DYNAMIC NOISE FILTER

PART TWO

by M.G. Strange

THE FILTER output is coupled to the detector via a small capacitor to make the low-frequency rolloff even steeper below 1.6 kHz. The precision full-wave detector uses diodes in the feedback circuit of an op-amp to effectively produce ideal rectification characteristics down to the millivolt region. The output amplifier doubles as a post-detection filter. Resistor R determines the gain, and capacitor C makes this stage behave as an operational integrator with time constant RC. A switch is provided for increasing the time constant by paralleling capacitor C1; this is helpful with sources having sharp impulse noise. The output of the detector/filter circuit controls the bandwidth of the dynamic suppression filter according to the curve of Fig. 9.

Early experiments showed that it is undesirable to make the no-signal cutoff lower than absolutely necessary to substantially reduce noise with a particular signal source. When the cutoff is made lower than actually needed, weak signals are unnecessarily band-limited and the dynamic filter produces such a level-dependent bandwidth contrast that its action is much more likely to be audible. Hence a BASE CUTOFF (not "BASS CUTOFF") control was found to be desirable. This control is simply a pot which offsets the detector output at zero signal level by applying a variable reference voltage to the op amp

non-inverting inputs. This voltage, variable from about −1 volt to −6 volts, establishes a "starting point" or base cutoff frequency which can be set just low enough to virtually eliminate no-signal noise.

VARIABLE-CUTOFF FILTER

The variable-cutoff filter, Fig. 8, is the very heart of the system. Since there is some part selection and adjustment necessary, it must be checked out separately. The basic configuration is similar to that of the pre-filter, except the latter's switch-selected resistors have been replaced by field-effect transistors (FETs). FET channel resistance R_{DS} changes as a function of gate voltage V_{GS} as shown in Fig. 11, thus varying cutoff frequency. A resistor across each FET establishes a solid lower cutoff limit and smooths the control characteristic as the FETs approach their "off" state. The gate circuit network, consisting of diode D1 and resistors R1 through R5, is used to empirically shape the control curve (Fig. 9) for best audible results. Diode D1 prevents excessive positive gate drive, maintaining isolation between the gate and signal circuits.

An input attenuator (R10 and R11) limits the signal amplitude presented to the FETs to about 0.1 volt p-p at 0 VU to ensure low distortion. Output amplifier A7 makes up exactly for this
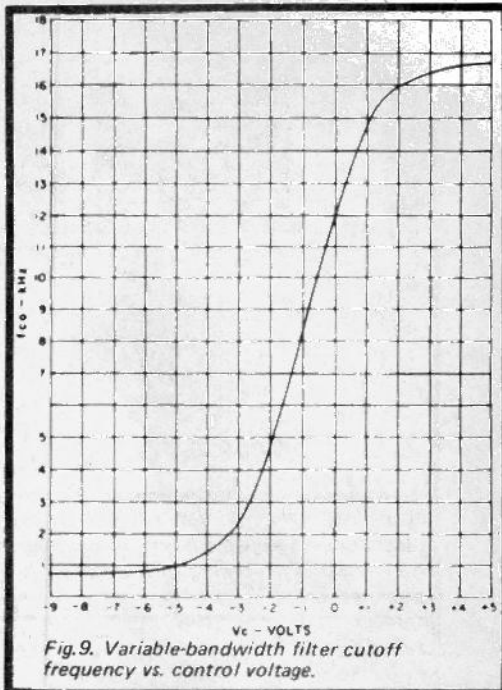
Fig.9. Variable-bandwidth filter cutoff frequency vs. control voltage.

loss. An op amp having external frequency compensation was used here so that this relatively high-gain stage could be tailored for flat response to 15 kHz (a μa741 could be used, but would roll off slightly above 10 kHz). Resistors R16 and R17 attenuate the output signal by an amount equal to the gain, so that this amplifier doubles as the unity-gain buffer required for filter operation. The highest cutoff frequency is dictated by minimum FET resistance and capacitors C1 and C2. The latter should have values in a ratio of about 3:1 to produce the desired Butterworth response. Figure 10 shows the measured response of the complete filter for four values of control voltage.

Unfortunately, FETs vary widely in characteristics, even between units of the same type, so these devices must be selected. The two FETs must be reasonably well matched over at 15:1 R_{DS} range for a 15:1 range in cutoff frequency (15 kHz to 1 kHz). (Dual matched FETs are available, but are more expensive and not necessarily matched for the parameter of interest here.) A transistor curve tracer is most convenient for this purpose and permits selection for best linearity as well as matching. I used N-channel 2N4220s on hand (60p each) and selected the best matched pair out of a group of six units. Figure 11 shows the VI characteristics of one of these. There are many other inexpensive FETs which should work as well, such as the 2N5484, 2N5716, and 2N5717. In fact, any general-purpose, depletion-type FET with fairly low zero-bias current (I_{DSS}) and pinch-off voltage (Vp) should be usable. P-channel units would require reversing diodes D1 and D2 and the polarity of the control voltage.
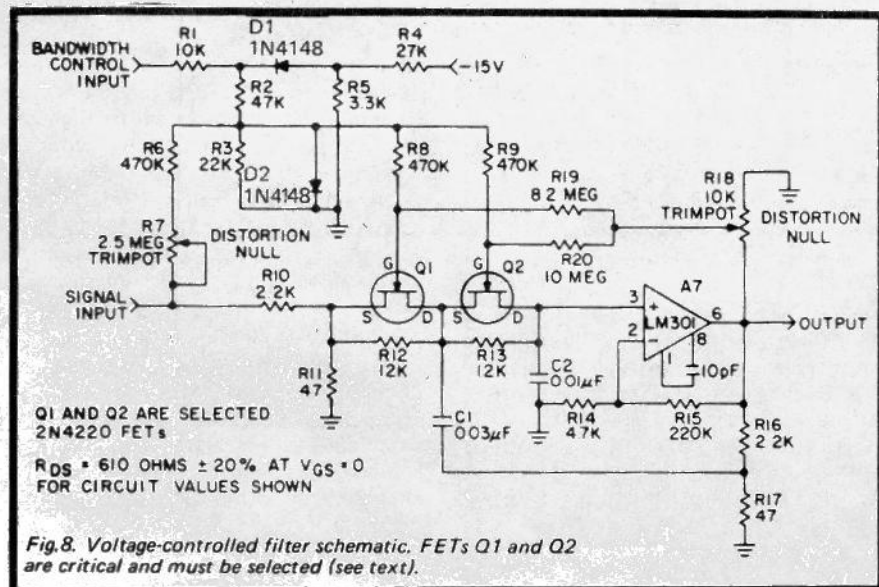
If a curve tracer is not available, the

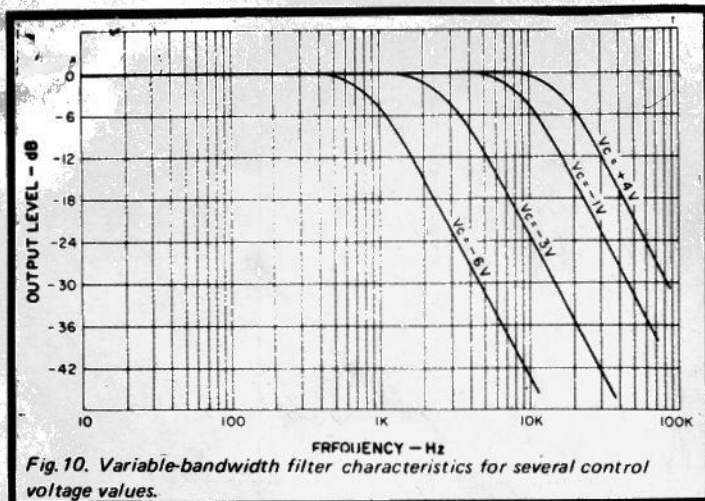Fig.8. Voltage-controlled filter schematic. FETs Q1 and Q2 are critical and must be selected (see text).

Q1 AND Q2 ARE SELECTED 2N4220 FETs

R_{DS} = 610 OHMS ± 20% AT V_{GS} = 0 FOR CIRCUIT VALUES SHOWN

Fig. 10. *Variable-bandwidth filter characteristics for several control voltage values.*

Fig. 11. *Variable-resistance characteristics of a junction field-effect transistor with low values of drain-to-source voltrage.*

setup of Fig. 12 can be used. A transistor socket will facilitate changing FETs. A good procedure is to first measure R_{DS} at $V_{GS} = 0$. Then increase V_{GS} (negatively for N-channel FETs) until R_{DS} is about three times the zero-bias value; this corresponds to a mid-range cutoff frequency where matching is the most critical. With this V_{GS} setting try different FETs until a 10 percent or better match is found. If R_{DS} values seem to cluster higher or lower, try another unit as a reference and try matching to it. When matched units are found, check the match at minimum R_{DS} ($V_{GS} = +0.5V$) and at 10 times this value of R_{DS}. A 20 percent mismatch can be tolerated at these extremes. My 2N4220s measure 610 ohms at zero bias, 360 ohms at $V_{GS} = +0.5V$., and about 8 kilohms at $V_{GS} = -0.7$ V. R11 and R12 are chosen for a cutoff of between 800 Hz and 1 kHz with the control voltage at its maximum negative value of about −6 volts. Circuit cutoff at zero FET bias should be roughly 12 kHz (see Fig. 9). A slight forward bias, limited to about +0.5 volt at the FET gates by diode D2, then boosts the cutoff to at least 15 kHz with maximum positive output from the precision detector.

Resistors R6, R7, R18, R19, and R20 reduce harmonic distortion significantly. R6 and R7 feed some signal to the FET gate circuit so that signal voltage does not appear between source and gate, which would make R_{DS} vary slightly with instantaneous low-frequency signal amplitude and polarity. R18, R19, and R20 feed back some output signal to the gates to further reduce distortion (this is a cancellation effect, not true negative feedback).

Distortion settings are best made in the vicinity of cutoff, where FET linearity is the most critical. Connect a variable-voltage d.c. source (the slider of a 5 k pot temporarily connected between − 15 V and ground will suffice) to the bandwidth control input and set it for a cutoff frequency of 2 kHz. Then, with a 2 kHz sinusoidal input at about 0 VU (2.2 V p-p), set trimpots R7 and R18 for lowest harmonic distortion at the output. It should be possible to sharply null the total harmonic content, which consists primarily of the 2nd and 3rd harmonics, to at least 60 dB below 0 VU. Then vary the cutoff frequency and make sure distortion is low for all settings. Of course, the filter itself will reduce harmonic distortion appreciably at its lower cutoff values. Lacking a distortion meter or wave analyzer, these adjustments can be made quite well by driving the input at 7 volts p-p (10 dB above 0 VU) to accentuate the
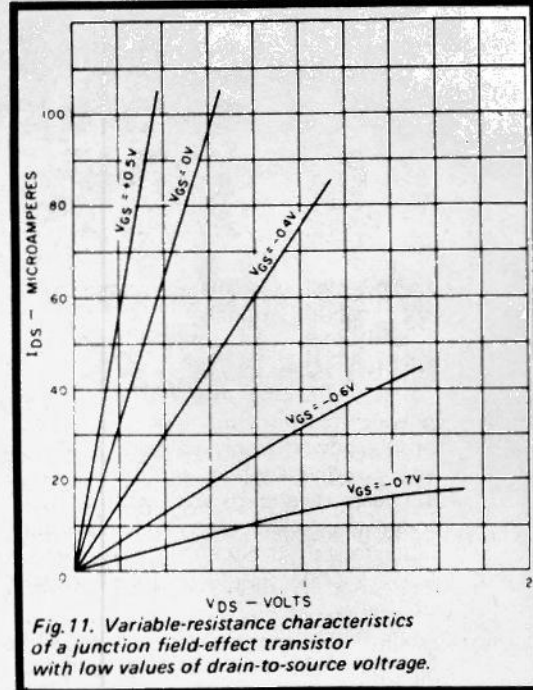
distortion and setting very carefully for a symmetrical output waveform as monitored by a 'scope. Fixed resistors, determined by two decade boxes (the settings interact somewhat), could replace the pots. These adjustments, once made, are permanent unless the FETs are changed.

Figure 13 shows the distortion of the complete noise filter measured at two fixed values of bandwidth control voltage. At normal levels, distortion is so low that it is largely a measurement of the harmonic distortion of the test oscillator. The large margin above 0 VU passes the highest programme peaks ever likely to be encountered without clipping.

The simple power supply of Fig. 14 easily supplies the power requirement of ± 15 volts at about 10 mA.

CONSTRUCTION

The entire filter can be duplicated for about £40 with new parts. Very few components are critical and substitutes can be used in most cases. Quarter-watt, 5 percent composition resistors are suitable. Layout is not critical, since signal levels are high and impedances are relatively low. I strongly recommend that each of the functional blocks of Fig.2 be built and checked for reasonable conformance with the curves before integration into the system. This makes troubleshooting for errors and occasional bad components much easier, practically ensuring success. My unit (Fig. 1 and lead photo) is a "breadboard in a box." The circuit is still undergoing occasional changes, even though it is a third-generation model. Parts are mounted on terminal boards which were on hand. A neater approach would be to use the
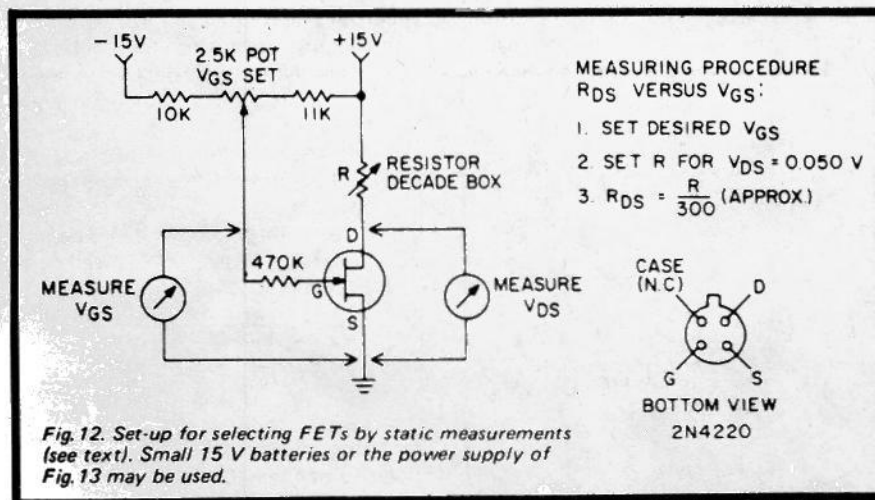

MEASURING PROCEDURE R_{DS} VERSUS V_{GS}:

1. SET DESIRED V_{GS}
2. SET R FOR $V_{DS} = 0.050$ V
3. $R_{DS} = \frac{R}{300}$ (APPROX.)

Fig. 12. *Set-up for selecting FETs by static measurements (see text). Small 15 V batteries or the power supply of Fig. 13 may be used.*

DYNAMIC NOISE FILTER

commercially-available   matrix-board
with snap-in terminals.

OPERATION

After checking the wiring, apply
power to the unit and check for
proper power supply voltages. Positive
and negative supplies should both be
between 14 and 16 volts with respect
to ground. Much lower values would
indicate a short circuit or bad op amp.
Current drain should be on the order
of 10 mA.

The noise filter can be conveniently
connected to your audio system by
means of the *Tape In* and *Tape Out*
jacks included on most preamplifiers.
An advantage to this connection is
that the processed signal passes
through the pre-amp tone controls,
which can be set for the most pleasing
final balance. For taping, the recorder
input is paralleled with the output
which drives the power amplifier.

For intial set-up experience, a record
having a good frequency range and
moderate, steady surface hiss is
desirable. (A slightly noisy FM station
can also be used, but results will not
be quite as good because of the latter's
flatter noise spectrum.) Initial control
settings should be:

Pre-Filter: Off
Rumble Filter: Off
Time Const.: Off
Peak Rej. Freq.: 5 kHz
Base Cutoff: CCW
Suppr. Gain: CCW
Dyn. Suppr.: Off
Sig. Compare: Input

The signal should now pass through
the unit unaffected, except the *Level
Set* control will vary the gain from
zero to 3.2 (10 dB). Set the level for 0
VU on signal peaks as you would set a
recording level. Whenever the source is
changed, the signal level should be
reset as necessary.

Now switch the *Sig. Compare* switch
to "output". The signal is now passing
through the rumble filter (if used) and
pre-filter, but bypassing the dynamic
filter. Lowering the *Pre-Filter* cutoff
setting should progressively cut off the
highs. At the lower settings, which are
primarily for acoustic records, the
signal will sound severely band-limited.
The best setting is the lowest cutoff
which does not significantly affect the
recorded bandwidth. I have found that
with vocal music, the unfiltered
sibilant sounds provide a means of
judging bandwidth. If sibilants are
quite strong and natural, a 7 kHz or
higher cutoff is indicated. If they are

Fig. 13. Overall harmonic distortion of the noise filter for two constant values of bandwidth-control voltage.

weak or have a slight "whistling"
sound, the upper limit is about 5 kHz.
If sibilants are lacking, a 4 kHz or
lower setting is best. Of course, the
presence of high-frequency distortion
may dictate a compromise setting a
notch or two lower than indicated
above. The filtered and unfiltered
sounds may be compared at any time
by means of the *Sig. Compare* switch.

The optional rumble filter is used for
the occasional records which have
warpage or bumps or low-frequency
noise in the recording. For *acoustic*
records it can be routinely left at 150
Hz, as nothing is recorded below about
200 Hz.

Next flip the *Dyn Suppr* switch to
"on", putting the dynamic suppressor
in the circuit. The sound should
become very dull and lifeless, as the
high-frequency cutoff is now 1 kHz or
less. Increase the *Base Cutoff* setting
until record noise just begins to be
audible. The signal will probably still
be quite lacking in high-frequency
content (if it is not, only the pre-filter
may be needed for this particular
source). Now turn up the *Suppr Gain*
slowly. This should "magically"
restore the highs without increasing
the noise level. The highest possible
setting which does not noticeably

increase the noise is normally best.

At this point it is edifying to monitor
the bandwidth control input signal to
the variable-bandwidth filter with a
d.c.-coupled   oscilloscope. The
instantaneous voltage here is a measure
of high-frequency programme
amplitude and dynamic filter
bandwidth (see Fig. 9). It should
follow transients rapidly and may
reach saturation (about + 14 volts) on
musical passages having high harmonic
content and on strong voice sibilants.

The *Peak Rej. Freq.* switch selects
the frequency of peak rejection by
choosing the appropriate filter curve
(Fig. 7) for separating the
bandwidth-control voltage from the
input signal. The *5 kHz* position is
used for most electrical 78 rpm
records. For acoustic records or very
noisy electrical 78s where the pre-filter
is set for 4 kHz or less, the *3.5 kHz*
position gives better results. Here the
Time Const. switch can be set for *15
mS*. The longer time constant also
helps to attenuate sharp clicks and
pops occuring in quiet passages, as it
prevents the bandwidth from
increasing rapidly enough to follow
their steep wavefronts. The *7.5 kHz*
position is used for wideband
recordings and tape.
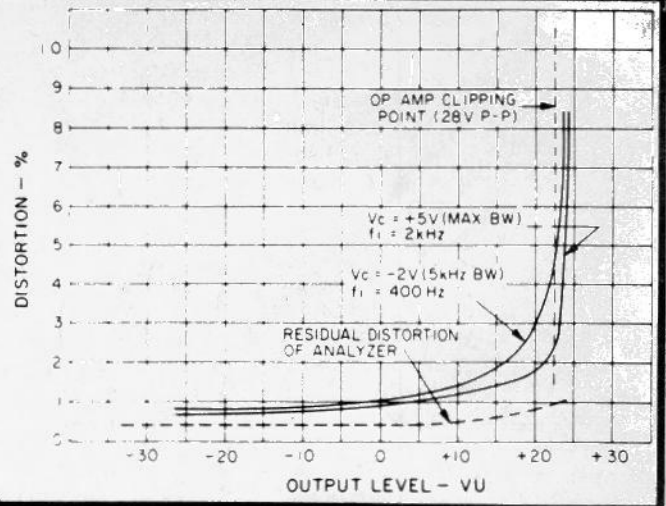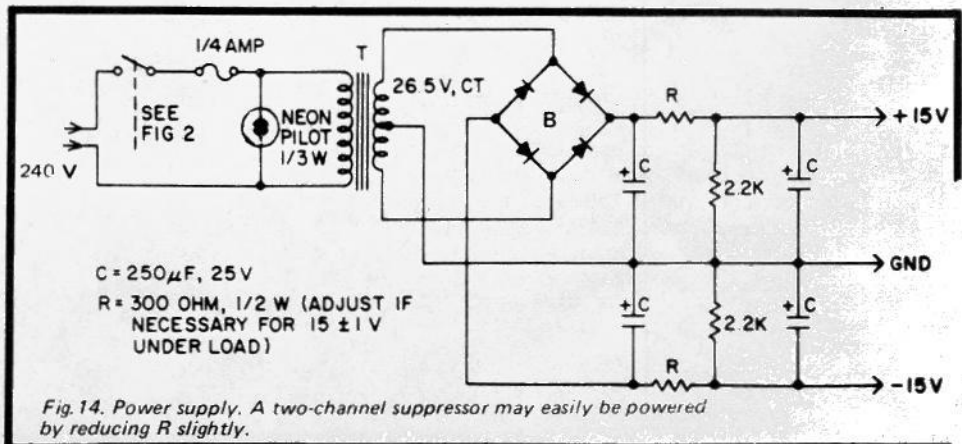
With a little practice, you will be able

Fig. 14. Power supply. A two-channel suppressor may easily be powered by reducing R slightly.

to set the controls quickly for optimum performance. It is often best to set the *Base Cutoff* for a significant improvement, rather than to try to eliminate the noise completely. This will minimize low-level band limiting, and the suppressor will be less likely to betray its presence with obvious bandwidth changes.

PERFORMANCE

Figures 5 and 10 indicate the bandwidth ranges available. The pre-filter and dynamic filter (slope is 24 dB/octave above both cutoffs) can together provide well over 60 dB of noise attenuation at 10 kHz and over 40 dB at 5 kHz. The overall improvement in signal-to-noise ratio is strongly determined by the character and spectrum of the noise, which varies greatly with records. With the steady hiss typical of new electrical recordings on shellac, an average improvement of 8 dB (unweighted) is realized from the dynamic filter alone. Including the effects of the rumble filter and pre-filter on band-limited material, S/N improvement can be more than 12 dB. The apparent improvement is even greater, since the ear heavily weights the higher frequencies where record noise is concentrated.

The effect of the noise filter is surprisingly great on records which were originally thought to be quiet without filtering. It is a little weird at first to hear a familiar old record with realistic strings and brass and clear voice sibilants, but with the background suddenly rendered deadly quiet. I have spent many hours listening to the records and tapes in my collection and enjoying them anew.

The noise filter works very well on tape noise, providing at least 8 dB total S/N improvement. A stereo version built for tape only could be simplified considerably, as only the *Level Set, Base Cutoff, Suppr. Gain, and Sig. Compare* controls would be needed. The power supply as shown can easily handle two channels.

The noise level of the filter itself depends mostly on output amplifier A7. Of several units I tried, the noise level ranged from 62 to 68 dB below 0 VU.

A few tips on the mechanical aspects of copying records are in order here. The importance of good tracking cannot be overemphasized. More can be gained here than with any amount of electronic processing. Groove radius, depth, and angle were not standardized on early discs, and experimentation with tracking force and stylus size, if possible, may yield a considerable improvement in both noise and distortion. The playback

stylus should, of course, ride on the sides of the groove. If it is too small it may ride the bottom of the groove and skate from side to side in a partially uncontrolled manner, creating severe distortion. If too large, it will ride high in the groove where it is more sensitive to surface blemishes. Also, larger styli cannot follow high-frequency modulation as well, especially on the inner record grooves. Elliptical styli are helpful on relatively wide-range 78s if the latter have not been damaged by previous playings.

Acoustic records (1925 and earlier) tend to have a larger groove, since with acoustic playback the mechanically-imparted stylus motion had to supply all the sound power. For these, a stylus of 4-mil (.004") radius may produce better results than the standard 3-mil size. Custom-made styli with a "truncated" tip (really a smooth transition from a 2- or 3-mil radius to about a 4-mil radius at the very tip) have been used to track the groove sides of 78s properly while avoiding contact with the bottom. (Truncated and other special styli are available from the International Observatory Instruments, 5401 Wakefield Drive, Nashville, Tenn. 37220). Although not a cure-all, these can give dramatic results on selected discs. A 2.5 mil stylus is best for most post-1946 transcriptions. Obviously, the pickup should have adequate lateral compliance and should produce no output for vertical motion. Incidentally, electrical recordings made before the mid-1940s are mostly recorded flat, that is, they have no high-frequency pre-emphasis, while later records have pre-emphasis of as much as 16 dB at 10 kHz.

Edison cylinders (160 rpm) and discs (80 rpm), some Pathe discs, and some early wax transcriptions are vertically modulated. Here the stylus does ride on the groove bottom, and the pickup should have only vertical response. This can be obtained (as can lateral-only response) from a suitably-phased stereo cartridge. Stylus radii of 4 to 10 mils are typical here; as always, experimentation is in order.

FUTURE DEVELOPMENT

The experimenter may want to try to improve the performance of the circuit described. Of course, additional types of processing can be added, such as more effective click suppression at the filter input or multi-channel equalization at the output. These would be electrically independent of the noise filter, and beyond the scope of this article. However, there are some possibilities for improving the noise filter itself. Many of these, unfortunately, would require an

incongruous increase in complexity and cost.

Sharper filter cutoffs give a marginal improvement on very noisy material, but setup adjustments become more critical. Dynamic high-pass (low-cut) filtering using a simple 6 dB/octave slope might be a reasonable addition. Since the noise-rejection frequency band of the low-pass dynamic filter should complement the noise spectrum of the signal, a statistical study of record and tape noise spectra might lead to a better shape for the bandwidth-control-signal separation filter of Fig. 7. The separation filter selector could be ganged with the pre-filter cutoff switch to eliminate one control knob. Perhaps a noticeable improvement could be realized by experimenting with the shape of the bandwidth control characteristic, Fig. 9. The attack time constant could be shortened by using a more elaborate filter at the precision detector output; this would improve the response to occasionally encountered wide-band transients.

An obviously desirable change would be to replace the FET bandwidth-control filter with one of the voltage-controlled state-variable types. This would eliminate the need for FET selection, but would increase the cost severalfold. It therefore appears that the original goal of high performance per dollar has been achieved, yielding a practical design which is within reach of the hobbyist.

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