp.

The bridge output, amplified by a 261† non-inverting chopper amplifier, is applied to a nonlinear filter that combines rapid slewing for weights greater than 4 lb. with a 1s-time-constant filter applied to small noise signals.

Because of the low levels, attention to grounding, shielding, and careful component selection are essential in order to obtain the specified performance of absolute accuracy to within 0.02% (0.05 lb.), repeatability and sensitivity of 40 ppm (0.01 lb.), operating temperature range 20° – 30°C, and no field adjustments. ▶▶▶

Figure 1. Block diagram of the weighing system.

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[1] The system is described in greater detail in an article appearing in EDN magazine (October 5, 1976, Vol. 21, No. 18).

*Patent applied for.

CIRCUITRY FOR HIGH SPEED AMPLIFIERS

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In many applications a practical high speed amplifier must provide output drive and good DC stability. Combining these attributes in a monolithic design is difficult, although they are achievable in a multi-chip design.

Figure 1 shows a good example. Here the LT1022, a 23V/µs, 8.5MHz gain-bandwidth unit, is combined with an LT1010 buffer for good speed and high output power.

The LT1010 permits ±150mA drive into resistive or complex loads while maintaining dynamic stability. Slew rate and bandwidth are dictated by the LT1022. DC offset, also set by the LT1022, is 250 microvolts with a drift of 5 microvolts/°C.

Figure 2 shows a simple way to get even better DC performance while maintaining the LT1022's speed.

The overall circuit is a unity gain inverter, with the summing node located at the junction of three 10K resistors. The LT1012 monitors this summing node, compares it to ground and drives the LT1022's positive input, completing a DC stabilizing loop around the LT1022. The 10K-300pF time constant at the LT1012 limits its response to low frequency signals. The LT1022 handles high frequency inputs while the LT1012 stabilizes the DC operating point. The 4.7K-220Ω divider at the LT1022 prevents excessive input overdrive during start-up. This circuit combines the LT1012's 35µV offset and 1.5V/°C drift with the LT1022's 23V/µs slew rate and 300KHz full power bandwidth. Bias current, dominated by the LT1012, is about 100pA.

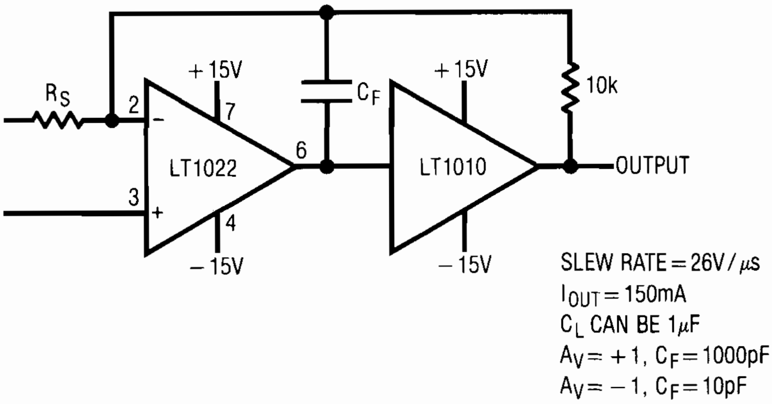


Figure 1. Fast, High Power Output Amplifier

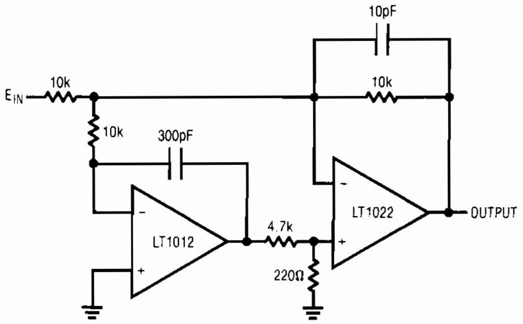


Figure 2. DC Stabilized Fast Amplifier

Figure 3 is similar, but uses discrete FETs to more than triple the speed. Here A1's input stage is turned off by connecting its inputs to the negative rail. The differentially connected FETs bias the second stage via A1's offset pins. This connection replaces A1's input stage, reducing bias current and increasing speed. FET mismatch would normally result in excessive offset and drift. A2 corrects this by monitoring the summing point (the junction of the two 4.7K resistors) and forcing Q2's gate to eliminate overall offset. The 10K-1000pf pair limits A2's response to low frequency, and the 1K divider chain prevents overdrive to Q2 on start-up. The 1K-10pf damper at the summing node aids high frequency stability. Figure 3 shows pulse response. Trace A is the input and Trace B the output. Slew rate exceeds 100V/μs, with clean damping. Full power bandwidth is about 1MHz, and input bias current is in 100 picoamp range. DC offset and drift are similar to Figure 2.

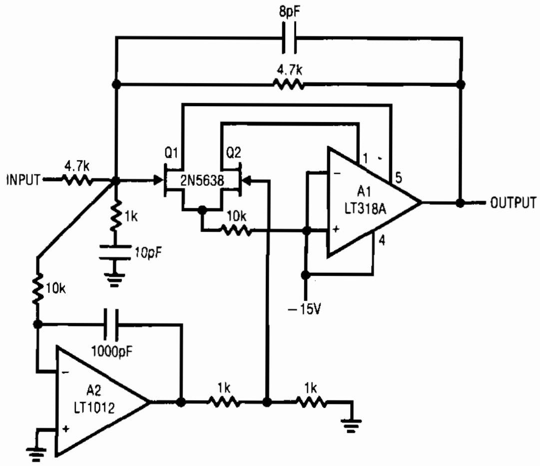


Figure 3. Fast DC Stabilized FET Amplifier

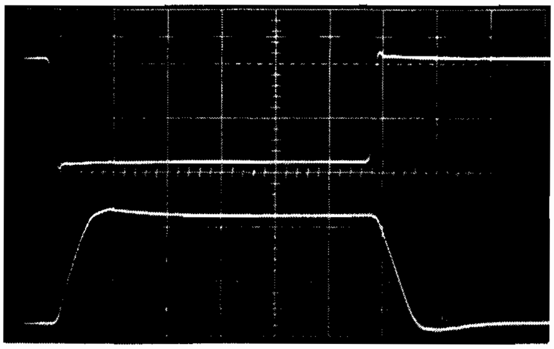


Figure 4. Figure 3's Waveforms

Figure 5 shows a highly stable unity gain buffer with good speed and high input impedance. Q1 and Q2 constitute a simple, high speed FET input buffer. Q1 functions as a source follower, with the Q2 current source load setting the drain-source channel current. The LT1010 buffer provides output drive capability for cables or whatever load is required. Normally, this open loop configuration would be quite drifty because there is no DC feedback. The LTC1052 contributes this function to stabilize the circuit. It does this by comparing the filtered circuit output to a similarly filtered version of the input signal. The amplified difference between these signals is used to set Q2's bias, and hence Q1's channel current. This forces Q1's V_{GS} to whatever voltage is required to match the circuit's input and output potentials. The 2000pf capacitor at A1 provides stable loop compensation. The RC network in A1's output prevents it from seeing high speed edges coupled through Q2's collector-base junction. A2's output is also fed back to the shield around Q1's gate lead, bootstrapping the circuit's effective input capacitance down to less than 1pf.

The LT1010's 15MHz bandwidth and 100V/μs slew rate, combined with its 150mA output, are fast enough for most circuits. For very fast requirements, the alternate discrete component buffer shown will be useful. Although its output is current limited at 75mA, the GHz range transistors employed provide exceptionally wide bandwidth, fast slewing and very little delay. Figure 6 shows the LTC1052 stabilized buffer circuit's response using the discrete stage. Response is clean and quick, with delay inside 4ns. Slew exceeds 2000V/μs with full power bandwidth approaching 50MHz. Note that rise time is limited by the pulse generator and not the the circuit. For either stage, offset is set by the LTC1052 at 5μV, with gain about 0.95.

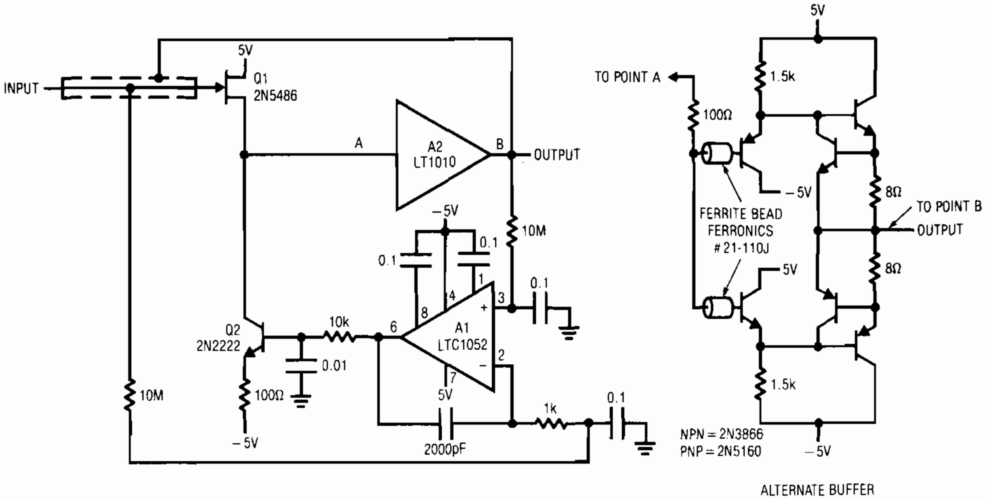


Figure 5. Wideband FET Input Stabilized Buffer

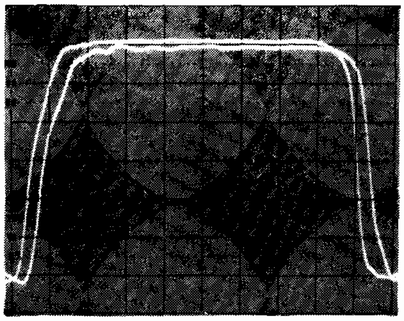


Figure 6. Figure 5's Waveforms

A potential difficulty with Figure 5's circuit is that the gain is not quite unity. Figure 7 maintains high speed and low bias while achieving a true unity gain transfer function.

This circuit is somewhat similar to Figure 5, except that the Q2-Q3 stage takes gain. A2 DC stabilizes the input-output path, and A1 provides drive capability. Feedback is to Q2's emitter from A1's output. The 1K adjustment allows the gain to be precisely set to unity. With the LT1010 output stage slew and full power bandwidth (1Vp-p) are 100V/ s and 10MHz, respectively. -3dB bandwidth exceeds 35MHz. At A=10 (e.g., 1K adjustment set at 50Ω) full power bandwidth stays at 10MHz while the -3dB point falls to 22MHz.

With the optional discrete stage, slew exceeds 1000V/µs and full power bandwidth (1Vp-p) is 18MHz. -3dB bandwidth is 58MHz. At A=10, full power is available to 10MHz, with the -3dB point at 36MHz.

Figures 8A and B show response with both output stages. The LT1010 is used in Figure 8A (Trace A=input, Trace B=output). Figure 8B uses the discrete stage and is slightly faster. Either stage provides more than adequate performance for driving video cable or data converters, and the LT1012 maintains DC stability under all conditions.

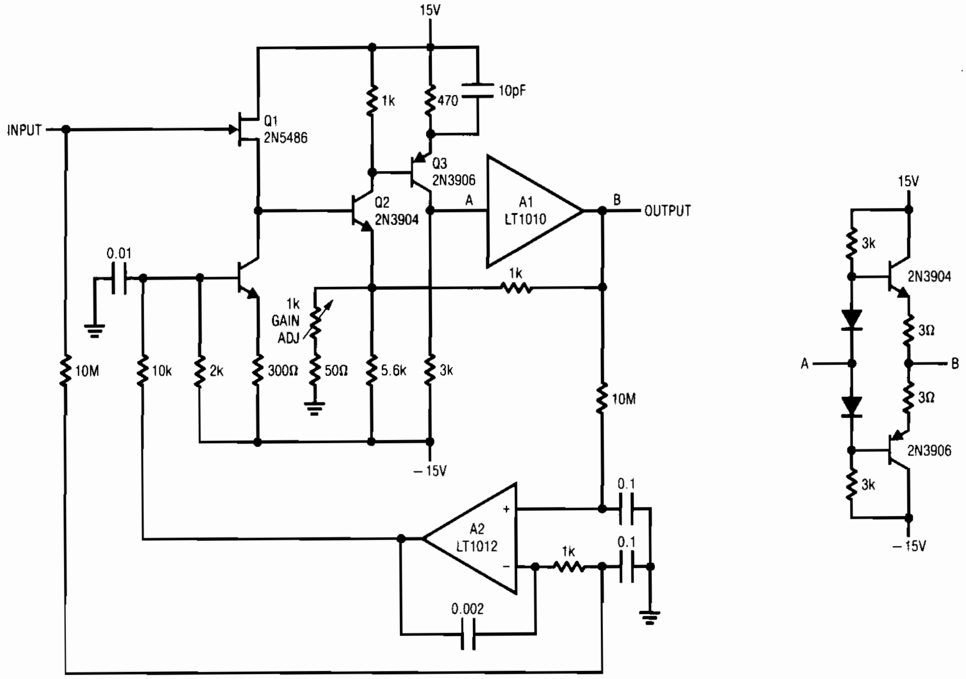


Figure 7. Gain Trimmable Wideband FET Amplifier

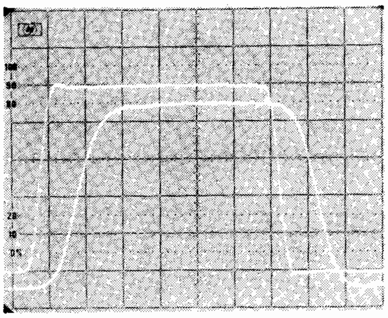


Figure 8A. Figure 6's Waveforms Using LT1010

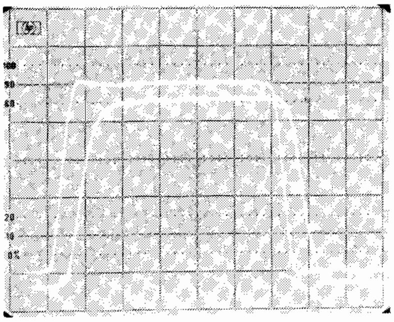
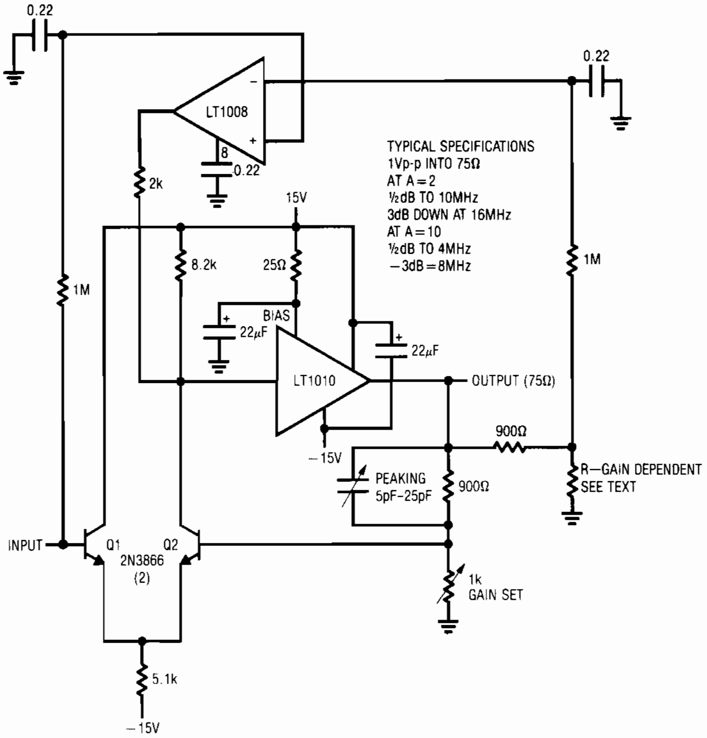


Figure 8B. Figure 6's Waveforms Using Discrete Stage



TYPICAL SPECIFICATIONS
1Vp-p INTO 75Ω
AT A=2
½dB TO 10MHz
3dB DOWN AT 16MHz
AT A=10
½dB TO 4MHz
−3dB=8MHz

Figure 9. Fast, Stabilized Non-Inverting Amplifier

Figure 9 is another DC stabilized fast amplifier which functions over a wide range of gains (typically 1-10). It combines the LT1010 and a fast discrete stage with an LT1008 based DC stabilizing loop. Q1 and Q2 form a differential stage which single-ends into the LT1010. The circuit delivers 1Vp-p into a typical 75Ω video load. At A=2, the gain is within 0.5dB to 10MHz with the -3dB point occurring at 16MHz. At A=10, the gain is flat (±0.5dB to 4MHz) with a -3dB point at 8MHz. The peaking adjustment should be optimized under loaded output conditions.

Normally, the Q1-Q2 pair would be quite drifty, but the LT1008 corrects for this. This correction stage is similar to the one in Figures 5 and 7, except that the feedback is taken from a divided down sample of the fast amplifier. The ratio of this divider should be set to the same value as the circuits closed loop gain. Frequency roll-off of this stage is set by the 1M-.022μf filters in the LT1008's input lines. The 0.22μf capacitor at the amplifier eliminates oscillations. The DC loop servo controls drift by biasing the DC operating point of Q2's collector to force zero error between the LT1008's inputs.

This is a simple stage for fast applications where relatively low output swing is required. Its 1 volt p-p output works nicely for video circuits. A possible problem is the relatively high bias current, typically 10μA. Additional swing is possible, but more circuitry is needed.

Figure 10's circuit addresses these issues. It trades speed for output swing and reduced bias current. As before, a separate loop maintains DC stability. This circuit is a good example of an approach made practical by composite techniques. Without the separate stabilizing loop, the DC imbalances in the signal path would preclude any level of operation.

In this arrangement a PNP level shifting stage (Q4) has been added to Figure 9's circuit to increase available swing at the LT1010 output. This is obtained at the expense of available bandwidth and amplifier stability. The 33pf capacitor from Q4's collector to the circuits summing note (Q3's gate) affords stable loop compensation. Figure 9's bias current errors are eliminated by Q3, an FET source follower. This device buffers the summing point from the relatively high bias current required by Q2. Normally, this configuration would cause volts of offset, due to Q3's gate-source voltage. Here, A1 closes a DC restoration loop, forcing Q1's base to whatever point is required to compensate for the offset. Thus, A1's operation not only provides low DC error but permits a simplistic approach to minimizing summing point bias current. Figure 11 shows operating waveforms for a 10 volt output. Trace A is the input, while Trace B is the output. Slew rate is about 100V/µs, with a full power bandwidth of 1MHz. The LT1010 allows 100mA outputs and makes cable driving practical at these speeds.

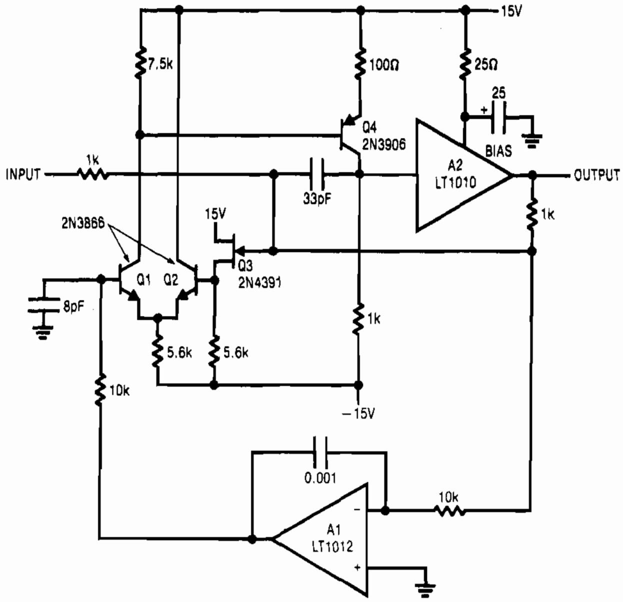


Figure 10. Fast, Stabilized Inverting Amplifier with Low Summing Point Bias Current

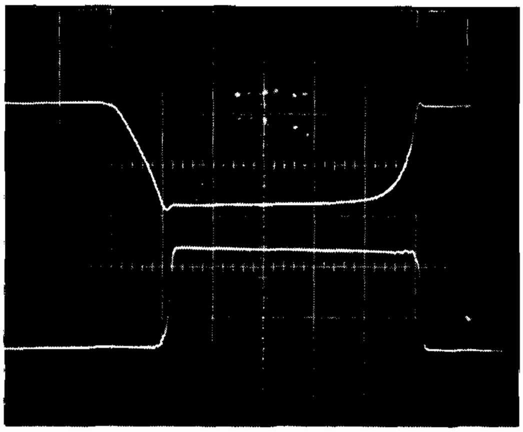


Figure 11. Figure 10's Pulse Response

Figure 12 shows another fast stage with wide output swing. The circuit is non-inverting, and has higher input impedance than Figure 10. Additionally, it's operation is based on an arrangement commonly referred to as "current mode" feedback. This technique, well established in RF design and also employed in some monolithic instrumentation amplifiers, permits fixed bandwidth over a wide range of closed loop gains. This contrasts with normal feedback schemes, where bandwidth degrades as closed loop gain increases.

The overall amplifier is composed of two LT1010 buffers and a gain stage, Q1 and Q2. A3 acts as a DC restoration loop. The 33 ohm resistors sense A1's operating current, biasing Q1 and Q2. These devices furnish complementary voltage gain to A2, which provides the circuit's output. Feedback is from A2's output to A1's output, which is a low impedance point.

A3's stabilizing loop compensates large offsets in the signal path, which are dominated by mismatch in Q1 and Q2. Correction is implemented by controlling the current through Q3, which shunts Q2's base bias resistor. Adequate loop capture range is assured by deliberate skewing of Q1's operating point via the 330 ohm unit. The 9K-1K feedback divider feeding A3 is selected to equal the gain ratio of the circuit, in this case 10.

The feedback scheme makes A1's output look like the negative input of the amplifier, with closed loop gain set by the ratio of the 470 and 51 ohm resistors. The outstanding feature of this connection is that bandwidth becomes relatively independent of closed loop gain over a reasonable range. For this circuit, full power bandwidth remains at 1MHz over gains of 1 to about 20. The loop is quite stable, and the 15pf value at A2's input provides good damping over a wide range of gains. The LT1010 buffers limit bandwidth in this circuit. Dramatic speed improvement is possible if they are replaced by discrete stages.

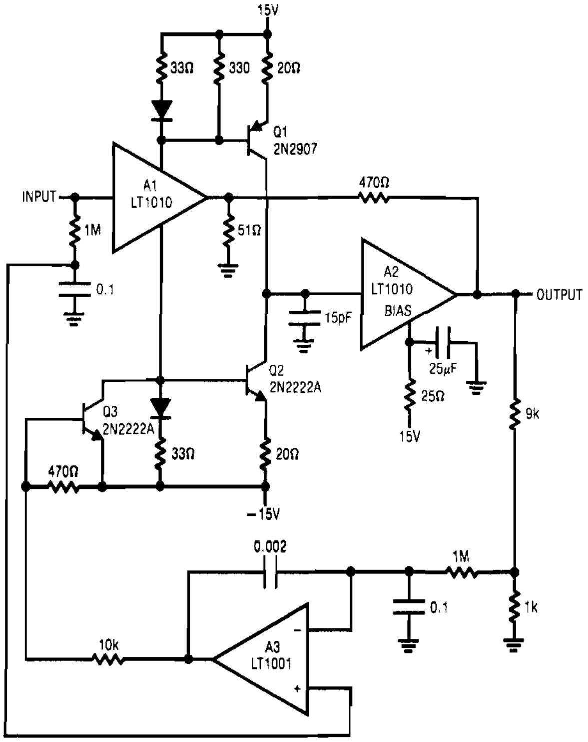


Figure 12. "Current Mode Feedback" Amplifier

Figure 13 substitutes discrete elements for Figure 12's LT1010s. Although this arrangement is substantially more complex, it provides an extraordinarily wideband amplifier. This composite design is composed of three amplifiers; the discrete wideband stage, a quiescent current control amp and an offset servo. Q1-Q4 replace Figure 12's A1, although complementary voltage gain is taken at the collectors of Q3 and Q4. Q5 and Q6 provide additional gain, similar to Q1 and Q2 in Figure 12. Q7-Q10 form the output buffer stage. The feedback scheme is identical to Figure 11's, with summing action at the Q3-Q4 emitter connection. To obtain maximum bandwidth, quiescent current is quite high. Without closed loop control, the circuit will quickly go into thermal runaway and destroy itself. A1 provides the required servo control of quiescent current. It does this by sampling a resistively divided version of the voltage across Q5's emitter resistor and comparing it to a power supply derived reference. A1's output biases Q4, completing a loop which forces fixed current through Q5. This action effectively controls overall quiescent current in the discrete stage. Simultaneously, A2 corrects for offset by forcing Q3's base to equalize the DC input and output values at the discrete stage. Because the closed loop gain is set at 10 (470

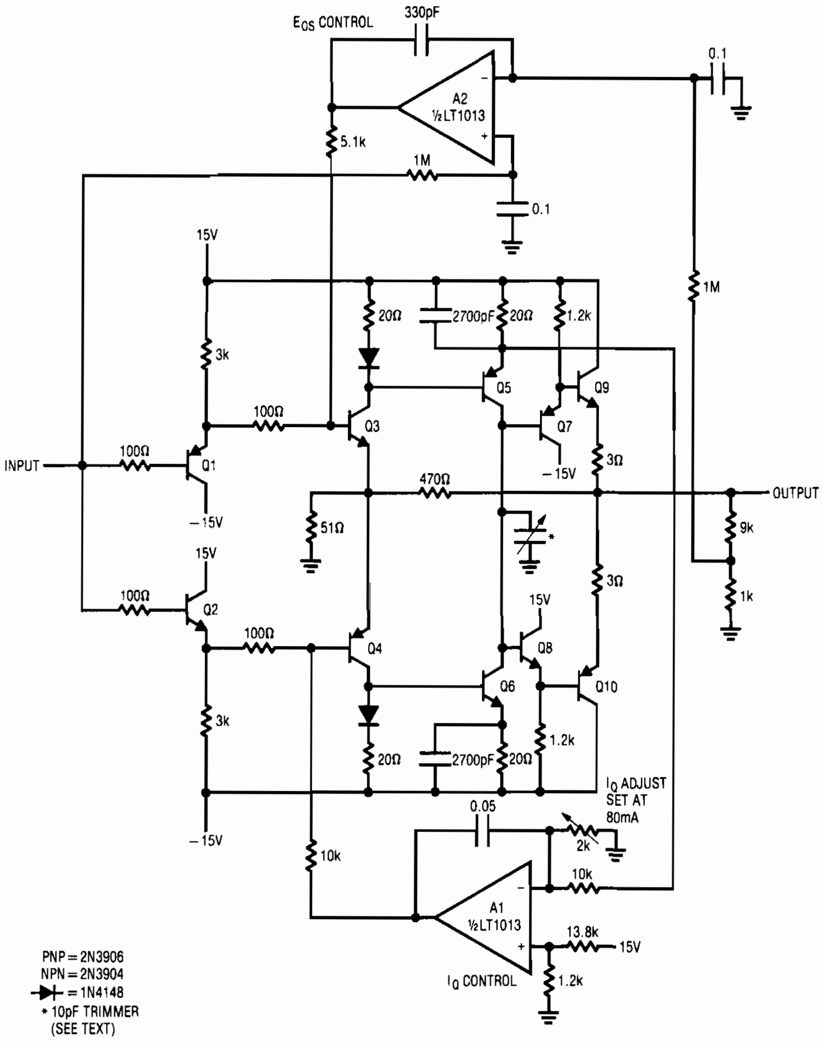


Figure 13. Stabilized, Ultra-Wideband "Current Mode Feedback" Amplifier (Son of Godzilla Amplifier)

and 51 ohm ratio), A2 samples the output via the 10:1 divider. Both A1 and A2 have local roll-off, limiting their response to low frequency. Casual consideration of A1 and A2's operation might raise concern about interaction, but detailed analysis shows this is not so. The offset and quiescent current loops do not influence each others operation.

When this circuit is constructed using high frequency layout techniques and a ground plane, performance is quite impressive. For gains of 1 to 20 full power bandwidth remains at 25MHz, with the -3dB point beyond 110MHz. Slew rate exceeds 3000V/µs. These figures can be improved upon by using RF transistors, although the types shown are inexpensive and economical. Figure 14 shows pulse response for a ±12 volt output (Trace B) at a gain of 10 (input is Trace A). Delay is about 6 nanoseconds, with risetime limited by the input pulse generator. Damping is optimized with the 10pf trimmer at the Q5-Q6 collector line. To use this circuit, adjust the I_Q level to 80mA IMMEDIATELY after turn on. Next, set A2's input resistor divider to a ratio appropriate to the closed loop circuit gain. Finally, adjust the 10pf trimmer for best response. Note that, in the interests of speed, this circuit has no output protection.

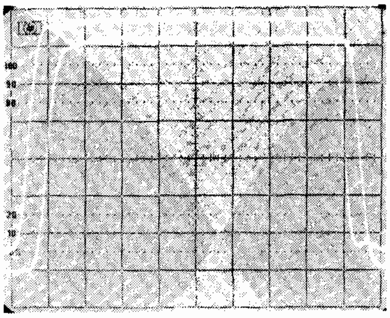


Figure 14. Figure 13's Pulse Response (Measurement Limited by Pulse Generator)

SESSION !: ANALOG TECHNIQUES

WAM 1.5: A 25MHz Thermally-Based RMS-to-DC Converter

[See page 288 for Tables 1, 2.]

James M. Williams, T.L. Longman

Linear Technology Corp.

Milpitas, CA

EARLIER DESIGNED monolithic circuits to convert waveforms to their dc rms equivalents utilized logarithmic techniques, limiting bandwidth to below 1MHz and crest factor performance to about 10:1.

Thermal computing provides improved bandwidth and crest-factor capability compared to logarithmically based converters.

A monolithically-based circuit which accomplishes this function appears in Figure 1. Here, the input signal drives R1, producing heating which lowers the emitter-base voltage of Q1. In response A1 drives R2 to heat Q2, closing a loop around the amplifier. Because the transistors and resistors are matched, A1's dc output equals the rms value of the input, regardless of input frequency or waveshape.

Parasitic thermal terms limit the circuit's practical performance. In particular, thermal cross coupling between the R1-Q1 and R2-Q2 pairs degenerates gain, degrading accuracy. Differences in the dissipation constants and thermal capacity of the R-Q pairs result in overall gain errors. Additionally, thermal resistance to ambient must be high, to maximize the signal from Q1 and Q2 for reasonable input drive. Finally, the thermal path between the thermally-mated resistor-transistor pairs must be designed for efficient, low loss heat transfer.

Although the converter's basic principle is straightforward, the electro-thermal design is carefully addressed to produce a practical monolithic circuit. These thermal considerations dominate the design and form of the circuit.

Figure 2 shows an electro-analog of the thermal terms in the converter. The overall lumped matching of these terms heavily influences achievable performance. In particular, the die attach thermal resistance dominates the thermal impedance path. If this resistance is made very high, mismatch in the other terms will not cause significant gain error.

Thermal cross coupling is almost entirely eliminated by using separate, identical die for the transistor resistor pairs. This eliminates cross heating more effectively than any possible single die approach. A time stable gain error, which is corrected by introducing a corresponding gain trim, is caused by residual mismatch in thermal terms. These include die size, dissipation constant, and thermal capacity differences. The most significant term is differing amounts and distribution of the die attach material. The gain-correcting trim is introduced by adjusting the value of the appropriate heater resistor, or by altering the gain of the output stage in Figure 1.

Because the die attach resistance is so important it must be carefully considered. Table 1 shows results for various die attach methods. As might be suspected, die suspended in free air offers the highest thermal resistance, although the approach is impractical. Conversely, standard eutectic bonding offers low thermal resistance, but is easily producible. Another die attach method, air impregnated polymer, is nearly as good as air suspension, and is practical.

Figure 3 is a photo showing the air impregnated polymer die attach beneath the die. Large areas beneath the die are filled with air, resulting in the high thermal resistance noted in Figure 3. Sufficient amounts of polymer attach material ensure a reliable die attach.

Figure 4 is a die view of one heater resistor-transistor pair. The circular, concentric heater resistor promotes evenly distributed, isothermal characteristics. The placement and resistivity of the heater rings and the spacing between them is optimized for an even thermal flow across the die. The sensing transistor is actually a paralleled quad located symmetrically about the die center. This quad arrangement provides improved temperature sensing characteristics over a single device. The die's center is occupied by a test structure, which is not used. It should be noted that the die contains only the basic thermal cell to maintain isothermal conditions. Inclusion of support circuitry would add thermally based error terms, degrading performance.

Results for the converter appear in Table 2. The accuracy figures quoted are applicable for a variety of waveshapes, including sines, triangles, square waves and low duty cycle pulses. The accuracy-bandwidth limits are primarily imposed by the effects of stray capacitance between the input heater resistor and its sensing transistor. This parasitic allows high-frequency components to influence the transistor's operation, limiting 1% accuracy operation to 25MHz. Crest factor performance is limited by available power supply range. The step response specification reflects the design's optimized thermal considerations. Figure 5 is a scope photo detailing Figure 1's response to a 5V input step. One per cent settling occurs within thirty milliseconds.

The converter treats ambient temperature shifts as a common mode effect, resulting in the low temperature drift noted.

Acknowledgments

The authors gratefully acknowledge the contributions of C.K. Lai, Repus Renez and Robert Dobkin.

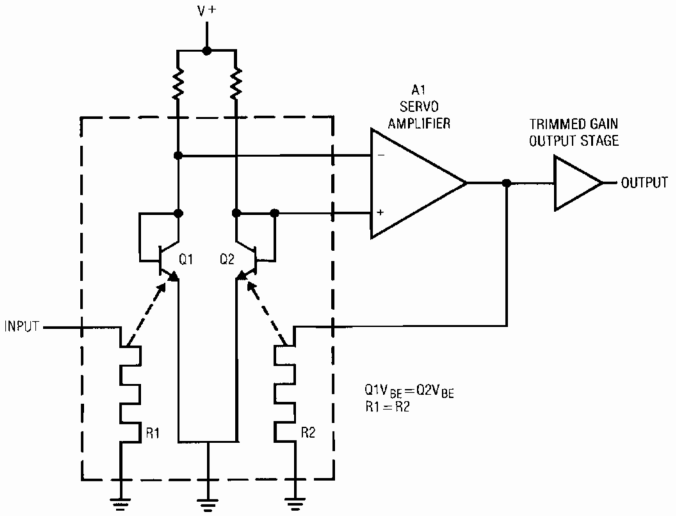
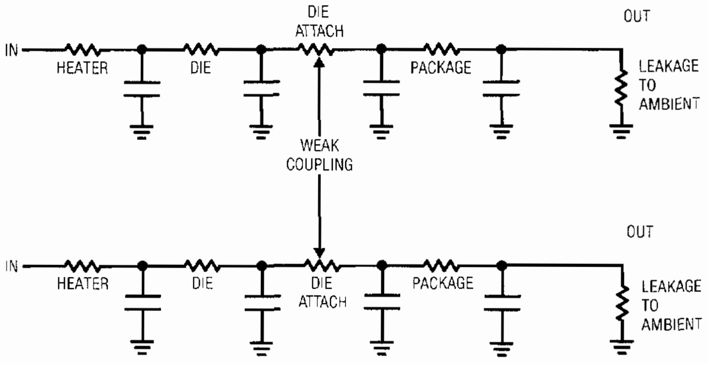


FIGURE 1—Thermal rms dc converter. Monolithic thermal cell is enclosed within dashed lines.



WHERE $R_{DIE\ ATTACH} \gg$ ALL OTHER R TERMS

FIGURE 2—Simplified electro-analog of the rms converter.

FIGURE 3—Air impregnated die attach details.

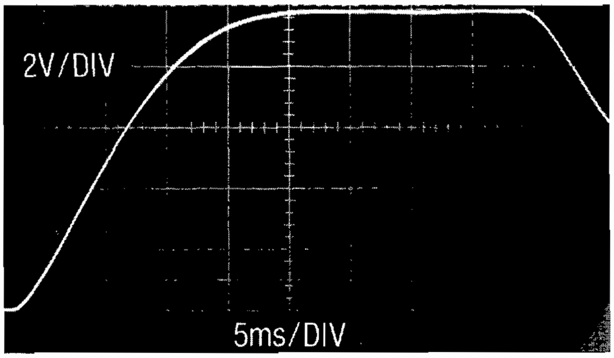


FIGURE 5—The rms converter step response.

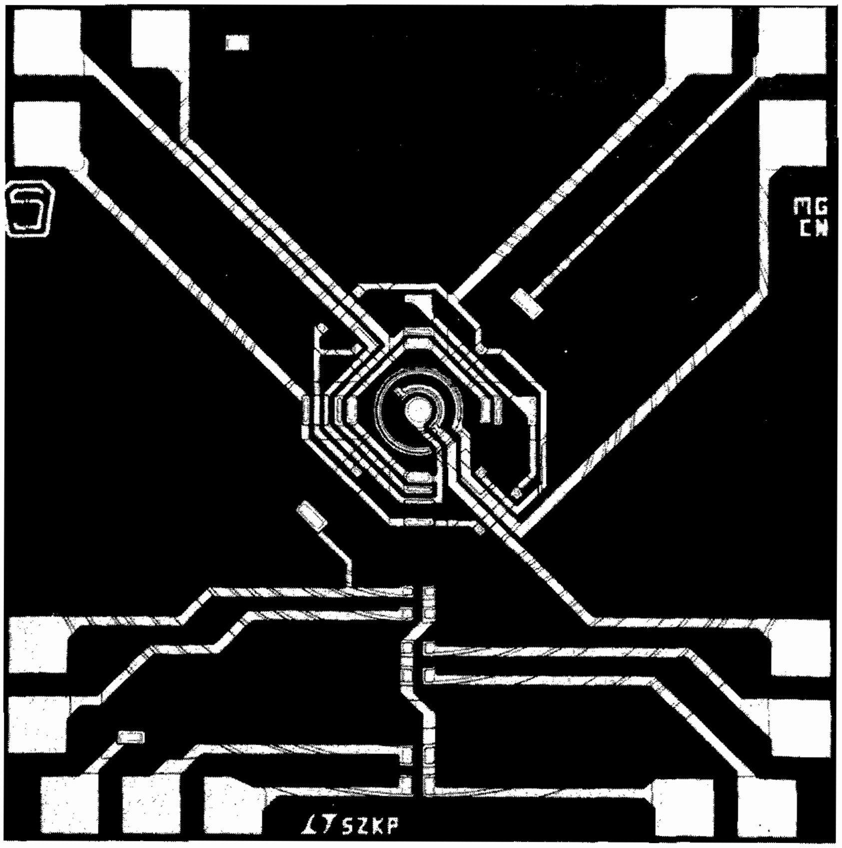


FIGURE 4—Die photo of a section of converter: size is 76 x 79 mils.

A 25MHz Thermally-Based RMS-to-DC Converter
(Continued from Page 21)

Die Attach Type	*Thermal Resistance °C Per Watt*
Air Suspended	460
Air Impregnated Polymer	380
Epoxy/2 Mil Polymer Barrier	250
Glass – 10 mil	115
Epoxy/1 Mil Polymer Barrier	107
Eutectic	54

TABLE 1—Thermal resistance for die attach types.

Parameter	*Results*
Accuracy	
DC-5MHz	0.4%
DC-10MHz	0.7%
DC-25MHz	1.0%
Crest Factor	
1/10 scale	100:1
Full scale	10:1
Step Response Time	30ms
Temperature Effect on Accuracy	50PPM/°C
Input Resistance	300Ω
Minimum Input for Rated Accuracy	5% of full scale

TABLE 2—Performance details with air impregnated die attach.

1 November 1988

A Prescription for Linear ASIC's--The predictions of five years ago have not been fulfilled

Jim Williams, Staff Scientist, Linear Technology
Corp., Milpitas, Calif.

VLSI SYSTEMS DESIGN Issue: 015

My wife Celia is a physician. When considering a problem she frames it in terms of what is not said, as well as what is said. She's often more interested in how things are perceived and presented than in what is stated.

This approach produces some well chosen questions. She has confidence in her own abilities but doesn't confuse this with the crucial issue of getting the problem straight before operating on it.

There is a lesson here that might help us understand why linear ASICs have been such a disappointment. Disappointment? Yes. The technical and economic predictions of five years ago have not been fulfilled. Linear ASICs are a tiny portion of the linear marketplace. At least two companies that started to bring linear ASICs to market are currently building standard linear products. No linear ASIC effort has achieved anything near the growth rate, profitability or size of comparable age standard product linear companies.

What's wrong? The computer tools and models necessary to build successful linear ASICs are still crude and incomplete. Methods for selection, characterization and control of construction technologies for linear ASICs are still elusive. These and related problems are real issues and need fixing before linear ASICs can provide the desired performance and profit advantages.

Even if these problems go away, linear ASICs have a more serious issue. Most silicon scribes don't know beans about systems, and systems is what linear ASICs are all about. Few IC people have instrumented a pharmaceutical plant, or shepherded a box level product through to production. Not many have worked with an interdisciplinary team to produce a medical instrument that really does what is required. IC hackers have not considered the practical realities of transducer fed measurement in an industrial environment, in an airplane, the human body, or on an oil rig.

This ignorance of systems makes listening difficult. It's hard to know when to question or what to ask when you're ignorant. Worse, our human nature often steers us to cling to what is familiar, producing false confidence, even arrogance.

This ignorance can cause critical flaws in problem definition and communication between customer and vendor. No matter how highly developed linear ASIC technology is, it's useless if these issues are not dealt with. This point is well illustrated by the experience of standard product linear houses. Customers keep vendors on the phone with questions about "simple" linear products that they've been using for ten years. Regardless of how well written the data sheet is, no matter how much characterization or information is available, issues come up-real issues, that can sink the customer. Sometimes it takes 45 minutes just to understand what the customer is talking about, let alone arrive at a satisfactory solution. Sometimes the customer doesn't really understand what the problem is, even when they think they do. Other times you don't understand, even though you're sure you do.

I can't imagine the calamity of supporting somebody who wants 50,000 pieces of some linear ASIC. He (and I) may not know it, but he's the one providing the characterization and writing the data sheet. He expects to ship product, and I expect to make money.

The customer-vendor relationship is as crucial as the technology in attempts to build linear ASICs. For people making the ICs, this means learning a lot more about what their customers are doing than they may be used to. It also means learning how to observe and listen before saying, or even thinking, anything.

If linear ASIC is to make a significant contribution the fast talking must be replaced with some slow listening.

JIM WILLIAMS is a staff scientist at Linear Technology Corporation, Milpitas, Calif., responsible for product definition, customer support and circuit design. Prior to LTC he worked at National Semiconductor and taught at M.I.T. for ten years. He has consulted for U.S. and foreign companies and governments and published over 100 articles covering analog circuit design.

Electronic Engineering Times

28 September 1992

Analog circuit content gets ready for 3.3-volt hand-held computers

JIM WILLIAMS

STAFF SCIENTIST LINEAR TECHNOLOGY CORP.MILPITAS, CALIF.

high-density integration and lower operating power are driving digital systems to 3.3-V operation. It is nearly certain that most, if not all, future microprocessors will operate from 3.3 V. Portable computers, benefiting from this trend, will offer increased computational capability with decreased operating power requirements and size.

The analog content of today's portable computers includes the main power supply, liquid crystal display (LCD) backlight and contrast supplies, peripheral drivers and battery charging/monitoring circuitry (Fig. 1). All of these analog functions will be affected by the move to 3.3 V. 3.3-V computers will be smaller, and lower-voltage battery supplies (e.g., two to four cells, or in the range of of 2.4 to 6 V, depending on battery type) will be common.

In general, the switching power supplies in portable computers run more efficiently at relatively high input voltages. This is because the fixed semiconductor junction and saturation losses are a small percentage of the operating voltage. As operating voltage scales down, these loss terms become more significant. Offsetting these increased losses requires careful attention to each analog subsystem.

The move to 3.3 V in portable computers, which must occur, will have significant impact on the machines' analog portions. Maintaining 90 percent power conversion efficiencies in a 3.3-V supply requires changes in the design approach, but new ICs permit this. The display and peripheral driving portions of the computer will benefit from analog ICs that function similarly to their 5-V relatives but work at 3.3 V. The battery charger, which may be within the smaller 3.3-V-powered computer, must have high efficiency to prevent heating.

Finally, 3.3-V-powered signal conditioning components will be used to determine the battery's charge state by keeping track of energy flow in the battery.

The main power supply converts the battery voltage to 3.3 V to run the machine's processor ancillary logic functions and memory. It may also provide a 12-V pulsed "Vpp" output for flash memory programming. Main power supplies in today's 5-V systems achieve 90 percent efficiency. The change to 3.3-V output cuts this figure to about 85 percent if the same design approach is used. A significant loss term is the output rectifier diode.

If the diode is replaced or augmented with a synchronously switched rectifier, most of the lost efficiency can be regained. Such schemes are conceptually more complex, but new analog ICs permit implementation of such architectures with minimal impact on cost and board space. In particular, newer analog ICs allow easy use of lower saturation and cost N-channel MOSFETs as high-side power switches, eliminating the higher losses of P-channel devices.

The LCD displays employed in portables require two power sources: a backlight supply and a contrast supply. The display backlight is the single largest power consumer in the machine, accounting for almost 50 percent of the battery drain when the display intensity control is at maximum. As such, every effort must be expended to maximize backlight efficiency. The backlight presents a cascaded energy attenuator to the battery (Fig. 2).

Battery energy is lost in the electrical-to-electrical conversion to high-voltage ac to drive the cold-cathode fluorescent lamp (CCFL). This section of the energy attenuator is the most efficient, with conversion efficiencies of 80 to 90 percent possible. The CCFL, although the most efficient electrical-to-light converter available today, has losses exceeding 50 percent. Additionally, the light transmission efficiency of present displays is about 25 percent for monochrome, with color even lower.

Clearly, overall backlight efficiency improvements must come from bulb and display improvements. The good news is that the power-supply portion of the backlight is relatively unaffected by the change to 3.3-V power. The supply's high-voltage, ac output eliminates rectifier diode concerns. The lower battery voltage somewhat magnifies the saturation losses in the backlight supply's power switches, but the effects are manageable. The contrast supply operates at much lower power than the CCFL supply and sees almost no impact from the reduced supply voltage.

RS232 ports, modems and disks are typical peripherals requiring power. RS232 is a special case, utilizing a bipolar high-voltage protocol. In 5-V systems driver receiver ICs that generate the RS232 voltages on-chip have been popular, and 3.3-V-powered versions of these devices are now available. Disk memories require regulated power for motor drive. The startup current at 3.3 V, well into the ampere range, is about twice what a 5-V-driven disk needs.

This means the main 3.3-V regulator must supply substantial peak currents without dropping out or poor recovery. Such untoward dynamics would cause erratic computer operation. Similarly, high-side power switching of the disk must be well controlled, and with low losses. N-channel FETs driven by ICs with on-chip gate boost supplies are ideal for such service.

The smaller size of 3.3-V-driven computers will put pressure on vendors to incorporate the battery charger-ac line adapter within the machine. External ac adapters will become increasingly unacceptable to consumers. Putting the ac-line-powered charger inside the computer means that the charger supply must be extremely efficient, or unacceptable heat rise will occur. Such heating can, at best, cause the LCD display to "bloom," making it unreadable. In the worst case, heating shortens component life and presents a fire hazard. Off-line switching regulator techniques permit the charger to be placed within the computer housing without significant heating penalty.

The battery's charge state must be continually monitored. Ideally, the battery would directly indicate its state of charge by providing information via a third electrode-a true "gas gauge." Unfortunately, such battery technology is not presently available. An approximation of this ideal involves constant monitoring of all current flow into and out of the battery. Combining this information with the battery's age and history permits a reasonably accurate determination of the battery's state at any time. Doing this requires low-loss-current monitoring, e.g., very small resistance shunts, and a/d conversion. These operations mandate low-voltage-powered precision amplifiers and a/d converters, which are presently available.

Jim Williams taught analog circuit design at MIT for 10 years. After a four-year stint at National Semiconductor, Williams joined Linear Technology, where he is responsible for product definition, development and support.

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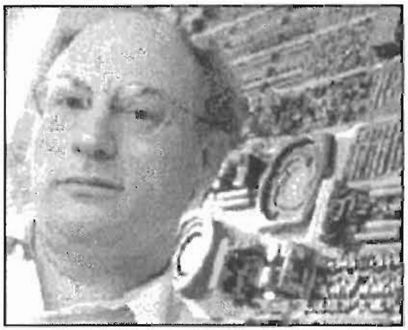
Linear/Mixed-Signal Chips: Jim Williams

Understanding analog is an art

By Stephan Ohr

At a recent luncheon talk, Jim Williams offered an anecdote to describe a significant shift in the world of analog design.



Williams sees users as not particularly interested in analog.

The staff scientist at Linear Technology Corp. (LTC) couldn't seem to keep his Jaguar XKE-with 167,000 miles on it-in tune, although he had the original repair manual and followed its instructions exactly. In desperation, he took it to an old-salt mechanic, who got it humming and purring again. "The manual was written for a new engine," said the mechanic. "Not one with the wear and tear yours has had. You need to change the viscosity of your oil."

Similarly, Williams concluded, there are a lot of textbooks on analog. There are a lot of digital cells that claim to replace analog circuit functions. There are a number of EDA tools that claim to encapsulate analog expertise. None of this stops Jim Williams' phone from ringing at Linear Technology Corp. "A lot of the time, they don't even know what you make," Williams complains. "All they know is that you do analog."

Fundamental changes in the electronics industry-viciously brutal time-to-market pressures combined with a distressing deficit in analog expertise-have changed the nature of the applications work he does. Instead of building a generalized circuit for one of LTC's part types and publishing an app note for everyone to marvel at and use, at least 50 percent of Williams' applications circuits are now built directly for customers who will simply add it-without modification-to the product they need to ship.

"You ship a piece of copper-clad board from your lab (sometimes with wires dangling from it) and if it works in your customer's system he 'postage stamps' it into his design," said Williams. "You're designing circuits for customers who are going right into production."

"That's a big change from 20 years ago," he said. "Twenty years ago, linear companies would not have wanted that kind of responsibility. Now, the service issue is dominating the business. The circuits you ship have to work in your customer's product." That makes analog design very targeted, very dedicated, he said. And it has a marked effect on how linear companies are run. "It means the value of your products [linear ICs] gets mixed up with the services you perform.

"Ten years ago, people generally knew what they were doing in analog; knew how to do it. If you showed them an interesting part type, they could probably figure out what to do with it. If they encountered you at a conference or got you on the telephone, it was to talk 'subtleties,' " said Williams.

"Lately, there's been a proliferation of people who are not particularly interested in analog but who are forced to do analog just to get their product out. It doesn't mean they lack the capability," Williams observes. "It's just that analog has become an item on their checklist. It's not a technology trend; it's a change in the user base."

Such a shift is undoubtedly distressing to someone who loves electronics-old electronics, analog electronics-as much as Williams. Though he seldom gets to spend much time relaxing there, his home laboratory is populated with working Tektronix 500-series oscilloscopes. He collects antique instruments, in fact, and has an electrometer that Lord Kelvin was said to have built.

Another prize is a 200-year-old Marine chronometer that's accurate to 1 ppm per month. Williams is fascinated with the way people solved measurement problems with the technology available to them at that time. "How did you hold 1 ppm 200 years ago?" he asks. "Questions like that make you truly interdisciplinary. You can't get too invested in the technology that's in front of you; you have to seek out all-encompassing solutions."

Like many engineers, Williams finds a certain beauty to electronics. The wall of his living room is graced by what, from a distance, looks to be a highly textured, vividly colorful tapestry. Moving closer, it becomes a series of populated electronic circuit boards, laid out flat in a frame. "The nose cone of a Minuteman missile," Williams said. "It was always armed, but the electronics ran so hot, that you'd have to cool it with liquid Freon to keep it from burning itself up. If the missile was ever fired, you'd have to disconnect the cooling system. The missile would have about 10 minutes to reach its target before the electronics overheated." It turns out, the liquid Freon was an excellent preservative for the color-coded resistors, the copper printed-circuit board traces, the gold and silver-cased transistors, and their green phenolyic substrate.

The hand-made digital clock in his dining room is a 3-D sculpture, using 14-gauge solid copper wire, copper tubing and plumbing pipes, which is in sharp contrast with some of the "rats' nest" try-out circuits that periodically pepper his test bench at Linear Technology.

Williams puts in a 60- to-80-hour work week. His time is equally divided between solving specific customer problems and completing long-range design projects. Some of it is done at home; some of it in his laboratory at work. "They have a tendency to transmute," he said. A "total disconnect" from the engineering world is skiing with his wife, he said, or playing with his son. Most of the time, with customers begging for assistance, he can't disconnect.

Such pressures can make Williams leery about answering his telephone. The callers have immediate analog-applications problems to solve. Their tone is often desperate. "The time between the customer's first call and your shipping him a copper-clad board to try out is sometimes no more than a week," said Williams. But because the caller's analog knowledge is increasingly limited, it is impossible to tell sometimes whether he is specifying the right things, and-as with all custom design-there is always the danger of delivering the wrong thing.

Board-level products offer a very flexible platform for analog circuits. "At the board level, you're working in the customer's domain," said Williams. You can get a sample circuit out the door very quickly, and can make easy changes if it doesn't seem right the first time. If you understand the customer's problem, you can win a slot for your company's parts.

Measurement and control, and low-end signal amplification always remain a challenge, Williams confirms. "Often, you have a 'bag of tricks' you can rely on to solve a customer's problem, but sometimes it's something original that will take some time and thought.

"The end user doesn't care if the solution is a single chip or not, especially if he's on a time line," said Williams. The goal of the LTC customer usually isn't to come up with one integrated chip, he believes. The goal of the customer is to ship on time-with performance and cost parameters intact.

LTC targets the ICs it decides to build very carefully. "We ask, 'Can we do this? Should we do this?' " Williams said. "You want to be careful of doing too many circuits that others can do, because then you're selling a commodity. People will obviously get better at putting big hunks on one chip," he acknowledges, "but can you get it out on time? Is it flexible? Can you test it? And can you make any money at it?"

Despite the pressures Williams feels from the scarcity of analog designers, he is not convinced the engineering colleges and universities can alleviate the problem. The best analog designers showed their interest in this long before college, he believes. Ironically, the situation is characterized by a kind of either off-or-on digital metaphor: chances are you are either an analog engineer or you're not. "If you're a dog," he quips, "you're gonna sniff trees."

Analog guru Jim Williams dies after stroke

EDN's Paul Rako and industry EEs reflect back on the life and work of Jim Williams, an engineer's engineer and analog expert, who died Sunday night after a stroke.

By Paul Rako, Technical editor -- EDN, June 13, 2011

Jim Williams, analog guru

Jim Williams, the world-famous analog guru that helped found and expand Linear Technology, passed away at 10:15pm pacific time Sunday night. He suffered a massive stroke on early Friday morning, June 10, 2011. He was 63 years old.

Jim had just returned to work from a well-deserved vacation. Jim was excited about the next two articles of his scheduled to be published in *EDN*, one on a sine wave oscillator currently slated for August 11, 2011. The last article Jim wrote for *EDN*will be his brilliant description of developing a 100A electronic load currently scheduled for the September 22, 2011 issue.

Jim was really pleased with that last article. Several times he confided that it was one of the few technical projects that "everything just worked perfect." He said it was rare to have all the parts of a complex design go so well. When he told me this I couldn't help but think how his awesome talent had to play a part in the ease of the design.

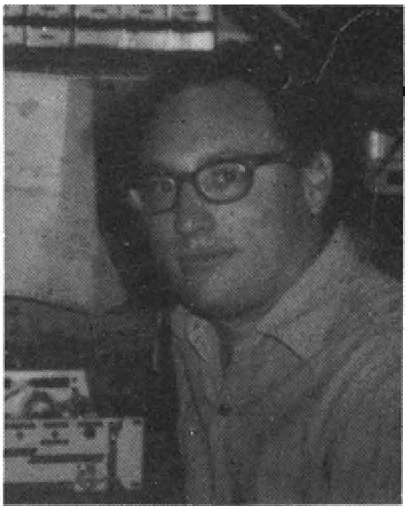
Now that talent is lost to the analog community, and we are all impoverished by the loss. Jim had a background that was as interesting as the circuits he designed. He did not have credentials. Indeed, he took one semester of psychology at Wayne State University in Detroit. Jim's good friend Len Sherman relates, "Jim had a modest upbringing during his childhood. His dad was a banker in Detroit during the peak of the US auto industry. His dad cut him off with no money once he dropped out of Wayne State. It wasn't personal, but his dad felt it was necessary for Jim to earn his own way if he wasn't going to complete college."

Growing up, Williams had a neighbor that loved electronics and would show Jim those big beautiful Tektronix oscilloscopes in the garage. Jim soon developed a passion for electronics and especially for test equipment. His passion led him to MIT. Not as a student, but as a lab tech that built hardware for the scientists and kept a whole slew of sophisticated test equipment working. Jim related how the department head once told him it would be impossible to fix a certain piece of equipment. That's all Jim had to hear. It took about three weeks, but Jim got it fixed.

Test equipment has to be more advanced than the circuits it tests. So learning the design of test equipment turned Jim into one of the best analog engineers in the world. He never confused description with understanding. When he would give seminars on how to design piezoelectric transformer lamp drivers, he pointed out that professors who fill the blackboard with math really don't know how a circuit works. Jim knew that the math can describe how a circuit works but understanding how it works was a much more fundamentally intuitive and poetic endeavor.

Jim began writing articles for *EDN* in 1975, when he still worked at MIT ("**Heavy-duty power supply regulates either voltage, current or power**," May 5, 1975). Those articles always stressed understanding. Jim did not condescend and write down to us. He never tried to impress you with his math or his intellect. He didn't make things complicated so you would think he was smart. He made things look simple. That is why he was brilliant. Anyone can learn a bunch of jargon and a few tricks and secrets and try to act smarter than you. Jim was the exact opposite. He took the trouble to describe the basic principles of what was going on. Then he showed you how to achieve the goals your designs needed to achieve.

The fact that Jim loved to get his hands dirty, hacking on copper-clad and brandishing a soldering iron rather than instruct a tech, serves as a great example for generations of analog engineers. He taught us all that if you do the work yourself, you will achieve a far deeper understanding of the design that if you just tossed a schematic to some poor hapless technician. Bob Dobkin, founder of Linear Tech and the recipient of many of Jim's pranks notes, "Jim lived electronics. Electronics was his art, as was humor." Jim's mantra of building your own prototypes and testing them taught tens of thousands of engineers the right way to get a working design off a sheet of paper and into production.



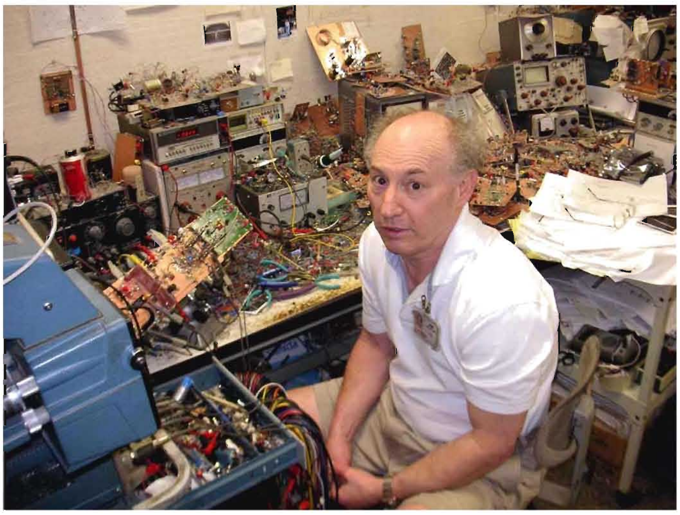
Jim Williams as featured in his first article for EDN,

Jim was a modest and humble man, for one so brilliant. His joining Linear Technology in the earliest days also made him wealthy, but it was hard to tell from his manner. He never acted stuck up, despite his money and his talent. He loved to talk to fellow engineers. Engineers would write *EDN* asking for Jim's e-mail address. We told them that Jim didn't have e-mail. He also didn't have a cell phone or voicemail. But Jim would pick up the phone any time he was at work. *EDN*would supply Jim's phone number to these interested readers, and most felt they could not impose on such a great man with a phone call. We had to assure them it was alright to call Jim. He always welcomed hearing from a fellow engineer. Jim would point out that he would learn a lot from the engineers that called him, and that he loved to hear from them, no matter how simple the problem.

Jim had a window office with a door, but the office phone was almost always forwarded to the lab bench where he loved to spend most of his time. Williams respected the best in people-their ability. He didn't care what country you came from, what car you drove, what breakfast cereal you liked. If you loved analog, that was all Jim needed to know. He was approachable and friendly, no matter what the situation.

In the late 1970s, Jim worked in the Boston area for several years, working for Teledyne Philbrick and consulting at Arthur D Little and Consultek. He did some work for Analog Devices. Dave Kress, director of technical marketing at Analog Devices, remembers, "Jim worked as a consultant for Analog Devices while he was at MIT and before he went to the west coast. He wrote several major pieces for us."

In the late 1970, the action in electronics was in Silicon Valley. Williams then went to work at National Semiconductor. Kress notes, "We tried to get him to stay in Boston, but the call of the West and all that action was too much to beat." When several National engineers left to form Linear Technology, Jim didn't go with them. He explained, "They didn't have any chips yet, what did they need an applications engineer for?" Eighteen months later that situation had changed, and Jim went over to Linear Tech as their first apps person. Kress recalls, "Jim and I were good friends, even at a distance and working for competitors, but we never personally felt competitive. He was extremely creative and very productive."


Jim Williams in his lab, 2007

Bob Dobkin, one of the founders encouraged Jim to write for the trade press, to demonstrate the capabilities of Linear Tech's parts. At the same time, the articles Jim wrote demonstrated his brilliant command of analog design. In the 1980's Jim wrote 60 articles for *EDN*. His natural emphasis on analog gave *EDN*an analog tilt that continues to this day. Loyal readers knew they could learn the best principles of analog design just by following the articles Jim wrote. Although Jim suffered from Parkinson's disease for the last five years of his life, he never let it slow him down or affect his prodigious output of work.

Jim's effect was profound. Alan Martin, himself a brilliant engineer, read Williams' articles. That instilled a love of analog in Alan. Alan soon moved from Colorado to Silicon Valley, and took at job at Linear Tech so he could work with Jim on a daily basis. Alan, too, has a passion for fixing test equipment. He and Jim would often challenge one another to troubleshoot an especially difficult problem. Alan recounts that late one Friday, Jim threw down the gauntlet as he left for home. "You would have to be one heck of an engineer to fix this thing ..." Alan had it working by Sunday night. Jim was impressed.

Jim had that effect on every engineer around him. He made you want to do the best work you could. He made you want to solve the intractable problems. He made you want to not just get it working, but to get working with elegance. Jim helped set the standard for analog engineers the world over. The whole world will miss his technical brilliance and his warm personality. I know I will.

Donations in Jim Williams' memory can be made to:
The Parkinson's Institute
675 Almanor Avenue
Sunnyvale, CA 94085

Remembering Jim Williams

Engineers come out to share their favorite memories of Jim. We encourage our readers to share their stories about Jim in the comments field below. (Please note that as more comments come in, existing comments are moved to a "talkback" page for this article that houses all comments posted. Click on any comment to see the full listing of comments.)

Jim's start at MIT is a colorful story. I started working in his lab in Building 20 at MIT in 1975. On the wall in the lab he had blue vinyl pouch in a frame on the wall. When I asked him about it, he said that when he came to MIT in 1968, to be where the "smart" people were, the only jobs he was offered were either as a janitor or mail boy at Draper Labs. He took the mail boy job figuring it would give him a chance to talk to people and see what was a going on. That the blue vinyl pouch on the wall was his mail carrier pouch from that first job. At the time he had no official credentials to do lab work at any level. But of course, Jim being Jim, it didn't take him long to talk himself into a technician's job working on the Apollo program. *-Len Sherman was a student at MIT when Jim Williams was working there. He worked with Williams at National Semiconductor. Sherman currently works as senior scientist at Maxim Integrated Products.*

The analog world has lost a uniquely gifted and genuine human being. Jim was always fun to be around. Regrettably, I saw Jim less frequently as I moved into executive management at LTC, but Jim never failed to brighten my day when I had the pleasure of visiting him in the lab. He always brought me back to the basics of what makes the analog business so unique.

Jim was always humble and down-to-earth, but he had the world's best understanding of the "messy" real-world aspects of analog design. Analog design never reaches an end - in pursuit of perfection there is a growing list of non-ideal limitations. That's what makes analog design so much fun, and that's where Jim excelled. He enjoying identifying those non-ideal parasitics and finding ways to outsmart them.

Jim's 3D breadboards looked like Rube Goldberg contraptions, and it was sometimes hard to believe they could actually work. But work they did, usually achieving levels of analog performance that no one else in the analog world could match.

Stories abound about Jim's pranks, but every once in a while the tables were turned. For several years my office was next door to Jim's, and I remember drilling a hole in a shared wall to mess with a huge functioning breadboard Jim proudly hung on the wall behind his desk. Jim was clearly frustrated by the intermittently malfunctioning circuit, but he was eventually victorious by tracing the wires through the wall into my office.

I'm sad to realize that Jim is no longer with us, but the analog word is a much better place because he enriched the lives of so many of us. *-Dave Bell, president and CEO of Intersil*

I am one of the lucky people who knew Jim as both a scientist and [an analog] brother. Jim was a very private person who had many profound insights. Jim and I met in the late 1980s when we were architecting the Apple Powerbook.

Jim always teased me that I f**ked him over by having him work on backlight circuits for 10 years. He got me back by suggesting I start BAM Labs five years ago. For more than 20 years Jim would come to my house every weekend for football or to just hangout, which really meant eating food that Siu wouldn't let him eat at home. His favorite was mac and cheese with a side of puffed cheetos and a few cokes. He then would play pool with his son Michael and me. Jim loved to eat almost as much as he loved Siu. There was never an excuse needed for Jim to eat. In fact, Jim would drag anyone he could to his favorite restaurant Sinola in Morgan Hill. We went hundreds of times and Jim always got the same thing: three beef tacos and a double rice.

Jim had the strangest eating habits, things were either meat or vegetables, vegetables were called enemies. Now, potato chips and corn were officially meat. Mac and cheese was meat, too. If you asked him to eat asparagus he would say, "Are you trying to kill me?"

Jim lived his life with strict rules, he had a very sensitive scale (100th/lb) in his bedroom and would weight himself every day. He would skip lunch if he was a bit over his goal. He invested and stuck to his plan. He was honest to a fault and you couldn't find anyone alive with more integrity than Jim. The only time I would say that he wasn't completely honest was when he would tell a story too many times and it would get better every time.

Everyone knew Jim loved his circuits, but Siu is Jim's true love. He outwardly was stoic about his feelings, but with Siu everything was different. His affection for her broke his rules for No Public Affection. Jim would show how much he cared for his Siu by touching her nose and smiling like he was the luckiest geek there was.

After his first date with Siu he called up and told me that he didn't think about circuits all night. ... That was a big deal for Jim. Last week Siu dragged Jim to Hawaii, Jim complained about going for weeks.

When we got back I asked about the trip and he said it was great. ... He and Siu just spent time together.

Siu was Jim's first love, Michael was his second. Mike is his son who he taught to drive on his lap when Michael was 5. Having Michael grow with Jim's high integrity was a priority for Jim and difficult for any child. Michael is now 21 and Jim was so proud of what a nice young man Michael has become.

Jim was a very generous guy; he would always step up to help someone if he could. He found great joy in teaching, he loved to go to work on the weekend and help someone with a problem of teach someone about electronics. He'd pull his

man purse out and take his stubby prehistoric mechanical pencil and try and write on a napkin without tearing the paper.
He would whip out a circuit and then draw a cartoon to finish.
He wanted everyone to think he was eccentric, but he was really a gentle soul who I am going to miss forever. *-Steve Young, CTO, BAM Labs*

I had long discussions with Jim Williams about various things including analog and radio circuit design, life in general, and engineering in both Russia and the United States. Here are some thoughts about Jim based on my own observations for the last 12 years. Jim brought and enforced a culture of intuitive analog design at Linear Technology. This gave him a very strong following, both inside and outside the company. Jim's personality was a unique mix of "components." He could be sarcastic, almost cynical, while at the same time being very passionate and very sensitive.
To a great degree, Jim would not consider any engineering solutions that were outside of true, old-fashioned analog design. He also refused to use modern test equipment. Younger engineers, especially those working outside of Linear Tech may have a hard time understanding this. Jim did accept my help in taking some measurements with modern RF test equipment. I am sure many engineers inside and outside of Linear Tech will continue with Jim's tradition of intuitive analog design in their specific areas. *-Vladimir A Dvorkin, RF applications engineering manager at Linear Technology*

I can't say I was a close friend of Jim's, but from afar I also tracked and enjoyed his writings. I learned from them, way before we finally met. He is indeed one of those people that make other folks' life better. I appreciated that we shared the love and sublimeness of settling time measurements. He appreciated other peoples' passions. The best prank would be his recovery. *-Barry Harvey, design manager at Intersil*

I first met Jim Williams on the shop floor of my consulting business. It was back in the late 1980s. I had been reading *EDN* magazine from cover to cover, knowing I had to have really good technical skills if I expected to be a consultant. In one of Jim's articles, his bio mentioned he collected old scientific instruments. My brother had given me a dual-pan balance he salvaged from the dumpster at the University of Toledo. It was an old unit in a wooden case with glass panels. It had a little gold chain that you would raise and lower with a wheel to fine-tune the weight. I called Jim up at Linear Tech and asked if he wanted it. He said he liked that kind of stuff, but he didn't think it was right to just take it. I explained that my brother gave it to me, and that I wasn't really giving it to him for free. The bargain was that he would have to chat with me for a bit when he picked it up at my shop.
Jim said fine and we arranged a time. I asked my mentor, Big John Massa, to come, as well. I knew John and Jim would enjoy each other's company. Jim must have gabbed with us for over an hour. We talked about electronics and Detroit, where we both had lived. I asked him about how National Semiconductor could let the whole Linear Tech crowd walk out of the building and start a new company. Jim explained that National, like most companies, was pursuing the big "G" -- Growth. Back when Linear Tech spun off of National, digital was the 20 billion dollar market and analog was one or two billion. Jim said he could understand how National would pursue the growth and try for a slice of that big digital market.
I also remember that Jim gave me a razzing about my owning a bunch of Harley Sportsters. Harley's reputation was in the tank back then and they had terrible reliability. Then later in the conversation, it came out that Jim drove a Jaguar XKE. Talk about poor reliability, I teased Jim about the Lucas "Prince of darkness" electrical system in his Jaguar. We all had a laugh about that.
I would see Jim at conferences and technical seminars. I remember his brilliant presentation on making high-voltage power supplies using piezo transformers. He also gave some seminars about various Linear Tech parts. He was always gracious and he always remembered our conversation in my shop.
In 1998, I had a contract at Hewlett Packard designing diagnostic equipment for automobile service. I was having a heck of a time trying to make a solid-state variable attenuator front end. I was using multiplexers and variable gain amplifier and all kinds of other approaches. The hardest thing was the whole front end had to withstand high-voltage faults. On top of that, the customer wanted 1dB accuracy over 10 MHz. I had spent weeks on the problem. Finally I figured I had to consult an analog great. So I called Jim up at Linear Technology. I was a little sheepish, since this time I was going to be asking for free consulting. Jim patiently listened to my problem and my extensive description of the system. He asked a few questions. He asked what I had tried and listened patiently as I described all my false starts. He paused for a few seconds. Then he asked, "Have you ever used a Tektronix oscilloscope?" I said sure, there was one a few feet away in my office. Jim then asked, "What happens when you twist the vertical attenuator knobs in that 'scope?" I instantly saw where he was going. I smiled and said, "I hear relays clicking as I change attenuation levels." "Yup," Jim said, "Expensive little high-bandwidth relays." Jim then politely explained that if Tektronix could not make a broadband solid-state attenuator, maybe I should not be trying. I understood the implications and changed the design to remove the need for variable attenuation in the front end.
Another long period went by and I did not see Jim much. Then I took a job at National Semiconductor as an application engineer. I worked in the amplifier group, with Bob Pease and Paul Grohe. It seemed everyone knew Jim or used to work with him. I heard stories of the pranks Jim used to play on co-workers (see "**Pranking friends co-workers and bosses**"). I would see Jim at the Electronics Flea Market that I had started attending with my friends. Jim and I would cross paths more and more. Then I met Alan Martin, who had just come to work for National from Linear Tech. He knew Jim well and I got so see Jim when he was hanging out with Alan.
Then I took the job at *EDN*. Then I got to see Jim every month. He still remembered me from the 1980s, when we hung out in my shop. Soon it seemed like I was talking to Jim every week. Slowly but surely, we were becoming friends. I would show Jim some of the circuits I had designed as a consultant, knowing he would appreciate the things I got working. He in turn would show me some of the things he was working on. Many times this was not for publication in *EDN*, it was just Jim helping out a customer. The last few months of his life, Jim would call me once or twice a week.

Sometimes it was to talk about and article he had coming out in *EDN*. Other times it was just to say hi. I would hang up after talking to him and just shake my head at the Cinderella nature of it all. Here was the guy that taught me analog design in *EDN* magazine, and now I work for *EDN* and Jim Williams is calling me up to say hi. What a blessing. Jim's friendship and teaching was a precious blessing.

I spoke with Jim on the fateful Thursday when he had his stroke. He was excited about the next two articles he was getting published in *EDN*. He talked about his recent vacation and why it was important to take a break now and then. He assured me that he would see me Saturday at the Silicon Valley electronic flea market. I told him I had all kinds of things to tell him, and I would see him there. Then I said I had to get back to work and he let me go. He had his stroke that night. A few days later, he was gone.

Will there ever be another Jim Williams? A passionate self-taught engineer that sets the bar for the entire community? I like to think so. If you went to the Embedded Systems Conference in Silicon Valley this spring, you could have seen Jeri Ellsworth's keynote speech. Jeri, too, is self-taught and passionate. She too is teaching by example and helping everyone she meets. Heck, the girl has a diffusion oven in her garage. Tom Lee, a professor at Stanford introduced Jeri to Jim at the e-flea market in 2011. I only wish that Jim could be around to get to know Jeri, they would have become close friends. So rest in peace, Jim Williams. And rest assured that the passion and love you have for technology has passed to the next generation, and the ones after that. But still, Jim was a unique analog guru and he will be impossible to replace. I will miss him, especially when I pick up my copy of *EDN* magazine. I will be reminded how we first met, with him teaching me the deepest darkest secrets of analog design. Oh what a sad, sad day this is. *-Paul Rako, analog engineer and EDN technical editor*

A BIBLIOGRAPHY OF JIM WILLIAMS

Version 0.8

Compiled by Kent Lundberg, Ph.D
`http://readingjimwilliams.blogspot.com`

October 27, 2011

Abstract

Jim Williams wrote over 350 publications relating to analog circuit design between 1971 and 2011. Here's what I've found so far.[1]

Photo credit: see page 20.

Contents

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[1] For the latest version of this bibliography, please visit `http://web.mit.edu/klund/www/jw/`.

1 Biography

Jim Williams (1948–2011) was at the Massachusetts Institute of Technology from 1968 to 1979 concentrating exclusively on analog circuit design. His teaching and research interests involved application of analog circuit techniques to biochemical and biomedical problems. Concurrently, he consulted U.S. and foreign concerns and governments, specializing in analog circuits. In 1979, he moved to National Semiconductor Corporation, continuing his work in the analog area with the Linear Integrated Circuits Group. In 1982, he joined Linear Technology Corporation as staff scientist. His interests included product definition, development and support. Jim authored over 350 publications relating to analog circuit design. Awards include the 1992 Innovator of the Year Award from EDN Magazine and election to the Electronic Design Hall of Fame in 2002. His spare time interests included sports cars, collecting antique scientific instruments, art and restoring and using old Tektronix oscilloscopes. He lived in Palo Alto, California with his wife and 62 Tektronix oscilloscopes.[2]

2 Massachusetts Institute of Technology

Jim wrote several M.I.T. internal reports [1, 2, 3, 4] while he worked for the Department of Nutrition and Food Science. Another report [5] was referenced in an EDN article without a publication date.[3]

3 National Semiconductor App Notes

Jim worked for National Semiconductor Corporation in the Linear Integrated Circuits Group from 1979 to 1982. During this period,[4] he wrote 21 application notes.

- App Note 256 [6]
- App Note 260 [7]
- App Note 262 [8]
- App Note 263 [9]
- App Note 264 [10]
- App Note 265 [11]
- App Note 266 [12]
- App Note 269 [13]
- App Note 272 [14]
- App Note 285 [15]
- App Note 286 [16]
- App Note 288 [17]
- App Note 289 [18]
- App Note 292 [19]
- App Note 293 [20]
- App Note 294 [21]
- App Note 295 [22]
- App Note 298 [23]
- App Note 299 [24]
- App Note 301 [25]
- App Note 311 [26]

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[2] The information in this biography was given to the author by Jim Williams in 2009 (see also Appendix A).

[3] There were probably other reports. Unfortunately, the M.I.T. Libraries don't seem to have copies of these reports (or anything written by Jim Williams, except his 1991 and 1995 books). Searching in the M.I.T. Institute Archives and Special Collections didn't turn up anything either.

[4] Getting a complete list of his app notes is a bit of a mystery hunt. There are several unfortunate reasons for this difficulty:

1. National doesn't always print bylines with author's names on their app notes.
2. National regularly deletes old app notes from their archives.
3. National sometimes updates the publication date of their app notes upon revision.

Thus, for all of these application notes, I had to infer Jim's authorship based on the right time period and other clues. One reliable clue was the inclusion of photographs of Jim's Tektronix 556 oscilloscope with the damaged graticule. In other cases, I made educated guesses based on his use of references, footnotes, or subject matter. A reference to one of Jim's past publications is a good hint, a footnote discussing the Hewlett Packard HP200 oscillator is a dead giveaway! Based on this research, there are (at least?) 21 application notes. Not bad for three years' work!

For more details on the frustrations of this mystery hunt, see `http://web.mit.edu/klund/www/jw/jw-nsc.html`.

4 Linear Technology

4.1 App Notes

Jim wrote 62 application notes for Linear Technology Corporation:

- App Note 1 [27]
- App Note 2 [28]
- App Note 3 [29]
- App Note 4 [30]
- App Note 5 [31]
- App Note 6 [32]
- App Note 7 [33]
- App Note 8 [34]
- App Note 9 [35]
- App Note 10 [36]
- App Note 11 [37]
- App Note 12 [38]
- App Note 13 [39]
- App Note 14 [40]
- App Note 15 [41]
- App Note 17 [42]
- App Note 18 [43]
- App Note 21 [44]
- App Note 22 [45]
- App Note 23 [46]
- App Note 25 [47]
- App Note 28 [48]
- App Note 29 [49]
- App Note 31 [50]
- App Note 32 [51]
- App Note 35 [52]
- App Note 37 [53]
- App Note 43 [54]
- App Note 45 [55]
- App Note 47 [56]
- App Note 49 [57]
- App Note 55 [58]
- App Note 61 [59]
- App Note 65 [60]
- App Note 70 [61]
- App Note 72 [62]
- App Note 74 [63]
- App Note 75 [64]
- App Note 79 [65]
- App Note 81 [66]
- App Note 83 [67]
- App Note 85 [68]
- App Note 86 [69]
- App Note 89 [70]
- App Note 90 [71]
- App Note 92 [72]
- App Note 93 [73]
- App Note 94 [74]
- App Note 95 [75]
- App Note 98 [76]
- App Note 101 [77]
- App Note 104 [78]
- App Note 106 [79]
- App Note 112 [80]
- App Note 113 [81]
- App Note 118 [82]
- App Note 120 [83]
- App Note 122 [84]
- App Note 124 [85]
- App Note 126 [86]
- App Note 128 [87]
- App Note 131 [88]

In October 2011, Linear Technology released a sixty-third app note, App Note 132 [89]. Although this note bears his name (as coauthor) and discusses an appropriate topic, (a high-purity sine wave oscillator[5]), Jim's signature touches are absent[6].

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[5] As Jim said in [52], "The sinewave is probably the paramount expression of the analog world. The Old Man Himself, George A. Philbrick, once elegantly discussed analog functions as 'those which are continuous in excursion and time'."

[6] The oscilloscope shots are not from his Tektronix 556, there's no hand-drawn cartoon, there are no voluminous appendices, and there are three pages on computer-screen captures. It just doesn't feel like Jim.

4.2 LT Magazine

Jim wrote several short articles for Linear Technology Magazine between 1991 and 2009:[7]

Volume 1 [90, 91, 92, 93]
Volume 2 [94]
Volume 3 [95, 96, 97]
Volume 4 [98, 99]
Volume 6 [100, 101]
Volume 7 [102]
Volume 8 [103, 104, 105, 106]
Volume 9 [107, 108]
Volume 12 [109]
Volume 15 [110]
Volume 16 [111, 112]
Volume 17 [113]
Volume 19 [114, 115]

4.3 Design Notes and Solutions

Jim also wrote some short (two-page) Design Notes:[8]

- Design Note 8 [116]
- Design Note 11 [117]
- Design Note 17 [118]
- Design Note 32 [119]
- Design Note 38 [120]
- Design Note 40 [121]
- Design Note 44 [122]
- Design Note 45 [123]
- Design Note 51 [124]
- Design Note 52 [125]
- Design Note 58 [126]
- Design Note 70 [127]
- Design Note 101 [128]
- Design Note 137 [129]
- Design Note 163 [130]
- Design Note 164 [131]
- Design Note 185 [132]
- Design Note 190 [133]
- Design Note 220 [134]
- Design Note 345 [135]

He also wrote Design Solution 11 [136][9].

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[7] See `http://www.linear.com/designtools/lt_journal.php`. This list is based on the issues found on the Linear Technology website. There may be some missing issues (there are gaps in the number sequence). For example, volume 11 only has one issue. Other obviously missing issues include vol. 10 no. 3, vol. 12 no. 1, vol. 13 no. 1, and vol. 14 no. 1.

[8] List `http://www.linear.com/doclist/?au=Jim+Williams` is incomplete. It lists all the app notes, but some of the design notes are missing, and there may be other missing items. I have a complete collection up to Design Note 69, but after that, my coverage is incomplete.

[9] Were there other Design Solutions?

5 Books and Book Chapters

Jim edited five books [137, 138, 139, 140, 141].

5.1 EDN Designer's Guides

Jim edited two books of collected articles from EDN in 1985 and 1987. The first one [137] included 25 collected articles from his time at M.I.T., Teledyne Philbrick, Arthur D. Little, and National Semiconductor. The second book [138] included 26 collected articles from the early days at Linear Technology. For a list of articles in these books, see Section B.1.

5.2 Analog Circuit Design

In the 1990s, he edited of two books on analog circuit design [139, 140] with a wide variety of authors submitting chapters. In these books, he authored several chapters himself:

- "Is analog circuit design dead?" [142]
- "Max Wien, Mr. Hewlett, and a rainy Sunday afternoon" [143]
- "Should Ohm's Law be repealed?" [144]
- "The zoo circuit: History, mistakes, and some monkeys design a circuit" [145]
- "The importance of fixing" [146]
- "Tripping the light fantastic" [147]
- "There's no place like home" [148]

5.3 Other Book Chapters

He also contributed a chapter [149] to Bob Pease's book, "Analog Circuits: World Class Designs", which is a reprint of the "The zoo circuit" [145].

5.4 Analog Circuit Design 3

In 2011, he co-edited a third book in this "series" with Bob Dobkin [141]. This final book is a collection of 41 reprinted Linear Technology Application Notes, of which Jim wrote 27:

- Chapter 2 is App Note 101 [77]
- Chapter 4 is App Note 126 [86]
- Chapter 6 is App Note 25 [47]
- Chapter 7 is App Note 35 [52]
- Chapter 8 is App Note 70 [61]
- Chapter 11 is App Note 122 [84]
- Chapter 12 is App Note 83 [67]
- Chapter 15 is App Note 81 [66]
- Chapter 16 is App Note 89 [70]
- Chapter 17 is App Note 90 [71]
- Chapter 18 is App Note 92 [72]
- Chapter 19 is App Note 112 [80]
- Chapter 20 is App Note 7 [33]
- Chapter 22 is App Note 86 [69]
- Chapter 24 is App Note 120 [83]
- Chapter 25 is App Note 3 [29]
- Chapter 26 is App Note 9 [35]
- Chapter 27 is App Note 11 [37]
- Chapter 29 is App Note 23 [46]
- Chapter 30 is App Note 28 [48]
- Chapter 32 is App Note 43 [54]
- Chapter 33 is App Note 47 [56]
- Chapter 34 is App Note 72 [62]
- Chapter 36 is App Note 93 [73]
- Chapter 37 is App Note 94 [74]
- Chapter 38 is App Note 106 [79]
- Chapter 39 is App Note 124 [85]

Unfortunately, unlike his other *Analog Circuit Design* books [139, 140], there is no original material in this book.

6 Magazine Articles

Jim wrote many, many articles in various trade magazines.

6.1 EDN

Papers published between 1975 and 2011. He wrote 35 full-length feature articles that appeared in EDN between June 1983 and November 1987 (according to [150][10]). EDN recently listed[11] some of the articles that he wrote between 1994 and 2011.

1975 [151]
1976 [152]
1977 [153] [154] [155] [156]
1978 [157]
1979 [158]
1980 [159] [160]
1981 [161] [162] [163] [164] [165] [166] [167] [168]
1982 [169] [170] [171] [172] [173] [174]
1983 [175] [176] [177] [178] [179] [180]
1984 [181] [182] [183] [184] [185] [186]
1985 [187] [188] [189] [190] [191] [192] [193] [194] [195] [196]
1986 [197] [198] [199] [200]
1987 [201] [202] [203] [204] [205] [206]
1988 [207] [208] [209] [210] [211] [212]
1989 [213] [214]
1990 [215] [216] [217] [218]
1991 [219] [220] [221] [222] [223] [224] [225] [226]
1992 [227]
1993
1994 [228] [229] [230]
1995 [231] [232] [233]
1996 [234] [235] [236]
1997 [237] [238]
1998 [239] [240] [241]
1999 [242] [243]
2000 [244] [245] [246] [247]
2001 [248] [249] [250] [251] [252]
2002 [253]
2003 [254] [255] [256] [257] [258]
2004 [259] [260]
2005 [261] [262] [263] [150] [264]
2006 [265] [266]
2007 [267] [268]
2008 [269] [270]
2009 [271] [272] [273]
2010 [274] [275] [276]
2011 [277]

6.2 Electronics

Papers published between 1974 and 1981.

1974 [278]
1975 [279] [280]
1980 [281]
1981 [282] [283] [284] [285] [286]

6.3 Electronic Design

Papers published between 1974 and 1985.

1974 [287] [288] [289]
1975 [290]
1977 [291]
1981 [292] [293] [294] [295] [296] [297]
1983 [298]
1984 [299] [300] [301]
1985 [302]

6.4 Other Magazines

Jim wrote a short article for Analog Dialogue in 1976 [303]. He wrote one article in Electronic Engineering in 1983 with George Erdi [304]. He wrote an article in New Electronics [305], an article in ESD [306], an article in VLSI Systems Design [307], an article in EE Times [308], and an article in Electronic Design Analog Applications [309].

Also, there were three articles in Electronic Product Design:

1983 [310]
1984 [311]
1986 [312]

7 Technical Publications

Jim coauthored two papers in Analytical Biochemistry [313, 314] while he was at MIT. Jim co-wrote one ISSCC paper in 1986 [315] on the LT1088 RMS-to-DC converter. He also wrote a 1986 Wescon paper [316].

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[10] Right now, I have 29 of them. He published two papers in May 1983; am I not supposed to count them?

[11] `http://www.edn.com/article/472111-Jim_Williams.php`

A How Many Oscilloscopes?

In the biography that Jim wrote in 2009 (see Section 1), he said he owned 62 Tektronix oscilloscopes. It is interesting to see how this number changed over time. In 1991 [139], he claimed 14 oscilloscopes. In 1995 [140], he claimed 28 oscilloscopes. In 2008 (in the bio with [149]), he claimed 84 oscilloscopes.

B Cross References

B.1 EDN Books

Jim edited two books of his collected articles from EDN.[12] The first book [137] included the following articles (in the order they appear in the book) [158] [175] [170] [173] [163] [172] [155] [166] [171] [168] [165] [317] [153] [318] [167] [319] [174] [151] [164] [157] [160] [161] [159] [154] [162].[13]

The second book [138] included the following articles (in the order they appear in the book) [178] [181] [183] [188] [189] [190] [196] [193] [194] [195] [158] [197] [176] [177] [182] [184] [186] [187] [191] [192] [198] [199] [200] [179] [180] [185].

B.2 National Semi App Notes

He cited some of his magazine articles in two of his app notes for National Semiconductor. These articles that were cited:

App Note 256 referenced [159].
App Note 260 referenced [290, 280, 157, 4].

B.3 Linear Tech App Notes

He cited some of his magazine articles in his app notes for Linear Technology. These articles that were cited (this list does not include cross references to other app notes) :

App Note 9 referenced [290]
App Note 13 referenced [160, 296]
App Note 14 referenced [157]
App Note 22 referenced [315]
App Note 28 referenced [153]
App Note 29 referenced [295, 174]
App Note 49 referenced [315]
App Note 55 referenced [1, 154, 315][14]
App Note 61 referenced [315]
App Note 55 referenced [1, 315]
App Note 70 referenced [295, 174, 209]
App Note 72 referenced [296]
App Note 74 referenced [185]
App Note 75 referenced [157, 185]
App Note 79 referenced [241]
App Note 81 referenced [165, 211]
App Note 83 referenced [315]
App Note 86 referenced [290]
App Note 89 referenced [1, 155]
App Note 92 referenced [183]
App Note 112 referenced [169]
App Note 120 referenced [241, 185]
App Note 128 referenced [241, 185]

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[12] Unfortunately, these books do not include any information about when the articles were originally published. Shameful. All dates listed in the bibliography entries have been found from secondary sources.

[13] I need more information about [317, 318, 319]. I can't find the original publication data.

[14] Reference 20 in this app note is "The Ultimate Oven," MIT Reports on Research, March 1972. This article is about Jim's work, but he didn't write it.

References

[1] Jim Williams, "Temperature controlling to microdegrees," Massachusetts Institute of Technology, Cambridge, Mass., Education Research Center, Oct. 1971.

[2] Jim Williams, "Portable wide range chopper stabilized temperature controller," Massachusetts Institute of Technology, Cambridge, Mass., Dept. of Nutrition and Food Science, 1974.

[3] Jim Williams, "An experimental microprocessor-controlled 18-bit single-slope A/D converter with 1-ppm linearity," Massachusetts Institute of Technology, Cambridge, Mass., Dept. of Nutrition and Food Science, 1975.

[4] Jim Williams, "Characterization, measurement, and compensation of errors in capacitors... a compendium of study, hacks, some good stuff, and a few pearls," Massachusetts Institute of Technology, Cambridge, Mass., Dept. of Nutrition and Food Science, 1975.

[5] Jim Williams, "A 0.1-Hz sine wave oscillator using thermal feedback," Massachusetts Institute of Technology, Cambridge, Mass., Dept. of Nutrition and Food Science, unknown date.

[6] Jim Williams, "Circuitry for inexpensive relative humidity measurement," National Semiconductor Corp., Santa Clara, Calif., Application Note 256, Aug. 1981.

[7] Jim Williams, "A 20-bit (1 ppm) linear slope-integrating A/D converter," National Semiconductor Corp., Santa Clara, Calif., Application Note 260, Jan. 1981.

[8] Jim Williams, "Applying dual and quad FET op amps," National Semiconductor Corp., Santa Clara, Calif., Application Note 262, May 1981.

[9] Jim Williams, "Sine wave generation techniques," National Semiconductor Corp., Santa Clara, Calif., Application Note 263, Mar. 1981.

[10] Jim Williams, "Applications of audio amplifier–transistor array ICs," National Semiconductor Corp., Santa Clara, Calif., Application Note 264, May 1981.

[11] Jim Williams, "An electronic watt-watt-hour meter," National Semiconductor Corp., Santa Clara, Calif., Application Note 265, Feb. 1984.

[12] Jim Williams, "Circuit applications of sample-hold amplifiers," National Semiconductor Corp., Santa Clara, Calif., Application Note 266, Jan. 1981.

[13] Jim Williams, "Circuit applications of multiplying CMOS D to A converters," National Semiconductor Corp., Santa Clara, Calif., Application Note 269, Sep. 1981.

[14] Jim Williams, "Op amp booster designs," National Semiconductor Corp., Santa Clara, Calif., Application Note 272, Sep. 1981.

[15] Jim Williams, "An acoustic transformer powered super-high isolation amplifier," National Semiconductor Corp., Santa Clara, Calif., Application Note 285, Oct. 1981.

[16] Jim Williams, "Applications of the LM392 comparator op amp IC," National Semiconductor Corp., Santa Clara, Calif., Application Note 286, Sep. 1981.

[17] Jim Williams, "System-oriented DC-DC conversion techniques," National Semiconductor Corp., Santa Clara, Calif., Application Note 288, Apr. 1982.

[18] Jim Williams, "Circuit applications of analog data multiplexers," National Semiconductor Corp., Santa Clara, Calif., Application Note 289, Jan. 1982.

[19] Jim Williams, "Applications of the LM3524 pulse-width-modulator," National Semiconductor Corp., Santa Clara, Calif., Application Note 292, Aug. 1982.

[20] Jim Williams, "Control applications of CMOS DACs," National Semiconductor Corp., Santa Clara, Calif., Application Note 293, Mar. 1982.

[21] Jim Williams, "Special sample and hold techniques," National Semiconductor Corp., Santa Clara, Calif., Application Note 294, Apr. 1982.

[22] Jim Williams, "A high performance industrial weighing system," National Semiconductor Corp., Santa Clara, Calif., Application Note 295, Mar. 1982.

[23] Jim Williams, "Isolation techniques for signal conditioning," National Semiconductor Corp., Santa Clara, Calif., Application Note 298, May 1982.

[24] Jim Williams, "Audio applications of linear integrated circuits," National Semiconductor Corp., Santa Clara, Calif., Application Note 299, Apr. 1982.

[25] Jim Williams, "Signal conditioning for sophisicated transducers," National Semiconductor Corp., Santa Clara, Calif., Application Note 301, Jan. 1982.

[26] Jim Williams, "Theory and applications of logarithmic amplifiers," National Semiconductor Corp., Santa Clara, Calif., Application Note 311, Jul. 1982.

[27] Jim Williams, "Understanding and applying the LT1005 multifunction regulator," Linear Technology Corp., Milpitas, Calif., Application Note 1, Aug. 1985.

[28] Jim Williams, "Performance enhancement techniques for three-terminal regulators," Linear Technology Corp., Milpitas, Calif., Application Note 2, Aug. 1984.

[29] Jim Williams, "Applications for a switched-capacitor instrumentation building block," Linear Technology Corp., Milpitas, Calif., Application Note 3, Jul. 1985.

[30] Jim Williams, "Applications for a new power buffer," Linear Technology Corp., Milpitas, Calif., Application Note 4, Sep. 1984.

[31] Jim Williams, "Thermal techniques in measurement and control circuitry," Linear Technology Corp., Milpitas, Calif., Application Note 5, Dec. 1984.

[32] Jim Williams, "Applications of new precision op amps," Linear Technology Corp., Milpitas, Calif., Application Note 6, Jan. 1985.

[33] Jim Williams, "Some techniques for direct digitization of transducer outputs," Linear Technology Corp., Milpitas, Calif., Application Note 7, Feb. 1985.

[34] Jim Williams, "Power conditioning techniques for batteries," Linear Technology Corp., Milpitas, Calif., Application Note 8, May 1985.

[35] Jim Williams, "Application considerations and circuits for a new chopper-stabilized op amp," Linear Technology Corp., Milpitas, Calif., Application Note 9, Aug. 1986.

[36] Jim Williams, "Methods for measuring op amp settling time," Linear Technology Corp., Milpitas, Calif., Application Note 10, Jul. 1985.

[37] Jim Williams, "Designing linear circuits for 5V single supply operation," Linear Technology Corp., Milpitas, Calif., Application Note 11, Sep. 1985.

[38] Jim Williams, "Circuit techniques for clock sources," Linear Technology Corp., Milpitas, Calif., Application Note 12, Oct. 1985.

[39] Jim Williams, "High speed comparator techniques," Linear Technology Corp., Milpitas, Calif., Application Note 13, Apr. 1985.

[40] Jim Williams, "Designs for high performance voltage-to-frequency converters," Linear Technology Corp., Milpitas, Calif., Application Note 14, Mar. 1986.

[41] Jim Williams, "Circuitry for single cell operation," Linear Technology Corp., Milpitas, Calif., Application Note 15, Nov. 1985.

[42] Jim Williams, "Considerations for successive approximation A→D converters," Linear Technology Corp., Milpitas, Calif., Application Note 17, Dec. 1985.

[43] Jim Williams, "Power gain stages for monolithic amplifiers," Linear Technology Corp., Milpitas, Calif., Application Note 18, Mar. 1986.

[44] Jim Williams, "Composite amplifiers," Linear Technology Corp., Milpitas, Calif., Application Note 21, Jul. 1986.

[45] Jim Williams, "A monolithic IC for 100MHz RMS-DC conversion," Linear Technology Corp., Milpitas, Calif., Application Note 22, Sep. 1987.

[46] Jim Williams, "Micropower circuits for signal conditioning," Linear Technology Corp., Milpitas, Calif., Application Note 23, Apr. 1987.

[47] Jim Williams, "Switching regulators for poets: A gentle guide for the trepidatious," Linear Technology Corp., Milpitas, Calif., Application Note 25, Sep. 1987.

[48] Jim Williams, "Thermocouple measurement," Linear Technology Corp., Milpitas, Calif., Application Note 28, Feb. 1988.

[49] Jim Williams and Brian Huffman, "Some thoughts on DC-DC converters," Linear Technology Corp., Milpitas, Calif., Application Note 29, Oct. 1988.

[50] Jim Williams, "Linear circuits for digital systems: Some affable analogs for digital devotees," Linear Technology Corp., Milpitas, Calif., Application Note 31, Feb. 1989.

[51] Jim Williams, "High efficiency linear regulators," Linear Technology Corp., Milpitas, Calif., Application Note 32, Mar. 1989.

[52] Jim Williams, “Step down switching regulators,” Linear Technology Corp., Milpitas, Calif., Application Note 35, Aug. 1989.

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Revision History

- **v0.1** Linear Technology application notes[15] and “Analog Circuit Design” books (72 references)
- **v0.2** National Semiconductor application notes[16] and EDN “Designer’s Guide” books (95 references)
- **v0.3** Magazine articles culled from the references in LT app notes (113 references)
- **v0.4** EDN articles culled from EDN books and EDN online listing[17] (220 references)
- **v0.5** Adding LTC design notes and data from various online sources and databases (288 references, that’s over 80% of 350 found!)
- **v0.6** First public release, 31 July 2011
- **v0.7** Added data on final book [141] in Section 5.4 and did a little reformatting
- **v0.8** Added information received from Siu Williams, also Appendix A, more articles from LT Magazine, [89] and [149] (319 references)

Known Errors

Other than being incomplete, there are no known errors in this list.

- The footnotes in the text detail some of the missing information
- Some EDN articles are missing volume, number, and pages
- Some EDN articles have page numbers from the European Edition (postfix e)
- I do not plan to include foreign-language translations in this bibliography

Please contact the author if you find any omissions, errors, or other problems.

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Colophon

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CTLdash_repeated_names = "no",
CTLname_format_string = "{ff }{vv~}{ll}{, jj}", }
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[15] `http://www.linear.com/doclist/?au=Jim+Williams`

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