APPENDIX

NOMENCLATURE

Admittance: For sinusoidal signals, the incremental ratio of a current to a voltage. A *self-admittance* describes the current-voltage relationship in a two-terminal element; a *driving-point* admittance relates the current into a terminal to the voltage between that terminal and common; a *trans-admittance*, in general, relates a current into any terminal of a circuit to a voltage between any pair of terminals.

Arbitrary Function Fitter: A circuit having an output voltage or current that is a presettable, adjustable, (usually non-linear) function of the input voltage(s) or current(s) fed to it.

Bandwidth: Generally, the frequency range over which a particular transfer characteristic (i.e., gain, attenuation, phase-shift, etc.) is maintained between two sets of terminals (i.e., input and output). In an Operational Amplifier, the frequency range over which the open-loop gain exceeds unity. In an Operational-Amplifier *circuit*, the frequency range over which the (small-signal) loop gain maintains the desired response, to the desired accuracy.

Bias Circuit: A (fixed or adjustable) circuit that is used to set amplifier (zero-signal) input-current or input-voltage level to an arbitrary value (normally zero). May be "temperature-compensating" . . . i.e., able to track the variation of amplifier input voltage or current with temperature, more or less perfectly.

Booster Amplifier: A circuit used to increase the output current or voltage capabilities of an Operational Amplifier circuit, without loss of accuracy (ideally) or inversion of polarity. Usually applied *inside* the loop, for accuracy.

Bound Circuit: A circuit designed to limit the excursion of a signal. The limit value it establishes may be nominal (when used for protection), or highly-precise (when used operationally).

Chopper: A circuit or device for interrupting (or at least modifying) a low-frequency signal path at a constant rate (i.e., carrier frequency), producing a wave, which is modulated by the DC signal magnitude, preserving the polarity of the DC signal. Generally associated with a *synchronous demodulator*, following amplification.

Common-Mode Error (CME): (referred to the input) A (generally) small offset voltage appearing between the input terminals of a differential operational amplifier, as a function of the *common-mode* voltage.

Common-Mode Rejection Ratio (CMRR): The ratio of common-mode voltage to common-mode error in a differential amplifier circuit.

Common-Mode Voltage: The voltage between the output signal return and (in this book) the positive input terminal of a differential operational amplifier.

Comparator, Precision: A high-gain amplifier circuit whose output changes decisively between two definite levels whenever the sum of the input voltages changes sign.

Controller: A portion of a feedback system in which the unregulated unbalance (or "error") signal is operated on by adjustable dynamic elements (proportional, integral, derivative, lead-lag, etc.) to affect the manipulated variable in such a way that desirable response criteria for the loop (stability, speed, accuracy) may be met.

Current Bias: See Bias.

Current Pump: A circuit that drives, through an external (load) circuit, an adjustable variable or constant value of current, regardless of the reaction of that load to the current, within rated limits of current, voltage, and load impedance.

Damping Circuit: A circuit used to limit, control, or prevent dynamic instability (oscillation or "ringing") in a closed-loop active circuit, or in a complex passive network having appreciable second-order (or higher-order) response.

Dead Zone: A range in which no output change is produced by substantial input variations; a circuit element having such response (or lack of response).

Differential-Input Amplifier: One in which the output is (ideally) a function only of the *difference* between the signals applied to its two inputs, both signals being measured with respect to a common "low," or "ground" reference point.

Differentiator: Ideally, a circuit having a response (output) proportional to the time-derivative(s) of one or more input signals.

Diode Bounding: A form of *Bounding* in which the nonlinear conducting properties of a diode (or diodes) are used to accomplish the magnitude-limiting action.

DC Beta: The DC current gain of a transistor; the ratio of the collector current to the base current that caused it, measured at constant collecter to emitter voltage.

Drift: A gradually-developing deviation in any voltage, current or impedance. For an Operational Amplifier, a gradually-developing change in the offset voltage or in either or both of the offset currents. Also, the bottom-most frequency range of the noise spectrum.

Electrometer Amplifier: An Amplifier circuit having sufficiently low-current drift and other noise components, sufficiently low amplifier input-current offsets, and adequate power and current sensitivities to be usable for measuring current variations considerably less than 10^{-12} A.

Emitter-Follower: In principle, a single-transistor amplifier in which the load is connected between the emitter and signal ground, so that the base-to-emitter-to-ground path (for the input signal) contains 100% negative feedback of the output voltage. The collector is returned (in principle) directly to the power supply. The gain is very nearly unity and the output signal is *not* inverted (i.e., it "follows" the input).

Error-Factor, Finite-Gain: That factor by which the "ideal" closed-loop response expression must be multiplied to yield the response for an amplifier with *finite* gain, A, rather than infinite gain, as is assumed in computing the "ideal" response.

Fault Current: The current that may flow in any part of a circuit or amplifier under (specified) abnormal conditions.

Follower-With-Gain: A Follower (which see) in which only a *part* of the output voltage is fed back in series opposition to the input signal . . . hence, closed-loop gain greater than unity is obtained over the rated range of operation.

Feedback Circuit: A causal circuit configuration in which (for the simplest circuit) the input and the output variables are combined and together determine the output.

Flicker: Noise in an amplifier, of higher frequency than drift, but lower than power-line or chopper-drive frequency noise. Also called "jitter" or "wobble."

Follower: A circuit in which the output of a high-gain amplifier is fed directly back to its negative input. The input signal is reproduced without polarity reversal. See also Emitter Follower, and Follower with Gain.

Flip-Flop: See Multivibrator, Bistable.

Frequency, Angular: The rate of change of the angle of a sine wave, expressed in radians per second, where 2π radians (360°) = 1 alternation (cycle).

Frequency, Break: In a plot of log gain (attenuation) vs. log frequency, the frequency at which the asymptotes of two adjacent linear slope segments meet.

Gain-Bandwidth Product: (1) The product of a specific frequency and the gain of a circuit, amplifier, or system *at* that frequency.

(2) For an Operational Amplifier, or any other circuit or device having the special property that its gain is inversely proportional to frequency, the G. B. P. is equal to the frequency at which the gain falls (by extrapolation) to unity.

Gain, Closed-Loop: The response of a feedback circuit to a voltage inserted in series with the *amplifier* input. Also the "noise gain."

Gain, Loop: In an Operational Amplifier circuit, the product of the transfer characteristics of all of the elements (active or passive) encountered in a complete trip around the loop, starting at any point and returning to that point.

Gain, Open Loop: The ratio of the (loaded) output of an Amplifier to its net input, at any frequency. Usually implies *voltage gain*.

Gate, Precision: A circuit that may be switched from closed- to open-circuit or vice versa without error (time, bias, impedance) in response to a command signal (voltage or current).

Ground, Chassis: The potential (assumed uniform) of the (metallic) structure on or in which the circuit is built.

Ground, Power-Common: The potential of the terminal or circuit point to which the output of a power supply (and often an amplifier output load) is returned (i.e., power-supply "zero").

Ground, Signal (or High-Quality): The potential of a terminal or circuit point to which all signal voltages are referenced, by convention or arbitrary assumption. Usually the signal-return of the lowest-level signal in a system.

"Hold" Mode: In integrators or other charge-storage circuits, a condition (or time-interval) in which input(s) are removed and the circuit is commanded (or expected) to maintain constant output.

Hysteresis: A form of non-linearity in which the response of a circuit to a particular set of input conditions depends, not only on the instantaneous values of those conditions, but also on the immediate past (recent history) of the input and output signals. Hysteretical behaviour is characterized by inability to "retrace" exactly on the reverse swing a particular locus of input/output conditions.

Idling Current: The zero-signal power supply current drawn by a circuit, or by a complete amplifier. Also called "Quiescent" current.

Impedance, Input, Common-Mode: The (internal) impedance between either one of the input terminals of a differential Operational Amplifier and signal ground.

Impedance, Input, Differential: The (internal) impedance observed between the input terminals of an Operational Amplifier.

Impedance, Negative: In general, the driving-point impedance of circuit in which a current increase produces a voltage decrease (and vice versa); for a *negative admittance*, a voltage increase produces a current decrease, and vice versa.

Integrator: A circuit having a response (output) proportional to the time-integral of one or more input signals.

Inverter, Voltage: A circuit having a response (output) proportional to a constant (the *gain*) times the input signal, but opposite in sign to it. In a unity-gain inverter, the output is (-1) times the input.

Lag: (noun) a delayed-response characteristic, or a circuit having such a delayed response. Usually 1st-order lag is implied unless otherwise specified.

(verb) to respond to a stimulus in delayed fashion.

Lag-Lead (lead-lag): A circuit whose response includes lag components and their derivatives.

Leakage: (Unwanted) current flow through a nominally-blocked (non-conducting) circuit or circuit element due to imperfections in its blocking behavior.

Limits: (See Bounds)

Memory, Peak or Valley Readout: A circuit in which the output remains at the condition corresponding to the most positive (least negative) or vice versa input signal since the circuit was set to initial conditions, until reset to those conditions.

Multiplier, Quarter-Square: A circuit that achieves true four-quadrant multiplication by taking advantage of the mathematical relationship that the product of two variables is equal to one quarter of the difference of the squares of the sum and the difference of the variables.

Multivibrator, Astable (free-running): A circuit having two momentarily stable states, between which it continuously alternates, remaining in each for a period controlled by the circuit parameters, and switching rapidly from one to the other.

Multivibrator, Bistable (Flip-Flop): A circuit having two stable states, in either one of which it will stay indefinitely, until triggered appropriately, immediately after which it switches to the other state.

Multivibrator, Monostable (one-shot): A circuit having only one stable state, from which it can be triggered to change state, but only for a predetermined interval, after which it returns to the original state.

Noise, amplifier: All spurious or unwanted signals, random or otherwise, that can be observed in a completely isolated amplifier in the absence of a genuine input signal. (See also: Drift and Flicker.)

Null Detector: A comparator (which see) having zero reference voltage. A *graded-null* detector has decreasing sensitivity away from the null.

Offset Current: A DC error current appearing at either input terminal of a DC amplifier.

Offset Voltage: A DC error voltage appearing in series with either input terminal of a DC amplifier.

Offset, End-Resistance: In potentiometers, the residual resistance between a terminal and the moving contact, at a position corresponding to full rotation against that terminal.

Passive Network: A network whose net influx (or efflux) of available energy is stored or dissipated within the network. There may be no sources of energy other than those explicitly bookkept as influxes.

Phase Characteristic: A graph of phase shift vs. frequency, assuming sinusoidal input and output.

Phase Shift: Phase angle between two related variables in a circuit (usually input and output voltage) when excited by sinusoidal signal(s).

Rate Limiting: Non-linear behavior in an amplifier due to its limited ability to produce large, rapid changes in output voltage (slewing)—restricting it to rates of change of voltage lower than might be predicted by observing the small-signal frequency response.

Reset Mode (Set Mode): In integrators, memories, or other charge-storage circuits, a state (or time-interval) in which the circuit is forced to return to a set of initial conditions, removing all record of its previous condition.

RMS Value: The square root of the time average of the square of a variable signal.

Roll-Off: The decrease in magnitude of gain with frequency. Typical roll-off (low-pass) of a circuit for which the dominant lag is first-order is 6 db per octave (inversely proportional to frequency). "Steep" roll-off might be at 12 or 18 db per octave (proportional to the inverse square or cube of frequency) or more.

Saturation Voltage: Generally, the voltage excursion at which a circuit self-limits . . . i.e., is unable to respond to excitation in a proportional manner. In Operational Amplifiers, the output-voltage saturation limits may be imposed by any stage, from the input to the output, depending in part on the external loading and feedback parameters.

Scaling: Adjusting the coefficient of a circuit to each of its one or more input signal terminals. The *relative* scaling (of one input to another) is called "weighting." In computing, relating problem variables to machine variables.

Slewing Rate: See Rate Limiting.

Soakage: The disability of a capacitor to come up to voltage instantaneously, without voltage lag or creep, during or after charging. The lower the soakage, the lower the lag and creep.

Stabilizer: (DC) A circuit that uses a chopper and preamplifier to maintain the net offset near zero at the input terminals of an Operational Amplifier. (See Chopper-Stabilized.)

(Dynamic) An element or circuit employed to promote dynamic stability, also *damper*.

Subtractor: An Operational Amplifier circuit in which the output is proportional to the difference between its two input voltages (or between the net sums of its positive and negative inputs).

Time Integral: The definite integral of a variable over an interval of time. Also the area under a curve of a function of time during that period. Divide it by the time interval to obtain the average value of the argument over that period.

Track-Hold Memory: A circuit that, in its "track" mode, develops an output that follows (ideally) the input exactly, or is proportional to it; and then, in its "hold" mode, maintains the output constant (ideally) at the value it had at the instant the circuit was commanded to change from "track" to "hold."

Transconductor: A device that produces a current at a given point in the circuit (usually an amplifier's summing point) as a function of a voltage or voltages, usually at its input or output.

Transdiode: A transistor so connected that base and collector are actively maintained at equal potentials, though not connected together. The logarithmic transfer relationship between collector current and base-emitter voltage very closely approximates that of an *ideal* diode.

Uncertainty, Input: In an Operational Amplifier, the algebraic sum of all the factors, including environmental and time effects, that contribute to the non-ideal behavior of the input circuit. See Sections I.7–14.

Weighting: See Scaling.

SYMBOLOGY

NOTE: This list includes terms used more or less frequently throughout the preceding pages, some of them in special senses. It omits familiar conventional symbols such as A (amperes), Hz (cycles/sec), π (3.1416), and Ω (ohms). Specific references, where given, are to modules where the symbol is first, or characteristically, used. Such physical quantities as voltage, current, etc., are described by lower-case symbols when circuit variables, upper case when constants or magnitudes.

SYMBOL	TERM	UNITS	EXPLANATION
A	Gain		Operational Amplifier open-loop voltage gain
A_0	Gain		Same, at DC
B	Booster Amplifier Normalized Bandwidth Bias Supply	Hz (cps) Radians/sec	See I.8
C	Capacitance, capacitor	Farads	Often with identifying subscripts e.g. C_a, C_2
C_c			Compensating capacitor
C_L			Capacitance of load, or capacitor that is part of load
C_s			Stray capacitance (general); capacitance from negative summing point to common
C_{STD}			Standard capacitance or capacitor
CME	Common-mode error	Volts	The effective offset voltage appearing between the amplifier input terminals as a consequence of the voltage level of the positive input (Common-mode voltage)
$CMRR$	Common-mode rejection ratio		$\frac{CMV}{CME}$
CMR		Decibels	The logarithmic form of $CMRR$. $CMR = 20 \log_{10} CMRR$
CMV	Common-mode voltage	Volts	See Nomenclature
D	Diode		
E	Voltage	Volts	DC reference voltage level, or effective reference voltage level
E_B			Power supply or zener diode breakdown voltage
E_b			Power supply or battery
E_{bb}			Battery terminal voltage
E_{in}			DC input signal level
E_n, E_0	Voltage, constant	Volts	DC null (or error) voltage

SYMBOL	TERM	UNITS	EXPLANATION
E_R			Generally, the voltage across a resistor
E_r, E_{REF}			Reference or bias
E_{RESET}			Level at which an initial condition is set
E_s			Generally, the reference level around which a signal varies
E_Z			Voltage across a Zener diode
e	Signal voltage	Volts	Output of operational circuit. Rarely e_o (never e_0) in Philbrick Literature
e_0, e_1, e_2			Input signal, also e_{in}, e_s
e_A, e_B			Signal voltages at points A and B in a circuit (to ground)
e_g			Signal generator output voltage Gate logic input
e_i, e_j			Two signal voltages in a numbered series
e_{LG}			AC signal voltage introduced by power line coupling to or from ground (see I.28)
e_N			Noise voltage source
e_n			Null voltage of an Operational Amplifier (error voltage)
f	Frequency	Hertz (cps)	
f_H	Frequency, high		The frequency at which amplifier open-loop gain is unity gain-bandwidth product product (see also ω_H)
G	Conductance	mho, ℧	
HQG	High Quality Ground		Signal ground; reference for lowest-level signal in the system (as opposed to chassis ground, earth, or power common)
I	DC current	Ampere	

SYMBOL	TERM	UNITS	EXPLANATION
I_A, I_B			Bias or reference current into or out of amplifier input terminal
I_o			Offset current
I_{oA}, I_{oB}			Offset currents associated with amplifier input terminals
I_{ss}	Current	(Amperes)	Idling current or steady-state component of current
i			Signal current; also the dynamic component of current; usually with identifying subscripts
i_D			Diode current
i_{in}			Input current
i_L			Load current
i_M, I_M			Meter current
i_{NA}, i_{NB}			Noise current associated with amplifier input terminals
i_s			Signal current
j	$\sqrt{-1}$		Imaginary term operator in a complex expression (mathematical "i")
K, k	Arbitrary constants		(Often with subscripts)
k	Boltzmann's Constant	Joule/degree K	1.38054×10^{-23}
M	Meter		
P	Potentiometer		
p	Heaviside operator	sec^{-1}	$py \equiv \frac{dy}{dt}, \frac{1}{p}y = \int y dt$
Q	Quality factor		Of a circuit or component; specifically the ratio of energy storage to energy dissipation therein. ($Q = \frac{1}{2} \zeta$) Also, charge (i.e., on a capacitor) (coulombs)
q	Charge	Coulomb	For example, charge of an electron
R	Resistance, resistor	ohms Ω	Usually with identifying subscripts
R_A, R_B			Input resistance, terminal A, terminal B to power common
R_{AB}			Input resistance, terminal A to terminal B
R_{be}			Base-emitter resistance of a transistor (sometimes r_{be})
R_i			Internal resistance, of an Operational Amplifier output circuit
R_{in}			Input circuit resistance or resistor
R_L			Resistive component of load
R_m			Meter resistance
R_s			Source resistance
R_{STD}			Standard (or reference) resistance or resistor
R_x			Unknown resistor or resistor to be measured

SYMBOL	TERM	UNITS	EXPLANATION
S	Switch		
T	Absolute temperature Time Constant RC	Degrees K Seconds	Sometimes θ (°C)
t	Time	Seconds	
V	Voltmeter		
V, v	Voltage	Volts	(See also E or e)
V_o			Offset voltage
V_{oB}			Offset voltage between amplifier input terminals
V_d			Junction voltage drop
V_f, v_f			Diode forward drop
X_c	Capacitive reactance	ohms Ω	
Y	Admittance	mhos ℧	The inverse of impedance, $Y = G + jB$ (for continuous sine waves)
Z	Impedance	ohms Ω	$Z = R + jX$ (for continuous sine waves)
Z_A, Z_B			Input impedance, terminal A to ground, terminal B to ground
Z_{AB}			Input impedance, terminal A to terminal B
Z_{AG}, Z_{BG}			Input impedance to ground, same as Z_A, Z_B
Z_f			Generally, feedback impedance
Z_{in}			Generally, input impedance
Z_L			Load impedance
Z_{REF}			Reference impedance or Z_{STD}, Standard impedance
Z_{ω_0}			Impedance at ω_0 i.e., at center frequency
α	Noise components, resistance ratio		
β	Feedback divider ratio Transistor current gain		Complex attenuation of feedback paths
$\Delta e, \delta e$	Null or error voltage		
ϵ	Base of natural logarithms		
θ	Phase angle	Degrees or radians	
	PHILBRICK/NEXUS		Leadership in feedback technology
ρ	Ratio		Fractional rotation of a potentiometer or rheostat
τ	Time interval, or time constant		
ϕ	Phase, phase shift		Also angle of phase shift
ω	Angular frequency	Radians/sec	$\equiv 2\pi f$
ω_C	Critical frequency		Or cutoff frequency: ω_{CU} and ω_{CL} are upper and lower cutoff frequencies
ω_H	Upper radian frequency		$2\pi f_H$ see f_H
ω_0	Center frequency		$\omega_0 = \sqrt{\omega_{CU}\,\omega_{CL}}$

BIBLIOGRAPHY

The Analog Art and the Operational Amplifier are inseparable, having common roots in feedback; and both have been sources of fascination to us during the past twenty years and more. Although the Operational Amplifier seems destined for a grand future as a component in instrumentation and "building-block" electronics, one can always find refreshment, inspiration, and guidance at the Source. As an example, we list here an incomplete sampling of the books to be found—not in our library, but—in our offices and laboratories, and, opened, on the desks of our engineers. Please note the rather heavy emphasis on Analoguery.

Following that list is one of articles and publications printed or reprinted by us in recent years and still available at no charge, arranged by subject. For a more comprehensive (though somewhat dated) list, see *The Lightning Empiricist*, Volume 12, Number 2, April, 1964. Admittedly, even these are but a drop in the ocean of literature that has been and (especially) is *yet to be* written on this subject.

For those who would dig even more deeply, we suggest reference to the applications publications of companies that manufacture analog products. Readers of this Publication are of course invited to keep up to date via the Philbrick mailing list. Among these, one should consider the continuing evolution of our own *Applications Briefs*, *The Lightning Empiricist*, new reprints, technical data, and catalog documentation. We also recommend to our readers the splendid service, now performed by Simulation Councils, Inc., of La Jolla, California, in their journal, *Simulation*, entitled "Simulation Survey and Literature Review," formerly published at the Georgia Institute of Technology as *Analog Computers Literature Review*, by Mr. L. W. Ross.

BOOKS

Analog Computation	Jackson	McGraw-Hill
Analog Computing in Engineering Design	Rogers & Connolly	McGraw-Hill
Analog Simulation	Karplus	McGraw-Hill
Analogue and Digital Computer Methods in Engineering Analysis	James, Smith, & Wolford	International Textbook Company
Analogue Computation (4 Vols.)	Fifer	McGraw-Hill
Analogue Computers (Translated from the Russian)	Eterman	Pergamon Press
Analogue Computing at Ultra High Speed	MacKay & Fisher	Wiley
Computer Handbook	Huskey & Korn	McGraw-Hill
Computers in Education	Hall	Pergamon Press
Design Fundamentals of Analog Computer Components	Howe	D. Van Nostrand Co.
Electronic Analog and Hybrid Computers	Korn & Korn	McGraw-Hill
Electronics for Scientists	Malmstadt, Enke, & Toren	W. A. Benjamin, Inc.
Elektronischer Analogrechner	Ernst	R. Oldenbourg, Munich
Experiments in Electronics	Evans	Prentice-Hall
Generalized Instrumentation for Research and Teaching	Morrison	Washington State U. Press (reprinted by and available gratis from Philbrick Researches)
Handbook of Computers and Control	Grabbe, Ramo, Wooldridge (Editors)	Wiley
High Speed Analog Computers	Tomovic & Karplus	Wiley
Introduction to Analog Computation	Ashley	Wiley
Introduction to Electronic Analog Computers	Warfield	Prentice-Hall
Introduction to Feedback Systems	Harris	Wiley
Mathematical Machines (Vol. 2)	Murray	Columbia U. Press
A Palimpsest on the Electronic Analog Art	Paynter	Philbrick Researches

REPRINTS & ARTICLES

I. APPLICATIONS

A. Bio-Medical Analysis

"Analog Computation of Respiratory Response Curve" T. W. Murphy, Memorial Sloan-Kettering Cancer Center, and R. Crane, Electronic Gear, Inc. (Reprint No. 41)

"A New Instrument For The Summation Of Evoked Responses From The Nervous System" Burton S. Rosner, Ph.D., Truett Allison, M.A., Elliot Swanson, B.S.E.E., and William R. Goff, Ph.D., West Haven Veterans Administration Hospital, Yale University School of Medicine, and Ampex Corporation. (Reprint No. 37)

"Respiratory Carbon Dioxide Response Curve Computer" J. Weldon Bellville, Sloan-Kettering Institute, and J. C. Seed, Wellcome Research Laboratory. (Reprint No. 26)

B. Computors

"Analog Techniques Applied To Business Models" F. M. Verzuh and P. D. Hansen. *The Lightning Empiricist* (XII:1).

"Analog Yesterday, Today & Tomorrow" G. A. Philbrick. *The Lightning Empiricist* (XI:4).

"Automatic Digital Setup and Scaling of Analog Computers" Dr. Henry M. Paynter, Massachusetts Institute of Technology, and Julian Suez, International Business Machines Corporation. (Reprint No. 47)

"Intentionally Unconventional Analoguery" *The Lightning Empiricist* (XI:1).

"Matrix Programming Of Electronic Analog Computers" R. E. Horn, Westinghouse Electric Corporation, and P. M. Honnell, Washington University. (Reprint No. 2)

"Modern Analog Computing Machines" G. A. Philbrick, Philbrick Researches, Inc.

"A New Active-Passive Network Simulator For Transient Field Problems" Walter J. Karplus, Dept. of Engineering, University of California. (Reprint No. 31)

"Precision Analog Memory Has Extended Frequency Response" T. A. Brubaker, Dept. of Electrical Engineering, University of Arizona. (Reprint No. 36)

"A Report To Engineers And Management" George A. Philbrick Researches, Inc. (Reprint No. 24)

"Ordering and Selection Processes and Ultra-Reliable Systems" H. M. Paynter, Massachusetts Institute of Technology.

"Time Domain Synthesis Based On A Passive Tardigrade Module" *The Lightning Empiricist* (XI:3).

C. Industrial Process Analysis

"Operational Amplifier Techniques in Process Control" Dr. Peter D. Hansen, Philbrick Researches, Inc. (Reprint No. 45)

"Computer Representations of Engineering Systems Involving Fluid Transients" F. D. Ezekiel, Massachusetts Institute of Technology, and H. M. Paynter, Massachusetts Institute of Technology. (Reprint No. 12)

"Contribution to the Stability Theory of Systems of Surge Tanks" Charles Jaeger, Water Turbine Dept., English Electric Company Limited. (Reprint No. 3)

"Dynamic Analysis of Heat Exchanger Control" Bruce D. Hainsworth, The Foxboro Company, Vincent V. Tivy, The Foxboro Company, and Dr. Henry M. Paynter, Massachusetts Institute of Technology. (Reprint No. 1)

"Fast Time Scale Simulation of a Reactor Control System" G. Friedensohn, Nuclear Dev. Corp. of America, and D. H. Sheingold, Philbrick Researches, Inc. (Reprint No. 11)

"Hydraulics by Analog" Henry M. Paynter, Massachusetts Institute of Technology. (Reprint No. 8)

"On an Analogy Between Stochastic Processes and Monotone Dynamic Systems" H. M. Paynter, M.I.T. (Reprint No. 5)

D. Instrumentation

"Capabilities of Some Non-Linear Instrument Circuits for Low-Level Transients" Bruce Seddon, Philbrick Researches, Inc. (Reprint No. 40)

"Vacuum Tube Electrometers Using Operational Amplifiers" G. F. Vanderschmidt, Lion Research Corporation. (Reprint No. 30)

"Subaudio Tunable Amplifier" J. M. Reece, Naval Research Lab. (Reprint No. 29)

"Operational Amplifier as Direct-Reading Precision Resistance Comparator" Philbrick Researches, Inc. Application Brief.

"P65A's Used to Form a Low-Noise Differential Instrument Amplifier" Philbrick Researches, Inc. Application Brief.

"A Precision Amplitude-Distribution Amplifier" W. F. Caldwell, G. A. Korn. V. R. Latorre, and G. R. Peterson, Dept. of Elec. Engrg., University of Arizona. (Reprint No. 28)

"Instrumentation Based on Operational Amplifiers" (Parts I & II). C. N. Reilley, University of North Carolina. (Reprint No. 42)

"Controlled-Potential and Derivative Polarograph" and "Controlled-Potential Polarographic Polarizing Unit with Electronic Scan and Linear Residual Current Compensation" M. T. Kelley, H. C. Jones, and D. J. Fisher, Oak Ridge National Laboratory. (Reprint No. 25)

"Electronic Analog Instruments As Tools of Research & Development" George A. Philbrick, Philbrick Researches, Inc. (Reprint No. 35)

"Electronic Controlled-Potential Coulometric Titrator" M. T. Kelley, H. C. Jones, and D. J. Fisher, Oak Ridge National Laboratory. (Reprint No. 20)

"Electronic Determination of the I, G, and I/G Parameters of a Tunnel Diode" C. R. Gneiting, The Johns Hopkins University, Radiation Laboratory. (Reprint No. 34)

"Incremental Approach to Derivative Polarography" Clemens Auerbach, H. L. Finston, George Kissel, and Joseph Glickstein, Brookhaven National Laboratory. "Stationary Electrode Polarography with a Staircase Voltage Sweep". Charles K. Mann, Florida State University. (Reprint No. 38)

"Operational Amplifiers Symposium"

"Generalized Circuits for Electroanalytical Instrumentation" W. M. Schwarz and Irving Shain, University of Wisconsin.

"A Multipurpose Operational Amplifier Instrument for Electroanalytical Studies" William L. Underkofler and Irving Shain, University of Wisconsin.

"Power of Time and Exponential Current Chronopotentiometry" Royce W. Murray, University of North Carolina.

"A Multipurpose Electromechanical Instrument for Control of Potential or Current" George Lauer, Helmar Schlein, and R. A. Osteryoung, North American Aviation Science Center.

"Electroanalytical Controlled-Potential Instrumentation" Glenn L. Booman and Wayne B. Holbrook, Phillips Petroleum Co., Atomic Energy Division.

"A Digital Readout Device for Analog Integrators" E. Clifford Toren, Jr., and Charles P. Driscoll, Duke University.

"A. C. Polarography Employing Operational Amplifier Instrumentation" Donald E. Smith, Northwestern University.

"A Practical Instrument Synthesizer" Charles F. Morrison, Washington State University.

"The Heath Analog Computer as a Versatile Analytical Tool" Galen W. Ewing, New Mexico Highlands University, and Thomas H. Brayden, Jr., Louisiana State University.

"Instrumentation for Cyclic and Step-Function Voltammetry Using Operational Amplifier Switching Modules" Richard P. Buck and Robert W. Eldridge, Bell & Howell Research Center.

(Reprint No. 43)

"Recording Optical Pyrometer" Norman A. Blum, Avco Manufacturing Corporation. (Reprint No. 17)

"Second Harmonic Alternating Current Polarography with a Reversible Electrode Process" D. E. Smith and W. H. Reinmuth, Columbia University. (Reprint No. 33)

E. Signal Conditioners

"Impedance & Admittance Transformations" D. H. Sheingold. *The Lightning Empiricist* (XII:1).

"Missile Rate Simulator Provides Sinusoidal Motion for Guidance Systems" Joel K. Nelson, Boeing Airplane Co. (Reprint No. 16)

"A Particular Application of FM Tape Used With An Analogue Computer" David J. Cholley, Hercules Powder Company. (Reprint No. 39)

II. CIRCUIT TECHNIQUES

A. Computor Techniques

"A Circuit With Logarithmic Transfer Response Over 9 Decades" J. F. Gibbons and H. S. Horn, Stanford University. (Reprint No. 49)

"Multiplication and Logarithmic Conversion By Operational Amplifier-Transistor Circuits" William L. Paterson, Litton Industries. (Reprint No. 46)

"New Integrating Circuit and Electronic Analog for Transient Diffusion and Flow" J. Ross MacDonald, Texas Instruments, Inc. (Reprint No. 14)

"Q3-M1P Multiplier" *The Lightning Empiricist* (XII:3-4).

"Rate-of-Change Indicator" *The Lightning Empiricis* (XI:4).

B. Fundamental Circuit Techniques

"Analog Methods" Bruce Seddon, Philbrick Researches, Inc. (Reprint No. 27)

"Analog Computor Techniques Applied To Industrial Instrumentation and Control" George A. Philbrick Researches, Inc. (Reprint No. 18)

"Operation Of The USA-3 Amplifier With Positive Open-Loop Polarity" Philbrick Researches, Inc. Application Brief.

"PP65 As Amplifier With High Input Impedance" Philbrick Researches, Inc. Application Brief.

"'Single-Ended' Inverted Amplifiers" Philbrick Researches, Inc. Application Brief.

"Stabilized Follower Amplifier" Prof. Donald Deford, Northwestern University. (Reprint No. 23)

"Typical Operational Amplifier Applications" D. H. Sheingold, Philbrick Researches, Inc.

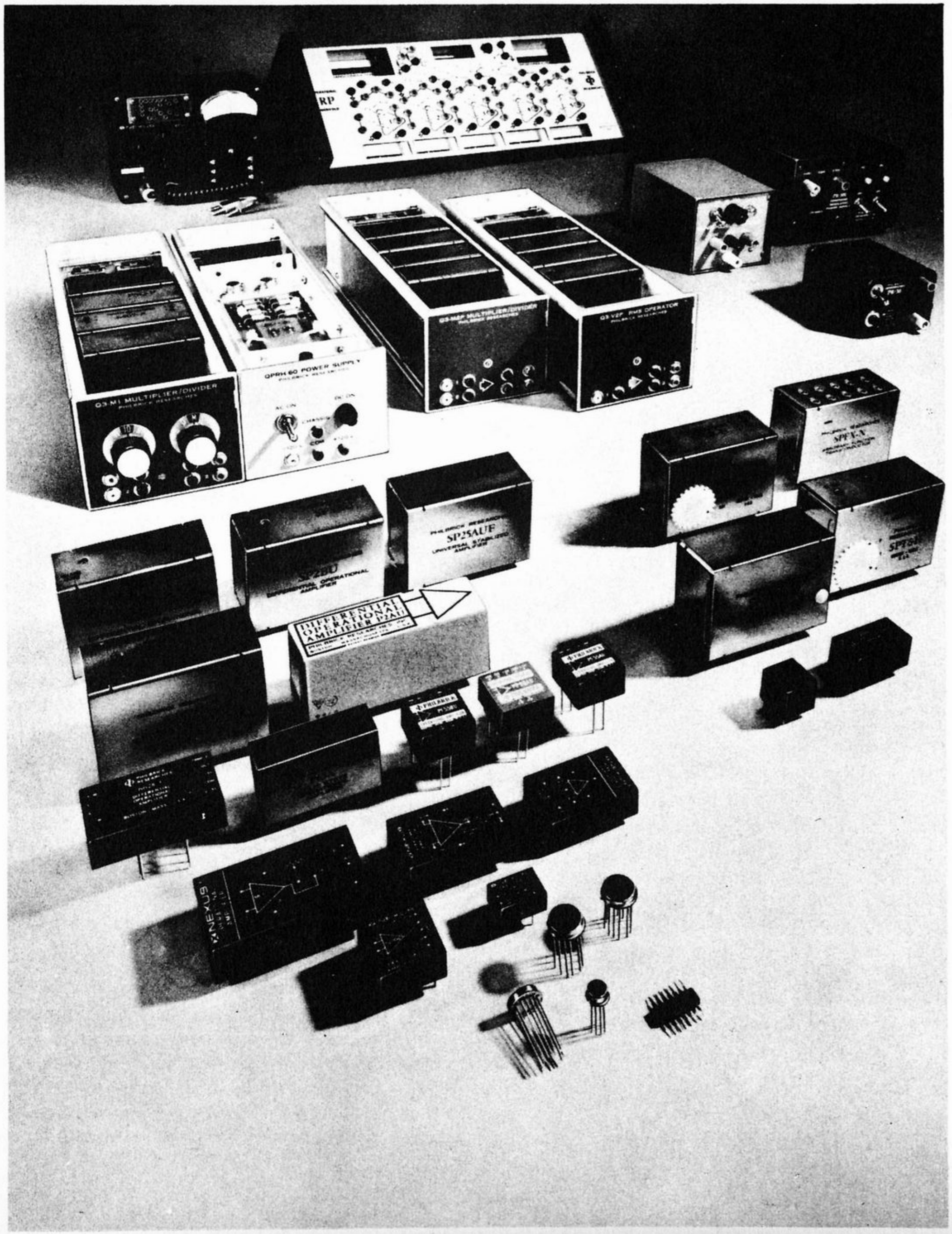
C. Voltage/Current Regulation

"Analog Computer Reference Supply" C. E. Foiles, J. P. Hartmann, and H. Koerner, University of Arizona. (Reprint No. 21)

"High Precision Large Current Regulator" K. C. Brog and F. J. Milford, Case Institute of Technology. (Reprint No. 32)

"Operational Amplifier As Constant Current Source—I" Philbrick Researches, Inc. Application Brief.

"Use of Operational Amplifiers in Precision Current Regulators and Use of Operational Amplifiers in Accelerator Beam Control Systems" Karl Eklund, Columbia University. (Reprint No. 22)



PHILBRICK/NEXUS: YOUR BEST SOURCE FOR ANALOG NEEDS

Philbrick and Nexus, world leaders in electronic analog computing equipment, combine to offer you the best in modern technology and the highest product integrity in the industry. Philbrick/Nexus Research, a Teledyne Company, brings to the analog instrumentation field unequalled capabilities in design, development and production of analog components, modules, instruments and systems. Philbrick/Nexus also exhibits unusual all-around abilities in the area of electronic circuitry and hardware.

Philbrick/Nexus can fill your needs for anything analog from the industry's broadest range of analog products — ranging from simple operational amplifiers to the most sophisticated analog systems. Philbrick/Nexus' 26 years of combined experience offer you the advanced-technology of the pioneer and the vitality of the customer-oriented organization dedicated to producing the answers to any of your unsolved problems. For prompt, competent applications, engineering assistance or advice, call your local Philbrick/Nexus field-engineering representative listed below or write, Philbrick/Nexus Research, Allied Drive at Route 128, Dedham, Massachusetts 02026.

PRODUCTS & SERVICES

DISCRETE-COMPONENT OPERATIONAL AMPLIFIERS
High-gain, low-gain, low-drift amplifiers for stable feedback loops. Provide precise, predictable operations on one or more input signals. Available in a wide variety of economy or premium grades (FET's, universal, wideband, high-voltage, general purpose) in plug-in or wire-in modules in every package style.

IC OPERATIONAL AMPLIFIERS
Micro-Hybrids combine linear monolithic chip and discrete microminiature component technologies to offer immunity to overloads, shorts and supply voltage stresses. Other types available include monolithic thin-film in TO-5 and dual in-line packages and hybrid thick-film operational amplifiers.

LOW-ERROR OPERATIONAL AMPLIFIERS
Ideal where drift and offset must be held over long operating periods through wide ambient temperature fluctuations. A wide variety of chopper-stabilized and parametric types are available.

DC POWER SUPPLIES, REGULATORS & BOOSTERS
Compound-regulated, stable, noise-free power supplies designed to meet the needs of high-performance, low-level analog systems. Rack, cabinet, modular, plug-in or built-in models available. Voltage regulators and high powered booster amplifiers are also available.

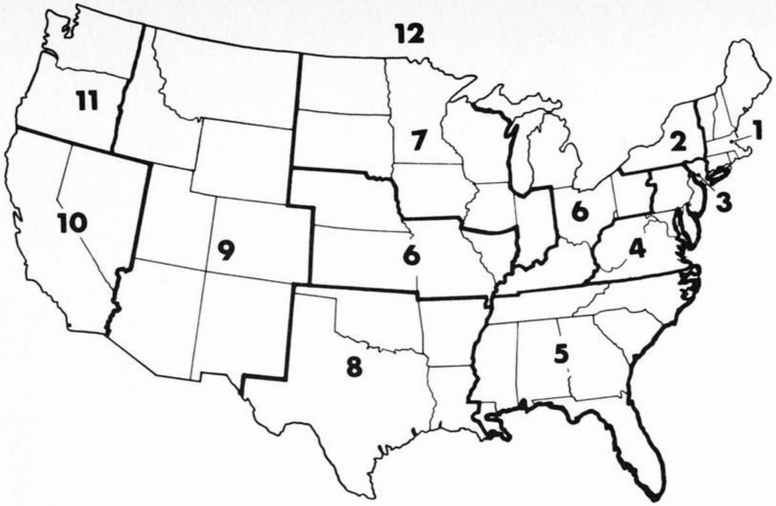
NON-LINEAR FUNCTION MODULES
Analog systems components for linearizing or performing non-linear functions. Available in natural continuous function or straight-line approximation types. Non-linear function modules include networks that accurately exhibit logarithmic, trigonometric and quadratic behavior.

Q3 MODULAR SYSTEMS
Modular components for implementing both analog and hybrid computers, simulators and analyzers include: arbitrary function fitters, universal linear operators, multiplier-dividers and manifolds. Modular front panels, chassis adaptors and accessories combine all modules into compact units.

OPERATIONAL MANIFOLDS
All-in-one self-powered analog instruments that virtually eliminate wiring problems. They simplify experimentation, simulation and instruction in the practical application of feedback techniques.

TECHNICAL SUPPORT SERVICES
Philbrick/Nexus Research welcomes opportunities to help you apply analog techniques and products in such areas as industrial and scientific instrumentation, process and quality control systems and in-line analog data processing. Customer services of Philbrick/Nexus include: applications engineering, technical bulletins, applications manuals, the "Lightning Empiricist," and factory or on-site application seminars.

ENGINEERING REPRESENTATIVES



1. **YEWELL ELECTRONIC SALES, INC.**
   Lexington, Mass. (617) 861-8620
   Easton, Conn. (203) 261-2241
2. **K.L.M. ASSOCIATES**
   New Hartford, N.Y. (315) 735-8525
   Palmyra, N.Y. (315) 597-9776
   North Syracuse, N.Y. (315) 458-6214
3. **CRANE & EGERT CORP.**
   Elmont, N.Y. (516) 488-2100
4. **ELECTRONIC MARKETING ASSOCIATES**
   Kensington, Md. (301) 946-0300
   King of Prussia, Pa. (215) 265-1600
5. **W. A. BROWN & ASSOCIATES, INC.**
   Fort Lauderdale, Fla. (305) 564-8000
   Fort Walton Beach, Fla. (904) 243-6424
   Orlando, Fla. (305) 425-5505
   Winston-Salem, N.C. (919) 725-5384
   Tucker, Ga. (404) 939-1674
   Huntsville, Ala. (205) 536-8393
   539-6884
6. **S. STERLING COMPANY**
   Southfield, Mich. (313) 357-3700
   Pittsburgh, Pa. (412) 922-5720
   Cleveland, Ohio (216) 442-8080
   Dayton, Ohio (513) 298-7573
   Indianapolis, Ind. (317) 545-2812
   St. Louis, Mo. (314) 542-3399
7. **TORKELSON ASSOCIATES**
   Minneapolis, Minn. (612) 920-1046
   Indianapolis, Ind. (317) 244-7867
   Northfield, Ill. (312) 446-8450
8. **APPLIED SCIENCE ASSOCIATES**
   Dallas, Texas (214) 526-8316
   Houston, Texas (713) 781-1441
   Tulsa, Okla. (918) 627-6199
9. **HYTRONIC MEASUREMENTS, INC.**
   Denver, Colorado (303) 388-4081
   Salt Lake City, Utah (801) 466-4924
   –Phoenix, Ariz. (602) 253-6104
   Albuquerque, N.M. (505) 268-3941
10. **WARD-DAVIS ASSOCIATES**
    Pasadena, Calif. (213) 684-2840
    San Diego, Calif. (714) 297-4619
    Palo Alto, Calif. (415) 968-7116
11. **DELTA MARK**
    Bellevue, Wash. (206) 747-4875
12. **MEGATRONIX, LTD.**
    Downsview, Ontario (416) 630-7672
    Ottawa, Ontario (613) 731-3860
    Montreal, Quebec (514) 488-0404

ARGENTINA
SIREX
Buenos Aires – Tel: 42-1927, 44-5781
AUSTRALIA
SAMPLE ELECTRONICS PTY. LTD.
E. Melbourne – Tel: 4192081
Sydney – Tel: 4391411
Adelaide – Tel: 517404
AUSTRIA
KONTRON GeS. m.b.H
Vienna 1060 – Tel: 561193
BELGIUM (LUXEMBOURG)
C. N. ROOD s.a.
Brussels 4 – Tel: 35.21.35
BRAZIL
LEVIANT INTERNATIONAL, INC.
Rio de Janeiro – Tel: 56-0893, 242-6589
Sao Paulo – Tel: 37-9068
CHILE
SIREX
Santiago – Tel: 39-4117
DENMARK
S C METRIC A/S
2850 Naerum – Tel: (01) 80-4200
ENGLAND (SCOTLAND)
PHILBRICK/NEXUS RESEARCH
Chichester, Sussex – Tel: Chi 8-3671, 8-3786
FINLAND
FINDIP A.B.
Helsinki – Tel: 71 77 99
FRANCE
IMEX FRANCE
(93) Montreuil-Sous-Bois – Tel: 808-1920
GERMANY
KONTRON GmbH & CO. KG
Munich-Feldmoching – Tel: 0811/3513075
2 Hamburg 39 – Tel: 0611/542017
6 Frankfort 50 – Tel: 0411/462038
GREECE
DEMETRIUS TZITZINIAS
Athens 906 – Tel: 88.10.49, 88.33.11
HAWAII (PHILIPPINES)
PACTRON SYSTEMS
Kailua, Oahu – Tel: (808) 261-1224
HONG KONG
SCHMIDT & CO. LTD.
Hong Kong B.C.C. – Tel: 240168, 232735
INDIA
ELECTRONIC ENTERPRISES
Bombay 4 – Tel: 353069, 375376
IRELAND
NELTRONICS
Dublin 6 – Tel: 685086
ISRAEL
EASTRONICS LTD.
Tel Aviv – Tel: 440466
ITALY
SOC. An. NA.s.a.s.
20144 Milan – Tel: 490378, 432817
JAPAN
TAKACHIHO KOHEKI CO. LTD.
Tokyo 102 – Tel: 263-3211
MEXICO
GUILLERMO MORENO FAJARDO
Mexico 4 D.F. – Tel: 417040
NETHERLANDS
C. N. ROOD n.v.
Rijswijk – Tel: 99.63.60
NORWAY
SCANCOPTER A.s.
Oslo 2 – Tel: 467317
NEW ZEALAND
SAMPLE ELECTRONICS
Aukland – Tel; 667-356
SOUTH AFRICA
K. BAKER ASSOCIATES (PTY.) LTD.
Johannesburg – Tel: 724-9341
Cape Town – Tel: 37769
Durban – Tel: 20272
SPAIN
HISPANO ELECTRONICA s.a.
Madrid – Tel: 2334664, 2335096
SWEDEN
SCANDIA-METRIC A.B.
Fack/Solna 3 – Tel: 08/82 0410
SWITZERLAND
KONTRON ELECTRONIC LTD.
8031 Zurich – Tel: 051-44-56-90
TAIWAN
INDUSTRIAL ELECTRONICS
Taipei – Tel: 74257

INDEX

Class I. Natural Function Logarithmic Transconductors

Model	Description	Fundamental e-i Relationship and Operating Ranges
PL1-N/P PPL1-N/P	Dual Element, connectable as diodes, transdiodes, or transistors; uncommitted as to interconnections.	$e = E_0 \log \frac{i}{I_0} \cong 60$ mV/decade of i
PL2-N/P PPL2-N/P	Quad Element, transdiode-connected, with all four bases connected together, and brought out on one terminal.	1 pA $< i_1 <$ 1 mA (9 decades)
PL3 PPL3	Quad Element, diode-connected; uncommitted as to polarity or interconnections.	$e = E_0 \log \frac{i}{I_0}\left(\frac{\beta}{\beta + 1}\right)$ 1 nA $< i <$ 1 mA (6 decades)
PPL4-N/P	Temperature-Compensated Transconductor: transistor connected log element, plus integral current-error and voltage-error compensation.	$e = E_R \log \frac{i}{I_R}$ (where E_R is selectable between 0.3 V 2.0 V. Nominal value of $I_R = 10^{-4}$A.)
SPL4-N/P	Same as PPL4 plus gain and reference current controls.	10 nA $< i <$ 100 μA (4 decades)
SPLR-N/P	Log-of-Ratio Transconductor: a pair of transistors as basic log elements, plus dual-purpose current-pump / scaling amplifier. Requires external activating amplifier.	$e = -nE_0 \log \left(\frac{e_2}{e_1}\right)$ or $e = e_2 10^{\left(\frac{e_1}{nE_0}\right)}$ -10 V $< e <$ 10 V 10 μV $< e_1, e_2 <$ 10 V

Class II: Straight-Line Approximation Transconductors

SPLOG-N/P	Logarithmic Transconductor	$-i = 5 \cdot 10^{-(e/5v)}$ μA 50 nA $< i <$ 500 μA (4 decades)
PSQ-N/P	Quadratic Transconductor with two inputs and built-in lower (Ω) or upper (U) input voltage selector respectively.	$\dot{-} i_1(\text{mA}) = 0.5\left[\frac{\Omega(e_1, e_2, 0)}{10 \text{ V}}\right]^2$ or $i(\text{mA}) = 0.5\left[\frac{\text{U}(e_1, e_2, 0)}{.10 \text{ V}}\right]^2$ -10 V $< e_1, e_2 <$ +10 V
SPSIN-N/P	Trigonometric Transconductor	$i(\text{mA}) = 0.5 \sin e \frac{\pi}{18}$ -10 V $< e <$ +1 or $-1 < e <$ +10 V
SPCOS-N/P	Trigonometric Transconductor	$i(\text{mA}) = 0.5 \cos e \frac{\pi}{18}$ -10 V $< e <$ +10 V
SPFX-N/P	Arbitrary Function Transconductor: 10 break points at 0.5, 1.5, . . . 9.5 V. Slopes screwdriver adjustable.	$i = f(e)$ -10 V $< e < 0$ or $0 < e <$ 10 V

Class III. Multiplier-Divider Transconductor

SPM1	Multiplier-Divider (Triangular Wave Bounding principle) when used with external Operational Amplifier. Nominal accuracy 1%.	$e = \frac{e_1 e_2}{e_3}$ -10 V $< e_1 <$ 10 V -10 V $< e_2 <$ 10 V 0 $< e_3 <$ 10 V

These non-linear circuits accurately implement such operations as multiquadrant squaring, generating sine and cosine functions, quadratic or logarithmic response, and the linearization of a multitude of non-linear transducers. They fall into two general classes: (1) Natural Continuous Function types, based on the continuous-function characteristics inherent in certain semiconductors operated in specific parametric regions, and (2) precise-linear-approximation types, using diode-resistor networks proportioned to approximate the desired function by a series of straight lines. Scaled and biased for use in conjunction with ±10-volt Operational Amplifiers, they constitute a convenient and effective means for generation of exponential, transcendental, and high-order mathematical functions. Except for Type (P) PL3, all units are manufactured in two forms (designated by suffixes "-P" and "-N"), one for each polarity of input signal; signals exhibiting both polarities sometimes require one of each gender. These units are available in the same mechanical configurations as solid state Operational Amplifiers.

PLUG-IN UNIT OPERATORS such as models SPL4A-N/P, SPLRA-N/P, and SPM1A are equivalent to a combination of Transconductor (SPL4-N/P, SPLR-N/P, and SPM1 respectively) and one or more Operational Amplifiers, as required to provide the specified operation on one or more input signals.

CONTROL MODULES

These standard modules are used to achieve multi-mode operation of many operational circuits. Appropriately combined with the Amplifiers and Transconductors listed in this catalog, they permit the construction of circuits for repetitive, iterative, and "hybrid" computing, as well as for data-acquisition.

SPG1 COMPLEMENTARY CURRENT GATES: Diode gates used to reset integrators at rapid rates on digital commands.

SPREL RELAY CONTROL UNIT: Relay gates, also used to reset integrators on digital commands, but at slower speeds. Has the additional advantage of a "Hold" position and very low leakage.

SPT&H TRACK-AND-HOLD UNIT: Performs the following switch-selectable functions: track and hold, peak or valley follow and hold. Optimized for use with an SP656 Amplifier in the loop.

PT&H
PPT&H TRACK-AND-HOLD UNIT: Performs the track and hold function on digital commands. Must be read out with a high impedance amplifier in the follower mode, e.g. P25AH.

PHILBRICK/NEXUS RESEARCH

A TELEDYNE COMPANY

Allied Drive at Route 128, Dedham, Massachusetts 02026

TEL: (617) 329-1600 TELEX: 094-6576 TWX: (710) 348-6726