Effect of Load Impedance on Magnetic Pickup Response

NORMAN PICKERING*

A discussion of operating conditions for the four popular types of magnetic pickups, together with a series of useful curves showing the effects of resistance and capacitance across the pickup on the over-all frequency response.

Audio systems designers and users are always greatly interested in frequency response; in fact, one might say that they are obsessed with it. And well might they be, since nowadays it is taken for granted that any audio system worthy of the name will have a frequency-response characteristic which is asymptotic to perfection. Another more cynical reason has often been advanced to explain the general and devoted attention to frequency response: it is so easily measured.

The accepted procedure for measurement of this parameter is to apply an input signal of known amplitude and frequency and to measure the amplitude of the output signal at each frequency. The difference between input and output signal amplitudes is the absolute gain of the device, when due allowance for impedance ratio has been made. When all of these differences have been plotted against frequency, a frequency-response curve results. If the device being measured is an amplifier it is a simple matter to achieve great accuracy. As soon as a transducer is involved, however, the measurements become much less reliable, although hardly more difficult to make.

Transducers

For one thing, absolute gain has no meaning in transducer measurements. It is necessary to settle arbitrarily on a definition of gain in order to compare transducers. For a phonograph pickup, for example, "absolute gain" might be: microwatts output per centimeter per second r.m.s. velocity at the stylus tip. Even this is incomplete, though, since no allowance has been made for the mechanical impedance at the stylus tip.

Whenever such definitions are proposed they usually meet with an apathetic reception for one or more of the following reasons: 1. It is hard to agree on units, since metric and English units are all mixed up in the recording business. 2. Most engineers feel that pickup efficiency is not important, since amplifier gain is cheap. 3. Absolute gain measurements require much care and some relatively expensive equipment.

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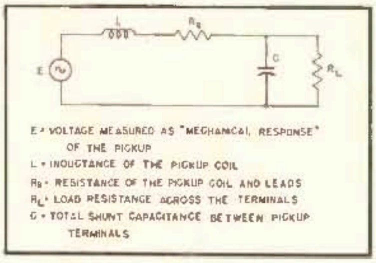

Fig. 1. Equivalent electrical circuit of a magnetic pickup.

Even if we ignore "absolute" response, then, how do we determine even the relative frequency response of a pickup to a fair degree of accuracy? The mechanical signal source is obviously of prime importance, and for practical measurements in the field is invariably a special phonograph record. This record may be an ordinary "frequency" record, a "glide-frequency" record or a "sweep-frequency" record. The usual frequency record consists of a number of bands of discrete frequencies recorded at what is hoped is a known amplitude. The glide record traverses the indicated frequency band at a slow rate, covering all of the frequencies between the starting and the final one. The sweep record does the same thing, but at a rapid rate (usually about 20 times per second) so that an oscilloscope can be synchronized to the sweep rate and the amplitude-frequency characteristic observed directly on the screen.

Each of these records is useful—and each is subject to considerable error. The fixed-frequency record is the only one which can be calibrated, and this procedure must be carried out on each pressing if precise results are to be obtained. The general willingness to rely upon frequency records indicates a lack of awareness, on the part of the user, of the many possible chances for error in this method of measurement, yet what is the poor fellow going to do? About all that is possible is to purchase a well-made record which shows a "flat" light-pattern and to discard it as soon as the noise level shows that severe wear has taken place. With some reproducers, at certain frequencies, two or three playings may make a particular band unfit for further use. The mechanical impedance of many reproducers is such that at very high frequencies with small stylus radii, inelastic deformation of the record material may occur.

Mechanical Response

It is not the purpose of this paper to analyze the situation existing in the mechanical system of the pickup. It will be shown that whatever the basic response of the pickup, however, it will be altered by the following electrical circuit, and such modifications may have a harmful or a corrective effect upon the frequency response.

If a frequency record is played by a given pickup, the open circuit response at the pickup terminals gives the desired information about the way in which mechanical excitation of the stylus tip is converted to electrical energy. This, for lack of a better term, might be called the "mechanical response" of the pickup. This response curve must be added to the electrical response about to be discussed to give the complete frequency response curve of the reproducer.

Electrical Response

Figure 1 gives a very close approximation to the equivalent electrical circuit for a magnetic pickup connected to an amplifier.

The useful signal voltage is that developed across R_L.

Network Equations

The total impedance in the circuit is:

$$Z_t = j\omega L + R_0 + \frac{R_L\left(-\frac{j}{\omega C}\right)}{R_L - \frac{j}{\omega C}}$$

which becomes:

$$Z_t = \frac{\left(R_0 R_L + \frac{L}{C}\right) + j\left(\frac{R_L \omega^2 LC - R_0 R_L}{\omega C}\right)}{R_L - \frac{j}{\omega C}}$$

If E is assumed to be unity, the current in the circuit is

$$\frac{E}{Z_t} = I = \frac{R_L - \dfrac{j}{\omega C}}{\left(R_o R_L + \dfrac{L}{C}\right) + j\left(\dfrac{R_L \omega^2 LC - R_o R_L}{\omega C}\right)}$$

The voltage across the parallel combination of C and R_L is IZ_s where

$$Z_s = \frac{-j\, R_L \left(\dfrac{1}{\omega C}\right)}{R_L - j\left(\dfrac{1}{\omega C}\right)}$$

Multiplying I by Z_s, the signal voltage across the load becomes:

$$E \text{ out} = \frac{R_L + j\omega R_L^2 C}{[R_L + R_o - R_L\omega^2(2LC + R_oC^2)] + j\,[\omega(R_L^2C + 2R_LR_oC + L - R_L^2\omega^2LC^2)]} \quad (1)$$

When $C = 0$, the expression becomes

$$E \text{ out} = \frac{R_L}{R_L + R_o + j\omega L} \quad (2)$$

On inspection it can be seen that the output voltage in Eq. (*2*) will fall off at high frequencies unless R_L is very large compared to $2\pi f L$. It is not so easy to tell from Eq. (*1*) exactly what is likely to happen.

Practical Values

It is in order at this point to examine the equivalent circuit and assign practical values to the parameters. The user has no control over R_o and L, so the values found in four popular pickups will establish the region of operation generally encountered.

TABLE I

Inductance and Resistance of Typical Pickups

Pickup	L	R_o
Audak L-6	0.780 Hy.	630 ohms
G. E. RPX-050	0.470 Hy.	370 ohms
Pickering 140 & 120	0.150 Hy.	600 ohms
Clarkstan	0.720 Hy.	1660 ohms

Frequency Response with Resistive Load

When the load has no appreciable capacitive component, the frequency response may be calculated from Eq. (*2*). *Figure 2* shows the results of such calculations for a pickup of 150 millihenries inductance and 600 ohms resistance. It will be seen that the response becomes asymptotic to 6-db-per-octave roll-off at the high frequencies, and this fact may be used to advantage in equalization circuits for pre-emphasized record characteristics. It will further be noted that the low-frequency level of the voltage output is uniformly attenuated because of the resistance R_o of the pickup coil. This constitutes a practical limit to the amount of attenuation which can profitably be done with only a resistor across the terminals. In cartridges which have a high ratio of L to R_o, more high-frequency attenuation can be achieved before low-frequency losses exceed a practical maximum (say 4 db).

Figure 3 shows the frequency response for a cartridge with a high ratio of L to R_o. L is 0.472 henries and R_o is 370 ohms. It will be noted that the effect on low frequencies is very much less than in the cartridge of *Fig.* 2.

This information gives a good indication of the nominal "impedance" of the cartridge. Since the generator impedance is reactive, the load resistance for flat response will depend on the inductive element. This is usually specified by the manufacturer to include effects of mechanical response, but for a working figure, the nominal impedance of the cartridge will be the value of $2\pi f L$ at $\omega = 1.25 \times 10^5$ (approximately 20,000 cps). At this point the electrical response will be down 3 db. *Figure* 4 shows the nominal impedance as a function of coil inductance. This illustrates clearly how the pickup with 780 millihenries inductance can have a nominal impedance of 0.1 megohms, although its d.c. resistance is only 630 ohms.

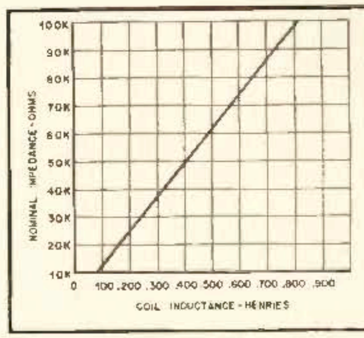

Fig. 4. Nominal impedance of a magnetic pickup as a function of coil inductance.

Effect of Capacitance

It is impossible to have a cartridge connected to an amplifier without having some capacitance shunting the pickup coil. Since virtually all high-impedance installations have one pickup lead grounded, it is the sum of all the capacitances from grid to ground which is the value of C in *Fig.* 1.

Referring to Eq. (*1*), it will be seen that C figures prominently in the frequency response of the cartridge, but since it appears both in the numerator and in the denominator, and both positively and negatively, it is difficult to see by inspection what the net effect will be.

Since C always occurs with R_L, it is apparent that the factor R_LC is more significant than the absolute value of C. It may be of interest to examine actual installations in order to determine possible actual values of C encountered in practice.

Practical Values of Capacitance

The Miller-effect capacitance of various input tubes is listed in Table II. The tubes indicated are those usually encountered in phonograph preamplifiers used for magnetic pickups.

The input connection to the preamplifier is usually made by means of shielded wire. The capacitance per foot of various types of wire is shown in Table III. In addition to these capacitances, there is generally an additional capacitance of

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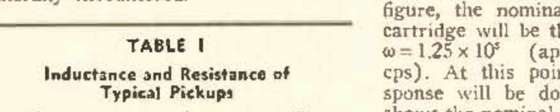

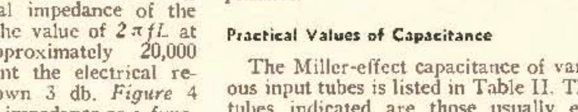

Fig. 2 (left). Curves showing the frequency response of a Pickering D120M pickup with various resistive loads. Fig. 3 (right). Frequency response of GE RPX-050 pickup with various resistive loads.

MAGNETIC PICKUPS

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from 10 to 50 μμf in the input wiring, plug and socket, and switch (if used) in the preamplifier.

From all this, it is apparent that a total shunt capacitance of at least 100 μμf is assured for any installation. A long run of shielded wire between the turntable and preamplifier with the use of high-mu triode tubes can easily bring the total capacitance to 1000 μμf or more. Nearly all practical installations will fall within these limits. Since most values of R_L will fall between 1000 and 200,000 ohms, a working range of R_LC will lie between 1×10^{-7} and 2×10^{-4}.

cutoff frequencies are shown in *Fig.* 5, for each of the four pickups calculated. For any cartridge at any desired cutoff frequency the values of R_L and C may be read directly from the left-hand scales.

Figures 6 to 9 inclusive show the effect of capacitance only on each of the four pickups. A wide range of values was used, to cover the range from 5000 to 20,000 cps in each case. From all of these curves it will easily be seen that significant changes in high-frequency response can occur as a result of the capacitance across the pickup terminals.

TABLE II

Miller-Effect Capacitance of Input Tubes

Tube Type	C_{GG}	C_{GP}	Amplification	Total Capacitance—μμf
6SN7 (6J5)	3.0	4.0	15	63
6SL7	3.4	2.8	52	159
6SJ7	7.0	.005	100	7.5
6AU6	5.5	.0035	100	6.5
6C4	1.8	1.6	15	25
6SC7	2.2	2.0	40	83

Calculation of Frequency Response

Equation (*1*) was reduced to a series of graphs, which were then used to calculate the electrical response of the four pickups under various load conditions. The response calculations were divided into the following classifications:

(1) $R_L = \infty$, C varied.
(2) C fixed, R_L varied.
(3) R_L and C chosen to provide the sharpest cutoff at certain frequencies.

It will be observed that L and C form a low-pass constant-K filter section, and that it is possible to choose values of C and R_L to satisfy the relationships:

$$L = \frac{R_L}{\pi f_0} \text{ and } C = \frac{1}{\pi f_0 R_L} \qquad (3)$$

The values of R_L and C for various

TABLE III

Capacitance of Various Shielded Wires

Wire Type	Capacitance—μμf per foot
Shielded hook-up wire	55 - 70
.140 O. D. Microphone cable	40
.200 O. D. Microphone cable	25
Heavy duty Microphone cable	33

The amount of rise at the peak depends, of course, on the Q of the circuit. The various pickups differ somewhat in that respect. Furthermore, the location of the peak depends on the inductance of the pickup coil, for a given capacitance. In general, therefore, the higher impedance (hence higher inductance) pickups are more sensitive to

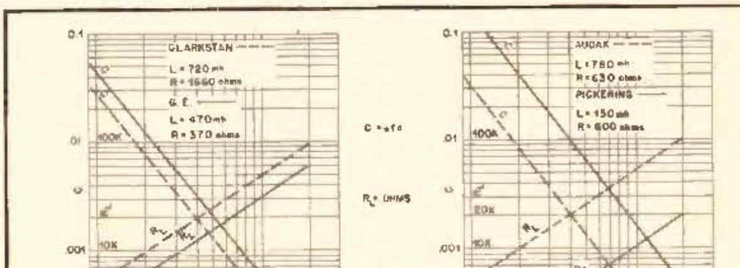

Fig. 5. Values of R_L and C for various cutoff frequencies for the four pickups.

shunt capacitance effects than are the lower impedance units.

In the very-high-impedance units, particular care should be taken to reduce shunt capacitance, since even 100 or 200 μμf will have a significant effect on the response above 10,000 cps.

The addition of a shunt resistance makes it possible to flatten out the resonance peak, but it is not possible to obtain any significant response above the cutoff frequency.

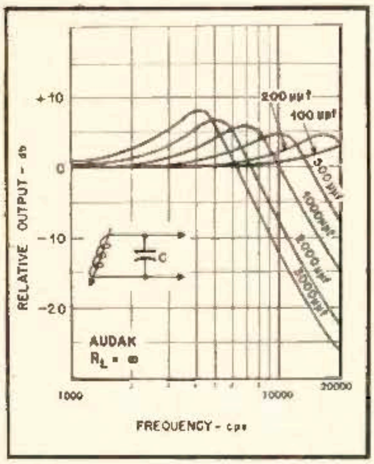

Fig. 6. Response of Audak L-6 pickup with various shunt capacitances and a resistive load of ∞.

Figures 10, 11, 12 and 13 show the effects of adding resistance in parallel with the shunt capacitance. It is apparent that a value of resistance can be found to give substantially flat response out to the cutoff frequency, but the upper frequency limit is definitely fixed by the product of coil inductance and shunt capacitance.

When the values of R_L and C satisfy the relationships expressed by Eqs. (*3*) and plotted in *Fig*. 5, a low-pass constant-*K* filter network results. To indicate the kind of result to be expected with each of the four pickups, *Fig*. 14

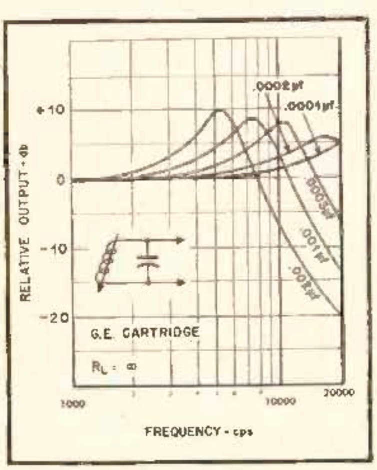

Fig. 7. Response of GE RPX-050 pickup with various shunt capacitances. $R_L = \infty$.

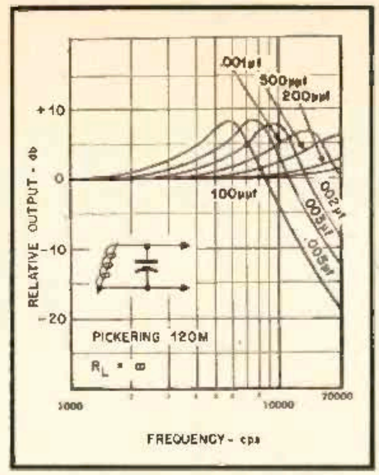

Fig. 8. Response of Pickering D120M pickup with various shunt capacitances. $R_L = \infty$.

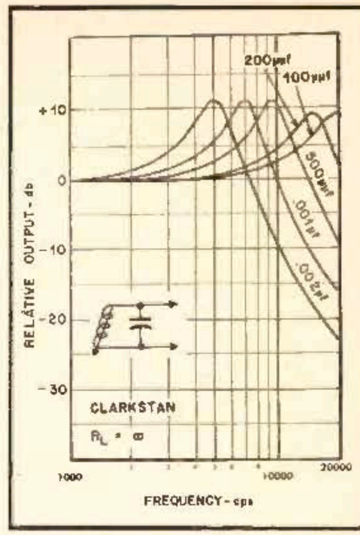

Fig. 9. Response of Clarkstan pickup with various shunt capacitances. $R_L = \infty$.

was prepared, using values selected from *Fig.* 5 for a cutoff frequency of 5000 cps. As might be expected, the sharpness of cutoff varies from unit to unit according to the Q of the coil. This Q cannot completely be represented by $\frac{\omega L}{R}$ where L is the coil inductance and R the coil and lead resistance. The actual Q depends on the a.c. losses (eddy currents, hysteresis, etc. in the soft-iron magnetic structures in the pickup) as well as the d.c. resistances. However, it was found that in devices of the type being discussed here, the discrepancy between calculated and measured response was less than the probable error of measurement.

To indicate what can be done with the cut-off filter effect, a single pickup was provided with four different sets of terminating *R-C* combinations selected from *Fig.* 5; *Fig.* 15 shows the results for 3000-, 5000-, 7000-, and 10,000-cps cutoff frequencies. It will be seen that the rate of attenuation above cutoff is very close to 12 db per octave.

In order to check the equations which were used to obtain the foregoing response curves, actual measurements were made by two methods: the pickups were tested on a standard frequency record, and they were also checked by the simulated-signal method. The measurements made with the frequency record gave close agreement up to 10,000 cps, and increasing spread, of a random nature, above that frequency. This is to be expected because of the high probable error in this method of measurement discussed earlier.

The second method gave complete agreement between measured and calculated results. The circuit of *Fig.* 16 was used.

Conclusion

It is evident that the load impedance across the terminals of a magnetic phonograph pickup will have a great effect

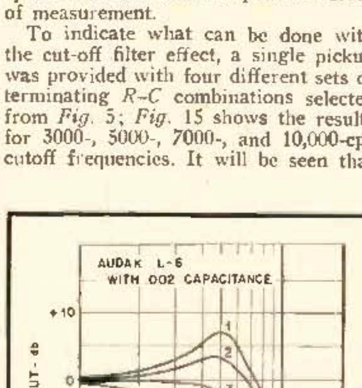

Fig. 10. Response of Audak L-6 pickup with shunt capacitance of .002 µf and various load resistances.

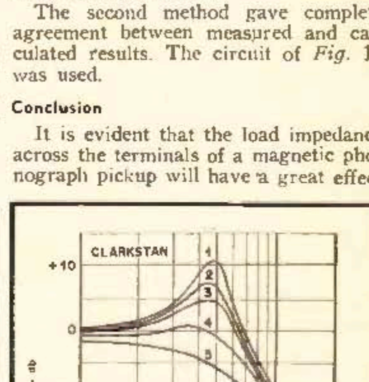

Fig. 11. Response of Clarkstan pickup with shunt capacitance of .002 µf and various load resistances.

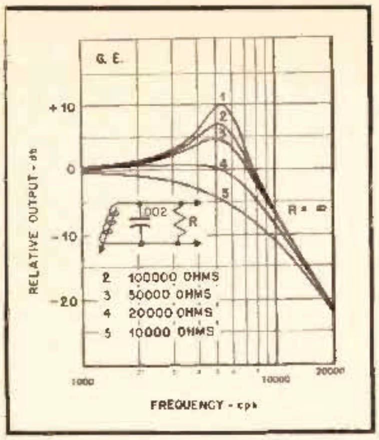

Fig. 12. Response of GE RPX-050 pickup with shunt capacitance of .002 µf and various load resistances.

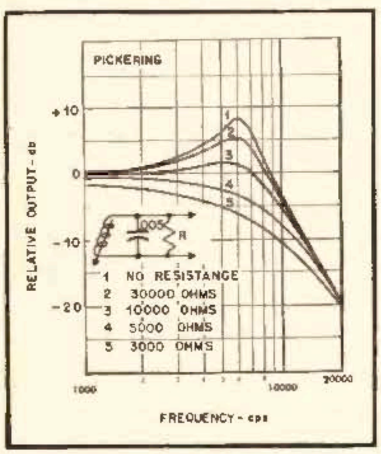

Fig. 13. Response of Pickering D120M pickup with shunt capacitance of .005 µf and various load resistances.

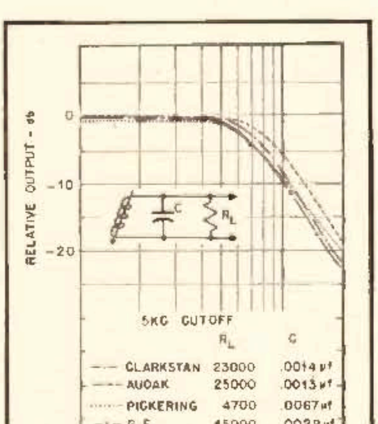

Fig. 14. Curves showing 5000-cps cutoff with the four pickups when shunted by resistors and capacitors shown in the legend.

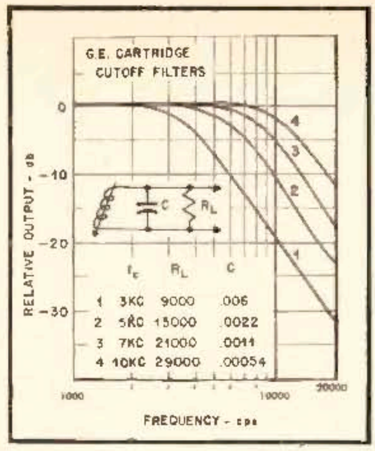

Fig. 15. Curves showing low-pass filter effect on response of GE RPX-050 pickup when shunted with capacitances and resistances indicated.

on the frequency response of the device. This effect can be accurately calculated for a given pickup of known coil resistance and inductance. A resistive termination causes a general drop in output at all frequencies, the loss increasing at high frequencies. A capacitive termination causes a peak at a frequency determined by the *LC* product, of a magnitude depending on the Q of the circuit. A combination of resistance and capacitance will modify the peak, and at one specific set of values for each case will constitute a constant-*K* low-pass filter. When the resistive shunt has a low value compared to the capacitive reactance, the effect approaches that obtained with resistance termination alone.

The foregoing information can be used to guard against unwanted modifications of the pickup frequency response, to determine the highest usable frequency obtainable under a given set of conditions, to compensate for frequency effects in other parts of the system, and to reduce noise from records by using the low-pass filter effect.

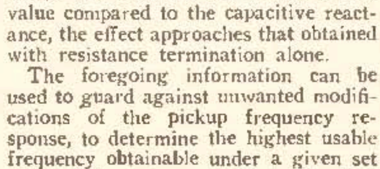

Fig. 16. Connection of equipment to obtain response curves shown. Values observed check with those obtained from frequency records.

REK-O-KUT FIRE

Serious damage by fire was suffered by the Rek-O-Kut Company, manufacturer of precision turntables, Long Island City, N. Y. on the night of January 31. Although production was entirely disrupted for a short time, the plant was back in operation within a matter of days, and is now functioning on a virtually normal schedule.