Design Classics

The first commercial op amp. Photo courtesy of Dan Sheingold and Analog Devices Inc.

Unsung hero pioneered op amp

There's little doubt that the first commercial operational amplifier was introduced to the market by George A. Philbrick Researches. That was in late 1952. But the forerunner of this amplifier and subsequent op amps as well as the basic design, many indicators suggest, came from a young engineer working at Columbia University: Loebe Julie.

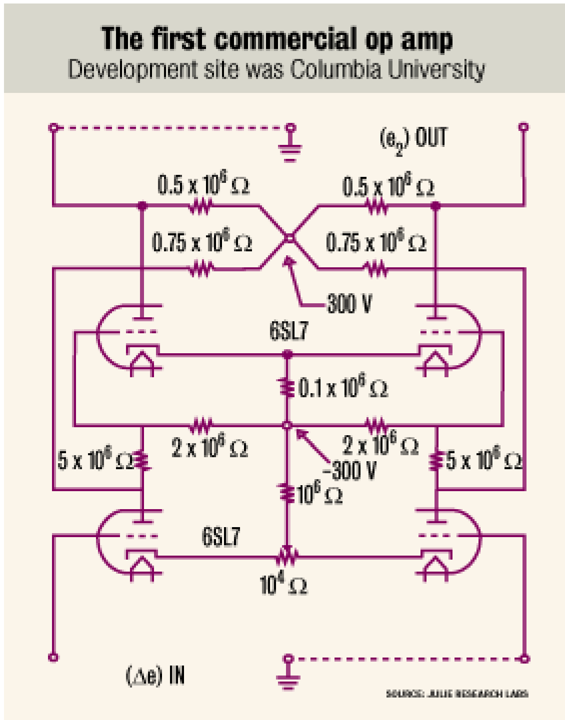
The sole public credit for this profound development appeared in an acknowledgment for contributions "to some phases of this development" at the end of a technical article, "Analysis of Problems in Dynamics by Electronic Circuits," in the May 1947 issue of *Proceedings of the I.R.E* .

The lead author was John R. Ragazzini, a professor in charge of an electronics lab at Columbia University. If Julie really did the basic design-and there is much evidence of this (including correspondence from one of Ragazzini's co-authors)-why was Ragazzini the lead author and Julie essentially buried in a scant acknowledgment?

Ragazzini is no longer around to provide his reason. But some observers surmise that, 50 years ago, it was by no means uncommon for a professor to take credit for a major achievement of an underling.

In fact, there had been amplifiers to perform some of the math operations we associate with operational amplifiers as early as the period preceding World War II. But they were bulky and slow and not commercially available. A five-pentode design was used in

Western Electric's M-IX artillery-gun director.



How did Julie get involved? It started with a bright physicist at the Massachusetts Institute of Technology, George Philbrick, who won a contract from the National Defense Research Council to build an electronic-sight simulator for fighter aircraft and a guided-bomb trainer simulator. The first system came to be known as Puss, for Pilot Universal Sight System. The second had twoelements: Guided Bomb (Azimuth Only), or Azon, and Guided Bomb (Range and Azimuth), or Razon.

Philbrick subcontracted the work. The Franklin Institute in Philadelphia was to design and construct the mechanical and optical system for a bombing simulator. The second contract called for what Philbrick termed an electronic analog computer/simulator using operational amplifiers like those in the M-IX gun director, which Bell Telephone Laboratories had developed for Western Electric.

The M-IX, Julie said, was very slow. It took more than half an hour to plot the differential equations for the trajectory of an artillery shell. The amplifiers had a corner frequency of about 1 Hz. That contract went to Columbia University.

One-man show

And here at Columbia was Loebe Julie, almost, but not quite, fresh out of school. He had earned his BSEE from the City College of New York in 1941, then spent a couple of years as a civilian engineer with the Army Signal Corps in Fort Monmouth, N.J. There he designed a compact dual-channel amplifier for a machine-gun and mortar locator.

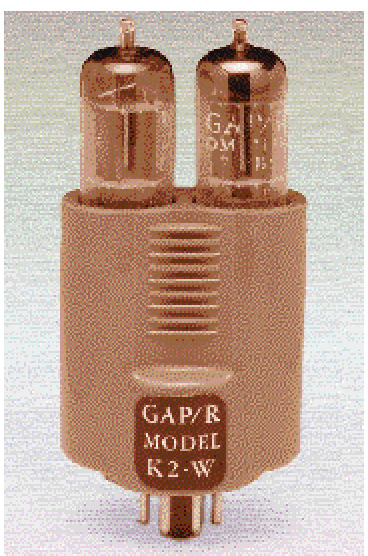
Along came a job offer from Columbia University's Division of War Research to become the entire engineering staff at one lab, an offer that Julie accepted. Then came the subcontract from MIT and George Philbrick, who introduced Julie to the amplifiers in the M-IX gun director. There were too many stages, Julie felt, and the devices, at about five pounds each, were heavy. A power-supply console that may have weighed 1,000 pounds supported 50 amplifiers, he recalls.

Based on his e xperience building a compact amplifier at the Signal Corps, Julie explained to project administrator Ragazzini that he could simplify and improve the design. Ragazzini rejected Julie's concept, Julie recalls, maintaining that it could never work. Ragazzini denied Julie permission to try his design.

When Philbrick visited Columbia again, Julie explained his idea. Philbrick asked how long it would take to build such an amplifier. When Julie asked for 30 days, Philbrick asked Ragazzini to give him a try.

It was one of those wonderful success stories encountered so often in our industry. In 30 days, Julie completed an op amp with a corner frequency extended to 1 kHz, with padding resistors and capacitors to kill parasitic oscillation and to stabilize the summing, integrating and differentiating operations.

He also built four regulated power supplies that could drive as many as 50 amplifiers. These occupied the space of a portable typewriter, a sort of primitive ancestor of laptop computers-albeit lar ger.



The first commercial op amp. Photo courtesy of Dan Sheingold and Analog Devices Inc.

Philbrick was more than pleased. He placed an order for 50 Julie amplifiers for the Puss, Azon and Razon projects.

When Julie's work on the amplifiers was almost completed, a short while before Philbrick placed his contract, Ragazzini hired two college professors, Robert Randall and Frederick Russell. To Ragazzini's displeasure, Julie taught them about his design. Ragazzini didn't particularly like Julie, Julie reported. He accused him of intellectual arrogance, deprived him of credit for his design and ended his draft deferment.

After a year's stint in the Army Signal Corps., Julie returned to school-New York University this time-for a master's degree in math in 1954. In 1956, he founded Julie Research Laboratories, which to this day makes calibration standards and precision components.

A decade earlier, in 1946, George Philbrick had started George A. Philbrick Researches, which sold analog c omputers for military aircraft. In 1951, the company sold an analog computer containing 40 K2-UXs (U for universal, X for experimental) to Stone and Webster. And in 1952, it offered the K2-W, the first commercial general-purpose differential op amp. The device had two miniature nine-pin 12AX7 high-mu dual triodes in a plastic shell that plugged into an octal socket. Julie's circuit was based on two octal-base 6SL7 medium-micron triodes, and it laid the groundwork for all subsequent op amps. The Philbrick amplifier had a gain of about 20,000 and a gain-bandwidth product of about 1 MHz. It dissipated about 4.5 W, and it cost $24.

Op-amp legacy

The op amp was a huge success. It generated sales; it generated new designs; and it generated competition. One op-amp competitor, Nexus Research Laboratory, was started by former Philbrick engineers Alan Pearlman and Roger Noble. The op-amp business looked good to a large conglomerate, Teledyne Inc., which acquired both Philbrick and Nexus in 1966, c reating Teledyne Philbrick Nexus, which, in time, became Teledyne Philbrick and then Teledyne Components. That company was acquired in 1993 and is now TelCom Semiconductor.

Acknowledgments: For help in providing information for this report, special thanks are due to Dan Sheingold, former engineer, director of applications engineering and vice president of marketing at George A. Philbrick Researches; to Robert A. Pease, former senior engineer, then vice president of development, at Philbrick; and to Loebe Julie, the former Columbia University engineer, now president of Julie Research Labs.

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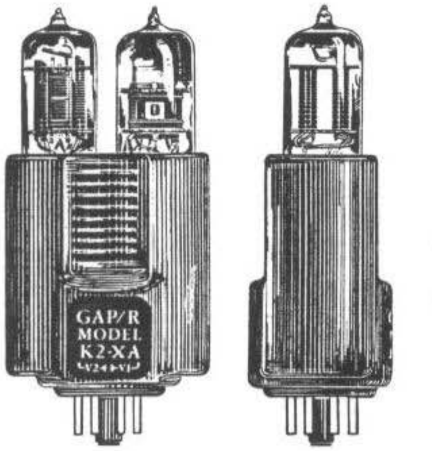
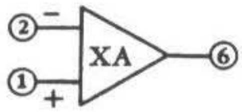
Model K2-XA Operational Amplifier



OPERATIONAL SYMBOL



GENERAL CHARACTERISTICS

Design Center Electrical Characteristics

Gain:
30,000 dc open loop (depending upon the applications — see text)

Response: — Small signal:
1 µsec rise time with bandwidth over 250 kc when used as a unity-gain inverter under ideal circuit conditions

Drift Rate:
±8 mv per day referred to the input (See text — "DRIFT")

Differential Input Levels:
Impedance: — Either input: typically above 100M (open grid)
Voltage Range:
Inputs together (common mode) −50 to +50 volts

Current: — Either input:
Typically less than 10^{-7} amp (insulation leakage and grid current)

Bias Required for Balance:
Adjustable from 1.1 to 2.0 volt between pins 1 and 2 (pin 1 positive with respect to pin 2) (See figure 3.)

Output Capabilities:

Output Voltage	Output Current (steady state) Normal	Case HP*
−100v	−2.8 ma	−4.1 ma
0v	+4.0 ma	+2.0 ma
	−5.0 ma	−7.0 ma
+100v	+6.1 ma	+4.3 ma

Maximum available transient output current is very much larger in the positive direction, but is the same in the negative direction.

Power Required: (for full output)
Normal Operation: (50K load)

Supply Voltage	At output +100v	At output −100v
+300	+10.4 ma	+3.4 ma
−300	−11.4 ma	−7.9 ma
6.3 vac or vdc	0.75 amp	0.75 amp

*Case HP (with 33K load)

Supply Voltage	At output +100v	At output −100v
+300	+14.1 ma	+3.7 ma
−300	−14.1 ma	−9.2 ma
6.3 vac or vdc	0.75 amp	0.75 amp

*With a 150K, 2-watt resistor connected between pin 6 (output) and pin 3 (−300v).

PHYSICAL CHARACTERISTICS

Tube Complement:
1 12AX7A or 7025
1 6BR8A or 6CL8A

Casing:
Molded plastic, sealed unit

Dimensions:
Overall: 4 11/16 in. h (max.)
Above Socket: 1½ w x 2⅛ lg. × 4⅛ in. h (max.)

Base: Octal plug

Temperature:
Maximum allowable case temperature (hot spot) +65°C (149°F) (See text)

Weight: Installed: 3¼ oz.
Packed: 6½ oz.

GENERAL DESCRIPTION

The Model K2-XA is a high gain, wide band, plug-in, dc operational amplifier, designed and constructed for use as a basic subassembly for analog computor and instrument applications. It is primarily useful in feedback circuits where a high open loop gain and an output voltage range of from minus to plus 100 volts are required. The open loop dc gain for normal operation with a ±60 volt swing and a 50K load is 30,000. With a ±110 volt swing, the dc gain may decrease to 10,000. With these units, computing devices of nearly all speeds can be assembled with a minimum of external circuitry.

Like K2-W the Model K2-XA features balanced differential inputs. Its range of operation is from DC to above 250KC when connected as a unity-gain inverter.

With appropriate circuitry, the K2-XA maintains the two inputs at nearly equal potentials. The residual offset can readily be biased out. (See BIASING METHODS.)

Operationally, the K2-XA plugs into the same socket as the K2-W, and uses the same connections for power and for computing signals. Although momentary short circuiting of the output does no harm, its output must not be grounded for an extended period. Load capacitances in excess of 200 µµf usually require additional stabilization networks.

APPLICATIONS

The K2-XA Operational Amplifier can be used for analog computation in feedback systems of any complexity. It is entirely compatible with the K2-W and the two can be used in the same assemblages, each being used to exploit its own special characteristics. The K2-XA permits steeper wave fronts and greater signal excursions. Also, its greater output power allows the use of computing networks that require higher voltages and currents than are possible with the K2-W. However, be sure to provide ample ventilation.

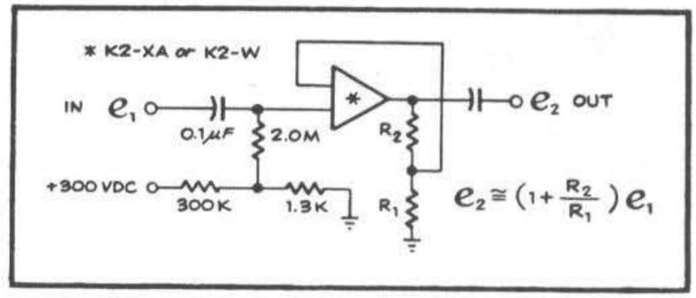


Figure 2. As an Ac Amplifier

The K2-XA, although inherently a dc operational amplifier, may suitably be used as an ac amplifier. The arrangement shown in figure 2 is typical of such application. The ratio e_2 to e_1 is given by $(1 + R_2/R_1)$ for all frequencies for which $RC >> 1/(2\pi f)$. For the examples shown, amplitude is "flat" and phase shift less than 6 degrees at 8 cps. Note that the network represented by R_{12}, R_2 may be complex or even non-linear. If required, narrow bandwidth may be obtained by shunting R_2 with a capacitance. This will obviously attain a very low noise figure. The K2-XA in figure 2 has a high input impedance which may be connected to a low impedance source. Unlike the conventional "operational" case, the mid-band gain of such a circuit is virtually independent of the input impedance.

INSTALLATION

Connect the desired external circuitry to a mica-filled or ceramic octal socket or a GAP/R Manifold and plug in the K2-XA (Information about GAP/R Manifolds is available upon request.)

NOTE

Operation of tubes for long periods with the cathodes heated and without plate voltage has been known to deactivate the cathodes. Therefore, if equipment is not to be used within a few hours, open the heater circuit.

All K2's made after Nov. 1, 1961 are housed in gray Lexan. The new case can withstand a much higher temperature than the 65°C. recommended max. for the yellow cases. However, longer component life will result, if the case hot-spot temperature can be kept below 45°C. Avoid severe overloading.

CAUTION

Although momentary shorting of the output to ground will not harm the K2-XA, prolonged operation under these conditions will cause overheating and subsequent damage. The K2-XA and its load may dissipate 14 watts. Unless there is plenty of free air under 30°C (86°F) around the unit, forced ventilation will probably be necessary. The K2-XA is not recommended for those applications where either the ventilation is poor or the ambient temperature high. For such applications the MIL equivalent K2-YJ is recommended.

DRIFT

The K2-XA needs a seasoning period of about 100 hours of operation. Then, under optimum conditions typically found in analog computor installations, and after temperatures have become equalized, the drift rate of the typical K2-XA will average about ±8 millivolts per day. The optimum conditions include heater voltage regulated to ±0.5%, the plate voltage regulated to 0.03%, the ambient temperature constant at about 86°F (30°C), adequate ventilation, and the heaters invariably warmed for at least one minute prior to the application of plate voltage.

In applications where optimum conditions do not prevail, the drift rate may be ten to twenty times as much as under optimum conditions.

If bias is derived from resistive networks (figure 3) or 300v sources than can shift 1%, for example, such shift will manifest itself as "drift" of 15 millivolts. Wirewound resistors and Philbrick tracking type power supplies are recommended (viz. R-100B).

If the amplifier is overloaded the drift rate may be ten to twenty times as much as under optimum conditions.

The introduction of the GAP/R K2-P Stabilizing Amplifier is recommended for those applications in which drift must be kept well under 1 mv long term. (See the K2-P Data Sheet, available upon request.)

BIASING METHODS

For most applications, a bias adjustment is necessary, and may be applied in any of several ways. Two arrangements are illustrated in figure 3. Variations of one of these arrangements have been found to be quite effective for cases involving differential inputs, as shown in figure 2. For further illustration ask for the Application Manual for Philbrick Octal Plug-in Computing Amplifiers.

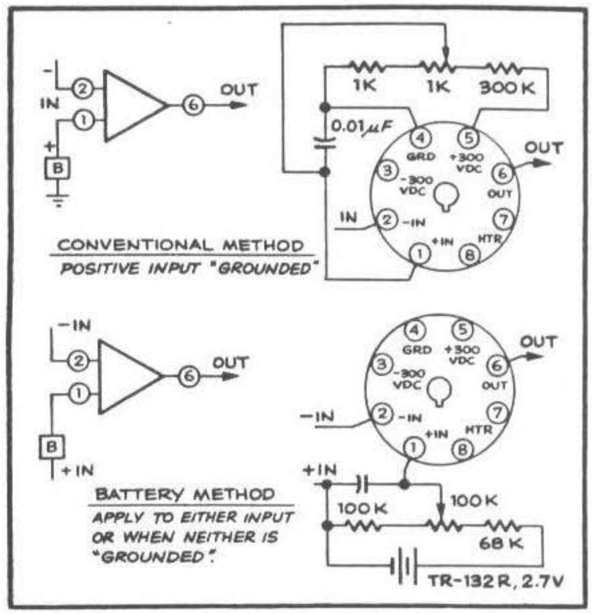


Figure 3. Biasing Methods

When using any of these methods, set the potentiometer for zero dc error under feedback. When setting the potentiometer, ground the input of the computing network for most accurate balancing.

AUGMENTED POWER — CASE HP

When substituted for a K2-W, a K2-XA will handle most computing networks with the higher performance already described. For still greater speeds and output, connect a 150K 2-watt resistor externally between pins 3 (−300 vdc) and 6 (output). (See figure 4.) The K2-XA (Case HP) will supply a load of 33K with a voltage swing from −100 to +100 volts.

This necessarily operates the 6BR8A near its maximum plate dissipation and shortens tube life.

The K2-XA is a higher output (±100v at 3 ma) version of the familiar octal plug-in Model K2-W Utility Differential Amplifier. It provides up to six times the output of the K2-W but ventilation sufficient to carry away a maximum of 12.1 watts must be provided. Gain and bandwidth are about one octave better than the corresponding quantities for K2-W over the ±50 volt output range.

MAINTENANCE

Preventive Maintenance

1. During operation:
   a. Make sure that tubes are firmly seated.
   b. Make sure that K2-XA is firmly seated.

Trouble Shooting

If trouble in the K2-XA is suspected:

1. Check the tubes by substitution.
2. Check for loose connections, ground, and/or shorts in the associated circuitry.
3. Check the plug-in by substitution.

Corrective Maintenance

1. Replace defective tubes.
2. Do NOT open the sealed case.

Opening the case voids guarantee. The unit should be returned to the factory for repair.

NOTE: For Quality Control Data and other general characteristics for circuit design use, ask for K2-XA Specification Control Data No. 6041-A-02.

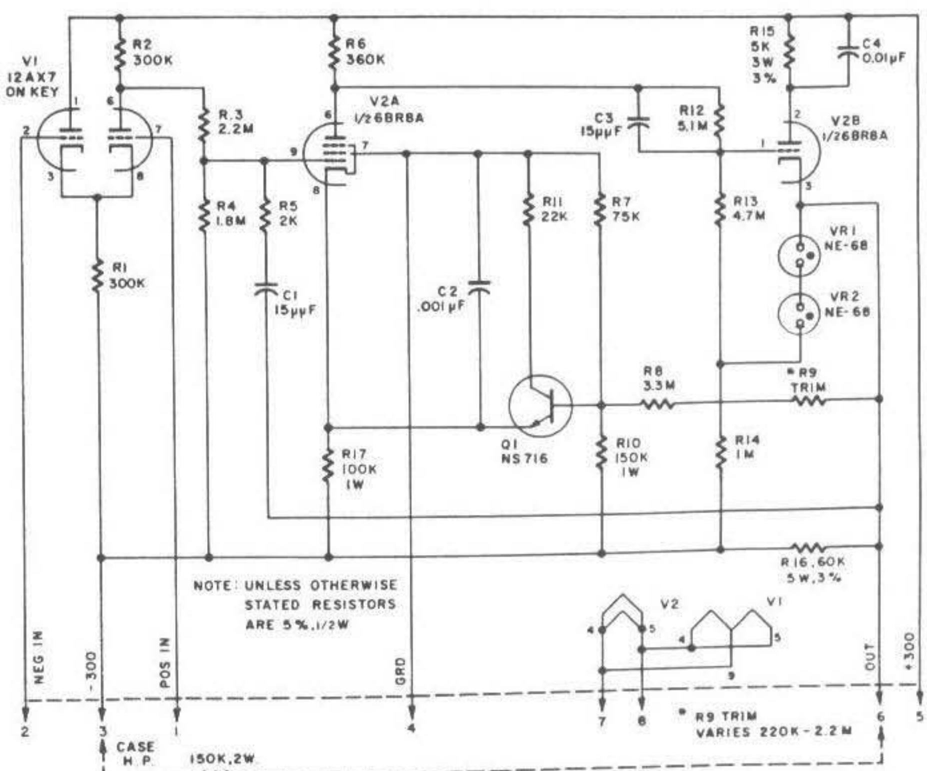


Figure 4. K2-XA, Schematic Diagram