High Fidelity Phono Preamp with FET's

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INTRODUCTION TO FET's

FET's or Field Effect Transistors are a newcomer to the family of amplifying devices which includes vacuum tubes and normal transistors, which are often called bipolar transistors in contrast to FET's. In bipolar transistors amplification is achieved by use of both types of carriers, electrons and holes, while a FET relies on carriers of one polarity only, such as electrons, and is also called a unipolar transistor.

FET's function very much the same way as vacuum tubes and amplification is achieved by control of an electric field. This field is set up in a semiconductor by applying voltage to the ends of a channel, such as a bar of N-channel germanium (rich in electrons or negative charges). The electrodes are termed source (cathode) and drain (plate) and are biased exactly like a vacuum tube for a N-channel device, with positive voltage to drain. In order to control the field set up in the semiconductor, a third, insulated electrode is added, the gate (grid), which is biased negatively with respect to source (cathode). In a field-effect device no gate (grid) current flows, but rather a control voltage is used to control gain just as in a vacuum tube. Because of this similarity, it is generally much easier to follow the existing tube circuitry for design. Knowledge of standard transistorized circuits is of little use with FET's. However, design with FET's is much simpler than with normal transistors, due to their high input impedance and ready capability. New work, shown in this article indicates the superiority of FET's over both vacuum tubes or normal transistors, particularly in audio applications.

For a better understanding, the chief characteristics of transistors, tubes, and FET's are summarized in Table I.

FET Performance Characteristics

NEW CIRCUIT DESIGN PROCEDURES for FET's were recently developed[1,2], which result in far superior circuit performance than is possible with the best transistor or vacuum tube circuits. It appears now, that FET's will replace both vacuum tubes and bipolar transistors in all linear (amplifier) applications within the next two to five years. Presently available FET's[3] surpass all previously known active devices with regard to noise, overload, linearity (distortion), gain, current economy, input impedance, and so on. For example, while transistors have a lower noise level than tubes (4 to 6 dB at audio frequencies, about 3 db in uhf-TV-tuners), FET's in turn are better than the best transistors. An improvement of 2 to 4 dB over the best bipolars was noted with presently available FET's in audio circuits. Tubes as a rule have an output capability from 12 to 20 dB higher than bipolar transistors in audio voltage-amplifier circuits. Again FET's provide more signal than even tubes for the same distortion.

The linearity of FET voltage amplifiers itself is phenomenal. Take the typical case of a transistor stage running about 5 per cent distortion in the output. If the distortion is measured directly at the base, it will read about 4.8 per cent. This is typical for normal transistors because the distortion is generated in the very nonlinear forward-biased base-emitter diode, while the amplification process itself is usually reasonably linear. The high distortion of normal transistors is inherent and cannot be removed but only minimized.

A vacuum tube by comparison may read 10 per cent distortion in the output, with about 0.5 per cent read directly at the grid. The distortion generated in the grid circuit is mainly due to the normal grid current of vacuum tubes of about 1 microamp.

A FET measured under the same conditions shows no measurable distortion in the gate at all. As a matter of fact, a FET single-stage amplifier was driven into heavy output overload (heavily clipped sine wave) with about 30 per cent distortion. When measured at the gate, the distortion still read 0.01 per cent (the distortion of the generator itself). This means that distortion in FET's is limited to output overload which is essentially determined by supply voltage. Below the start of output clipping, output distortion in FET's runs at extremely low levels, far less than with both vacuum tubes or transistors.

The reduced noise level and higher output capability result in an increased dynamic range for the FET amplifier. Other characteristics, such as gain in excess of pentode amplifiers and performance at low current levels are obvious advantages. Among these is excellent temperature stability. FET circuits were demonstrated which perform without deterioration when submerged in liquid nitrogen (−200°C) and at ambient temperatures as high as +180°C.

Circuit Designs with FET's

The obvious question then is what circuit-design procedures must be followed to obtain this excellent performance. Briefly, the essentials are correct d.c. biasing, realistically specified FET's, and high-impedance amplifier design as with vacuum tubes.

A FET behaves in any respect as an ideal pentode not having a screen grid (with the possible exception of feedback capacitance). FET's, being "field" devices, want to operate at high voltage for best performance. Drain current is of little importance as long as the drain voltage itself is correct. Extensive tests indicated that the optimum drain voltage in voltage-amplifier applications falls at 45 per cent of the supply voltage, regardless of the specific FET or drain current. Also, for the best all-around performance in audio circuits, a load resistance of 100k ohms is best (lowest distortion, wide frequency response). Another good choice is 220 K ohms where increased gain is achieved with increased distortion and somewhat reduced frequency response. All of this is quite familiar from vacuum-tube design. The objective is then to bias the FET so that the required

[1] "Biasing Consideration for FET's," Engineering Report 2. (Available from Dickson Electronics Corp., 310 S. Wells Fargo Road, Scottsdale, Arizona.) *Literature*

[2] "Design Criteria for FET Voltage Amplifiers", Engineering Report 3. *ibid.*

[3] Q-series by Dickson Electronics

drain voltage is achieved (determined by the above conditions).

It was clear after running numerous tests that conventional FET specifications fall far short of what is essential amplifier information. For example, tests performed on one type of FET (one 2N number from one manufacturer), showed the optimum gate voltage to range from 0 to 10 volts. What makes matters worse is that the exact gate voltage must be accurate to a tolerance of 20 per cent in practical circuits. Consequently, every FET needed a tedious manual adjustment and production circuits on that basis are, of course, impractical. The following parameters of FET's were found absolutely meaningless: pinch-off voltage, shorted drain current, shorted transconductance, and so on. Going through a typical FET data sheet, not a single parameter was found that was useful for amplifier design. It was a situation similar to a case where fifty different tube types were dumped into one basket and labeled by the same type number based on a parameter such as cathode current or filament voltage, or the like. Intelligent circuit design is then an impossibility.

TABLE 1
COMPARISON OF TUBES, TRANSISTORS, AND FETS
(Approximate normal values)

	Vacuum Tube	Transistors (NPN)	FET (N-Channel)
Electrodes	Plate	Collector	Drain
	Cathode	Emitter	Source
	Grid	Base	Gate
Plate Supply	100 to 250 V.	10 to 35 V.	100 to 250 V.
Grid Bias	−0.5 to −10 V.	+0.2 to 0.6 V.	−0.5 to −10 V.
Grid Current	1 μA	100 μA	1 nA
Plate Load	22 to 220 k ohms	1 to 22 k ohms	22 k to 220 k ohms
Filaments	yes	no	no
Power Gain	high	low	very high
Noise Level	medium	low	very low
Distortion	low	high	very low
Input Resistance	50 M ohms	1000 ohms	5000 M ohms
Temperature Range	−50 to +200°C	−50 to +80°C	−200 to +80°C

At least one manufacturer[4] has recognized this problem and has come out with a new series of FET's fully specified for amplifier performance. Using these devices, truly excellent performance is possible.

In addition to correctly specified devices, a few points on circuit design should be observed. Biasing of FET's is about as critical as for a pentode[4] if a high supply voltage is used (120 V). At bipolar transistor voltages (15 V.) bias becomes much more critical (2 per cent tolerance) and this causes difficulties in practical circuits. Therefore, high voltage operation is essential. Since the drain voltage in small signal amplifiers is close to but never more than 60 volts, a minimum FET breakdown of 60 volts is required for small-signal applications (100 volts and up for large-signal applications). Only for lowest noise operation is a reduced supply voltage justified (30 volts), particularly since distortion is not as critical in input stages.

Gate bias itself is best achieved by a self-bias resistor in series with the source-terminal. Due to the lower current drain of FET's as compared to tubes, this self-bias resistor is usually considerably larger than with vacuum tubes and generally should be bypassed. If feedback is to be applied to the source terminal, this is best accomplished by a separate feedback resistor in order to keep the local feedback down.

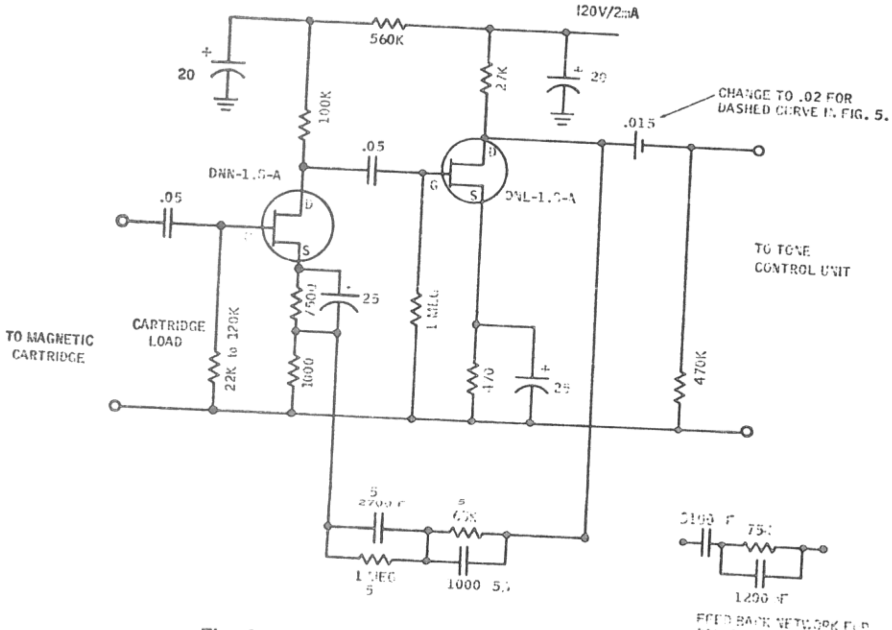

Fig. 1. Phono equalizer-amplifier with FET's.

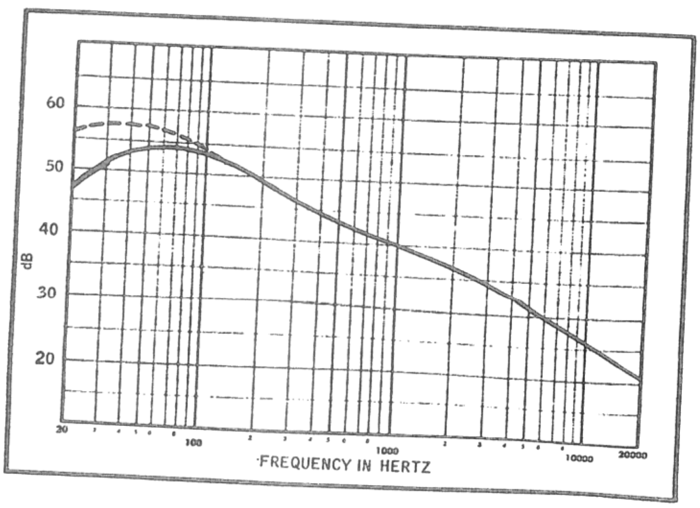

Fig. 2. Response of equalizer-amplifier of Fig. 1.

Phono-Equalizer Section with FET's

For the hifi-hobbyist, the superior performance of FET's suggests their immediate application to all kinds of hi-fi circuits. For the purists (like the author himself and many professional audio people), transistors were never a substitute for tubes. They simply had too much distortion and were

[4]Dickson Electronics Corp.

too unstable. Perfectionists who are used to equalization tolerances of ±0.1 dB never could "warm up" to transistors. Also, the peaks of certain musical instruments are up to 30 dB above the average, and the required high output capability is simply not possible with bipolar transistors. The situation is quite different with FET's.

The first portion of a phono-preamplifier consists of a phono equalizer. The circuit for this equalizer is shown in *Fig.* 1 and its frequency response in *Fig.* 2. The popular two-stage feedback circuit is used with series voltage feedback from the output into the first "source." This type of feedback decreases the output impedance and increases the input impedance particularly at the high frequencies where this is most beneficial. Any incorrectness in equalization (which is sometimes called a disadvantage of the circuit) is easily compensated by added components in the feedback network. The following changes as compared to a vacuum tube circuit are noticed:

a) Self-bias in the first stage by a bypassed 7500-ohm resistor. This resistor may have to be changed for different type FET's.
b) Large decoupling resistor for the first stage (560 K). This resistor drops the first-stage drain supply to about 30 volts for least noise.
c) Drain resistor for second stage is 27 K. This resistor was accurately adjusted for least distortion with feedback connected. Due to the parallel loading of the feedback network itself, a rather low value of drain resistence results.
d) The gate resistor of the first stage is made equal to the load resistor for the cartridge rather than using a 1/2-Meg. gate resistor and a separate cartridge load. A smaller gate resistance results in reduced noise due to possible leakage currents. While the amplifier will work with large gate resistors, it is a good idea (also in tube circuits) to keep the d.c. gate resistor as low as possible. Since the cartridge load is needed at the high frequencies only, a.c. coupling is permissible. As a matter of fact, d.c. coupling may also be used, although here some rejection of unwanted lows was desired. The exact cartridge load depends on the compliance of the stylus and the cartridge inductance and is best determined with a test record. The correct value results in the flattest response above 10 kHz. (Before this test, the minimum stylus force should have been determined, usually at 100 Hz and peak amplitude by observing tracings distortion on the oscilloscope.)

In addition, the following comments are offered regarding low-frequency equalization: Most musical instruments (with the exception of the organ) produce no significant fundamental output below about 80 Hz. For correct bass boost, for example, frequencies from 70 to 150 Hz only should be boosted. Boost below 70 Hz results in change of tonal character, and above 150 Hz in so-called "boomy" bass. Consequently, equalization extending indefinitely at low frequencies is a serious shortcoming of many preamplifiers because noises other than music are emphasized. Ideally, a rather sharp roll-off should be provided. Two possibilities are given in *Figs.* 1 and 2 to suit the individual's needs. Both input and output coupling capacitors are utilized for low-frequency rolloff. Therefore, these capacitors may need a slight readjustment with different resistors for the cartridge load or the input of the following tone control.

The performance of this phono-equalizer is excellent and reliable. Different FET's of the same type will operate equally without circuit readjustment. The equivalent input noise at 1000 Hz is −114 dB[5], the wideband output noise is −74 dB[5] (gain is 40.0 dB at 1000 Hz). This noise level is 8 dB lower than in the best professional tube circuit using d.c. filaments and with all traces of hum removed. It is 2 dB better than the best transistor circuit[6]. The overload level for 1 per cent distortion is +31 dB[5], 5 dB better than a tube circuit (even operating at twice the supply voltage) and 18 dB better than a normal transistor circuit. Distortion at 30

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TABLE II
COMPARISON OF PHONO PREAMPLIFIERS

	Tube	Transistor	FET	
Device, 1st stage	ECC83	2N1192	DNN-1.8-A	
Device, 2nd stage	ECC83	2N1193	DNL-1.8-A	
Gain, 1000 Hz	40	40	40	dB
Min. Output Noise, wideband	−66	−72	−74	dB*
Min. Input Noise, at 1000 Hz.	−106	−112	−114	dB*
Max. Output Level, per cent THD.	+26	+13	+31	dB*
Distortion at 30 V. output	in heavy overload		0.06	per cent
Overload-to-noise ratio	92	85	104	dB
Supply Voltage	180	15	120	V.
Current Drain	1	5	2	mA.

Note: All measurements with identical equalization and gain.
*With respect to 1V.

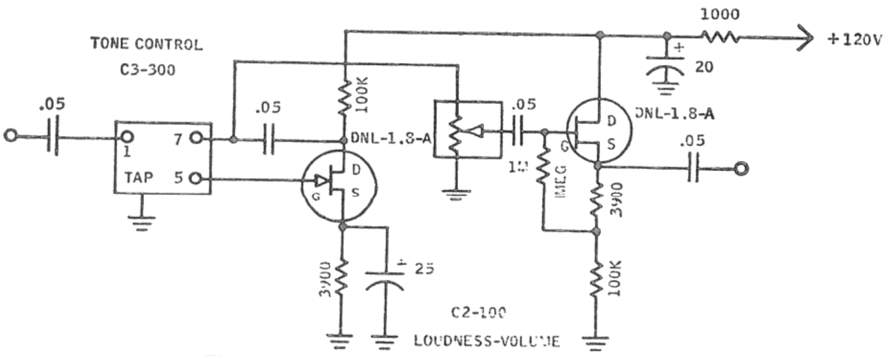

Fig. 3. FET audio control circuit, simplified.

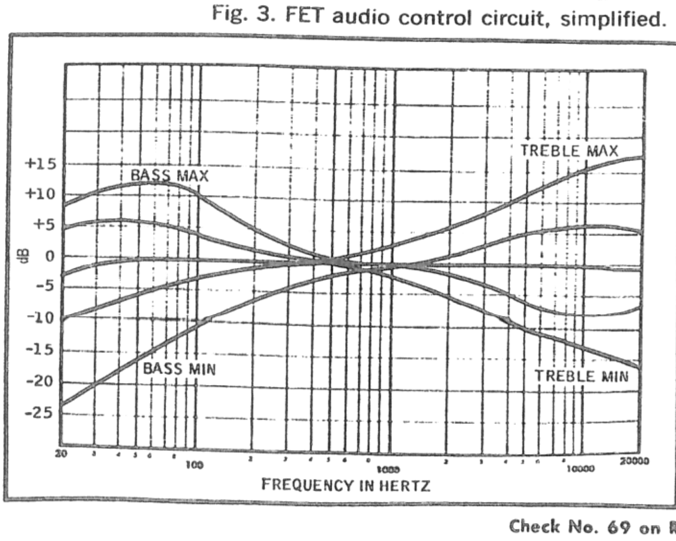

Fig. 4. Tone-control response curves from the Baxandall circuit of Fig. 3.

FET's *(from page 30)*

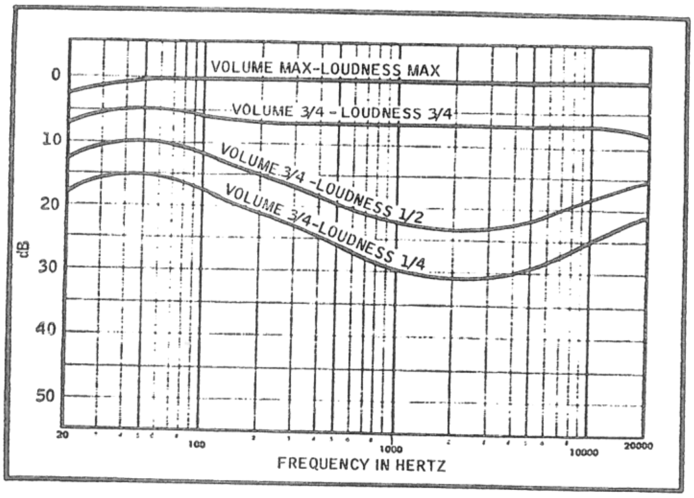

Fig. 5. Response obtained with the Centralab C2-100 loudness control as used in the circuit of Fig. 3.

volts output was 0.06 per cent while even the tube circuit was already in heavy overload. All measurements were taken under identical equalization and gain with all circuits adjusted to the optimum (Table II).

This phono equalizer may be installed directly with the turntable (the author's preference) with the tone and loudness control remote as a separate, compact unit next to the preferred listening position. With this concept, the critical cable from cartridge to equalizer is kept short and full control from a listening position is possible. Two identical units are needed for stereo. Up to 200 feet of cable may be run from the equalizer[5] relative to 1 V. rms.

In the other concept, the phono-equalizer is combined with the following tone control in one chassis. Generally a remote d.c. power supply is preferable to avoid magnetic hum from power transformers to be picked up by the cartridge.

Tone Control Section

The tone control uses the Baxandall[7] circuit which features a variable point of inflexion. It is a feedback-type control of superior quality. The design is greatly simplified by using special components available as low-cost printed circuits (Centralab parts C3-300 and C2-100). These components were originally made available for a high-quality tube control unit designed by C. G. McProud[8]. The circuit of the FET tone control is shown in *Fig.* 3 with curves in *Figs.* 4 and 5. The circuit very much reminds one of a standard tube circuit, although the self-bias resistors are somewhat larger. Also, due to higher loop gain of FET's, feedback circuits perform exceedingly well. It must be remembered that FET's have a voltage gain of about 50 dB as compared to 40 dB for a pentode and 30 dB for a triode. As can be seen from the curves, the performance of the unit is excellent. Gain at 1000 Hz was −1.5 dB due to the feedback with all controls set flat and volume maximum. Noise level was more than 80 dB below 1 V. Overload was 25.5 dB above 1 V. at 1 per cent distortion. This is still an excellent value as compared to tube circuits, but it is somewhat less than for the phono equalizer or the output stage itself. The distortion was traced to diagonal loading of the tone control stage. Where an even higher output level is needed, the source follower may be directly coupled to the drain of the tone control unit with the 1-Meg. and 3900-ohm resistor of the source follower removed and the 100 K resistor

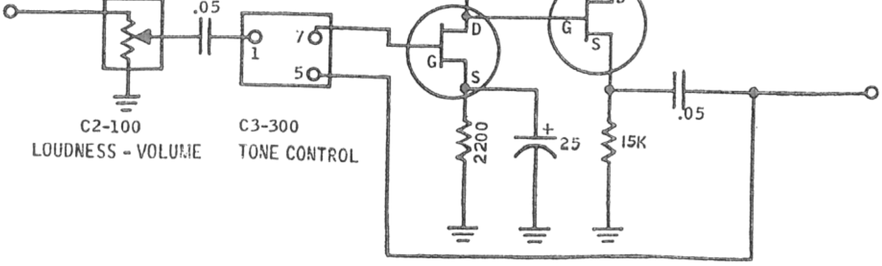

Fig. 6. Alternate circuit of tone control section, with relative locations of the components reversed.

changed to 15 K. The .05 μF coupling capacitor into pin 7 of the Baxandall unit is then removed from the drain of the first stage and tied directly to the source of the output stage. The loudness-volume control must then be relocated to the input of the unit. This modification (*Fig.* 6) results in an overload of 30 dB above 1 V. However, the action of the tone control is not as correct at high volume settings because the Baxandall circuit works best from low-impedance generators (less than 10 K).

Application of FET's to Other Hifi-Circuits

From the previous discussion, it is clear that superior performance is possible in all hi-fi circuits with FET's except where power is required since power-FET's have not become available as yet. The large dynamic range has been used for superior microphone amplifiers[9]. The author has also converted various power amplifiers to FET's with the exception of the push-pull output stage itself. In all cases, superior performance resulted[10]. It was found that a FET phase splitter could drive a pair of EL 34's to 100 watts with ease (distortion out of the phase splitter at this level was 0.1 per cent). FET's are applicable to all kinds of tape-recorder circuitry with the exception of the bias oscillator. Also, superior AM and FM tuners may be built with FET's. Due to the different voltage requirements, it appears that hybrid design with transistors will be unsatisfactory, while hybrid tube designs are entirely possible. It is the author's opinion that it will be only a few years until tubes and regular transistors have been completely replaced by FET's in all amplifier applications. The cost of FET's while still higher than transistors at the moment, will drop sharply since there is no basic reason other than the newness of the device why cost should not be on the order of 50c. It should be clear to the reader that an exciting new era of solid-state design is on the way, particularly in the hi-fi field. Æ

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[5]relative to 1 V. rms.

[6]W. Rheinfelder, "Noise performance of transistors in audio circuits" *Electronics World*, Jan. 1965.

[7]P. Baxandall, "Negative Feedback Tone Control," *Wireless World*, Oct. 1952, pg. 402.

[8]C. G. McProud, Preamp with Presence, AUDIO ENGINEERING, Jan. 1954.

[9]"Professional Microphone Amplifier FETs," Engineering Report 8. *(ibid.)*

[10]"Convert Your HiFi to Solid-State the Easy Way with FETs," Engineering Report 10. *(ibid.)*