

On the Noise Performance of a Magnetic Phonograph Pickup

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The thermal noise of a magnetic phonograph pickup has been studied in detail. The analysis has been made using computer-aided design techniques employing a new empirical model of the electrical impedance. Two types of pickups are considered. The frequency spectra and the total rms value of the thermal noise have been studied, and the factors which are taken into account are the value of the load capacitance, the load resistance, the RIAA equalization, and subjective weighting according to the IEC 268-1 standard *A* curve.

The noise performance of the pickup when used in a phonograph amplifier system has also been studied. It was found that with a preamplifier using modern semiconductor devices it is possible that the pickup can contribute as much as twice the noise voltage compared with the semiconductor devices alone. Attention should thus be placed on the noise performance of the pickup when considering the overall noise performance of a phonograph system.

INTRODUCTION: There are many different sources of noise introduced by a pickup into a phonograph amplifier. Some of these are the surface noise of the disc caused by dust, dirt, and irregularities in the groove, electrostatic discharges, electromagnetic stray fields, mechanical vibrations, and speed variations, that is, wow and flutter. There is another type of noise: It is a random noise with a peak in its frequency distribution around 10 kHz and is present even when the pickup is not lowered onto the disc. It is caused by the thermal noise in the pickup and noise sources in the amplifier.

The signal-to-noise ratio (SNR) of a phonograph amplifier system can never be better than that of the pickup. Therefore it is of interest to know more about the detailed noise characteristics of the pickup. This paper discusses the typical thermal noise performance of the magnetic pickup alone and also when used together with a preamplifier.

First an accurate model of the electrical impedance of the pickup is developed. This model is then used in the calculations of the thermal noise of the pickup. The influence on the thermal noise of the load capacitance and of subjective weighting according to the ear's sensitivity is considered. Maximum SNR figures for two types of pickups are also

given. The performance of each pickup together with different types of active devices is then discussed. Finally a preamplifier circuit example is analyzed in detail in order to see how the pickup and different parts of the phonograph system contribute to the total noise.

A more detailed description of amplifier noise performance, the effect of the circuit configuration, and the limitations imposed by transistor noise have been given in [1], [2]. The analysis described here has been greatly simplified by using computer-aided design techniques, details of which have been described elsewhere [3], [4].

IMPEDANCE OF THE MAGNETIC PICKUP

The equivalent circuit shown in Fig. 1 is often used to represent the electrical impedance of a magnetic pickup of the moving magnet and variable reluctance type. (For a detailed description of phonograph pickups see, for exam-

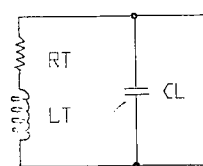


Fig. 1. Equivalent circuit of magnetic pickup.

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ple, [5].) RT is the dc resistance and LT the inductance. The capacitor CL is the load capacitance made up almost entirely of the capacitance of the cable between the pickup cartridge and the amplifier.

The circuit of Fig. 1 is a parallel resonance circuit which has a Q value of 30–50 for parameter values of a typical magnetic pickup. An example of an impedance curve is shown in Fig. 2. However, this curve does not agree with experimental observations. As has been pointed out [6], the inductive component of the pickup is heavily damped. This can be represented in the equivalent circuit by a resistor RLT connected across the inductance (see Fig. 3).

IMPEDANCE MEASUREMENTS

The impedance of two different types of magnetic pickups has been measured with a method similar to [7]. The voltage on the pickup was kept within the normal working range of ≤ 25 mV. By taking great care to avoid stray capacitances and by connecting capacitors with known values across the pickup, it was possible to measure the impedance at values of load capacitances from 4 to 500 pF. The results from the measurements show that RLT can be described by the equation

$$RLT = R \cdot \omega^k \quad (1)$$

where ω is the angular frequency and R and k are constants unique for each pickup type. Table I shows some typical

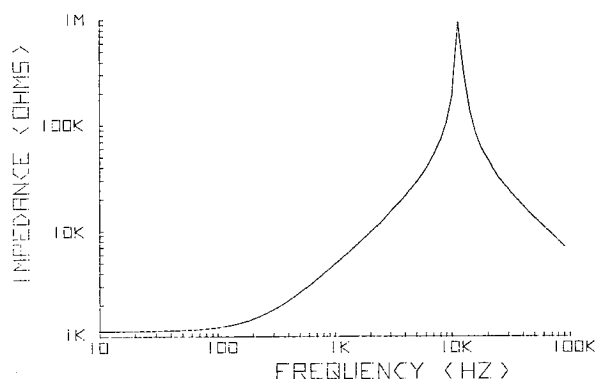


Fig. 2. Impedance curve of circuit of Fig. 1 with parameter values of pickup A.D.C. 27.

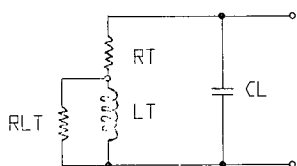


Fig. 3. Improved equivalent circuit of magnetic pickup. RLT represents losses.

values for two pickups. RLT represents the losses in the pickup. The magnetic material and mechanical construction are factors which influence the value of RLT. Fig. 4 shows impedance curves for different values of load capacitance.

Experiments were also made to find out if the electrical impedance could be changed by mechanical forces. The pickup stylus was loaded and removed from the pickup cartridge. No change in the static impedance of the pickup could be detected.

THERMAL NOISE

An accurate model of the impedance Z of a magnetic pickup is the parallel resonant circuit of Fig. 3 with RLT given by Eq. (1). The corresponding parameter values are shown in Table I. The spectral density $S(f)$ (noise power per unity bandwidth) of the thermal noise is

$$S(f) = 4k \cdot T \cdot \text{Re}(Z) \quad (2)$$

where k is Boltzmann's constant, T is the temperature in degrees Kelvin, and $\text{Re}(Z)$ is the real part of the impedance of the pickup.

A convenient way to represent the spectral density is in the form of a plot versus frequency. The plot is obtained by calculating Eq. (2) for the 83 frequencies:

$$f(n) = 1000 \times 10^{(n-42)/10}, \quad n = 1, 2, \dots, 83.$$

These tedious calculations have been considerably eased by using a computer program [4].

A mean value of the noise can be obtained by integrating the spectral density in one-third-octave frequency bands from 8.8 Hz to 114 kHz.

A complement to the spectral density plot is the power spectrum [8] plot obtained by multiplying the spectral density by the value of its frequency for each frequency.

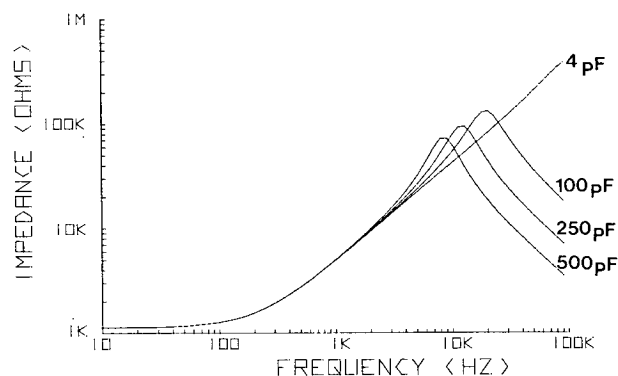


Fig. 4. Measured impedance curve of ADC 27 for different values of load capacitance CL.

Table I. Measured parameters for two pickups.

Pickup	Dc Resistance (k Ω)	Inductance (mH)	R^* Ω/rad	K^*
A.D.C. 27	1.13	750	53.8	0.67
SHURE M75	0.63	720	272	0.51

* For explanation see text.

It often gives a more direct and useful information about the frequency distribution of the noise.

CALCULATION RESULTS

Pickup Loaded with 250 pF

A plot of the spectral density is shown in Fig. 5. There is a dominating peak at about 10 kHz. This corresponds to the peak in the impedance curve, see Fig. 4. At low frequencies the dc resistance of the pickup determines the level of the noise.

Fig. 6 shows the corresponding power spectrum plot. The thermal noise has a very marked peak at about 10 kHz. The total rms value of the noise is $3.72 \pm 0.02 \mu\text{V}$. As seen from Fig. 6, it is generated in the frequency range of 6–30 kHz.

A magnetic pickup is intended to be used together with an amplifier with a certain type of frequency correction, that is, RIAA. If the thermal noise is weighted with an RIAA curve with 0 dB at 1 kHz, the result is shown in Fig. 7. The spectral density has now a completely different look than that of Fig. 5. The low frequencies are amplified up to 100 times by the RIAA curve. However, even now the small peak at about 10 kHz dominates the noise performance of the pickup. This is clearly illustrated by the power spectrum plot in Fig. 8. As seen there are noise contributions from below 10 Hz to 30 kHz with a small peak at 50

Hz and a large one at 10 kHz. The rms value of the total noise voltage is now $0.86 \mu\text{V}$.

The RIAA equalization decreases the rms value of the thermal noise from the pickup about 5 times. It changes the frequency distribution of the noise but the peak at about 10 kHz still dominates.

Pickup Loaded with 47 k Ω and 250 pF

A magnetic pickup is intended to be used together with a resistive load usually 47 k Ω . As seen from Fig. 9, the spectral density shows a wider peak in this case and is decreased in level.

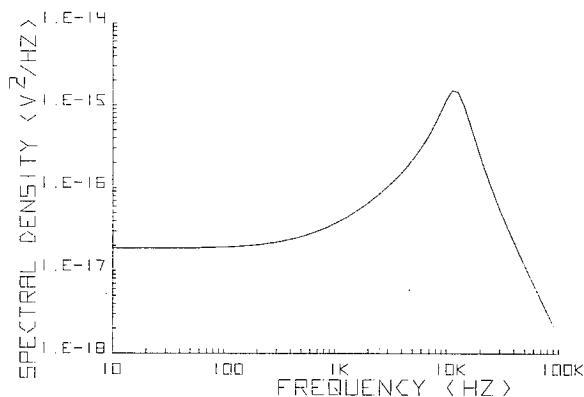


Fig. 5. Spectral density of thermal noise of ADC 27; CL = 250 pF.

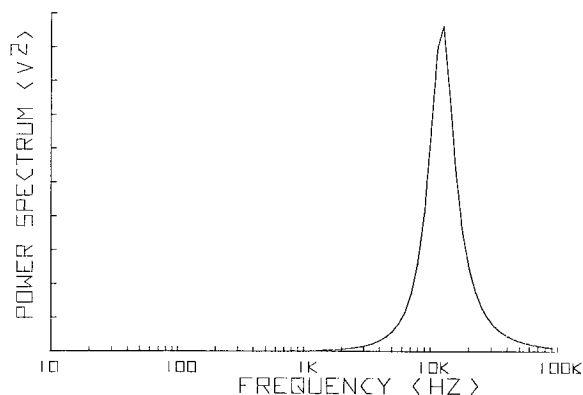


Fig. 6. Power spectrum plot of thermal noise of ADC 27; CL = 250 pF. The power scale is linear but adjusted so that the maximum value always fills the scale. The curve is distorted due to the limited number of plotting points used.

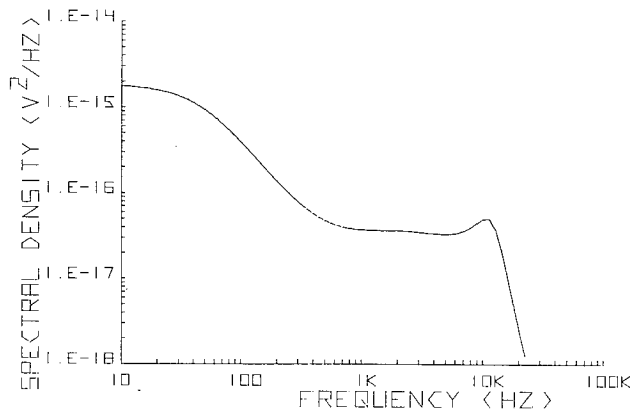


Fig. 7. Spectral density of thermal noise of ADC 27; CL = 250 pF, RIAA weighted.

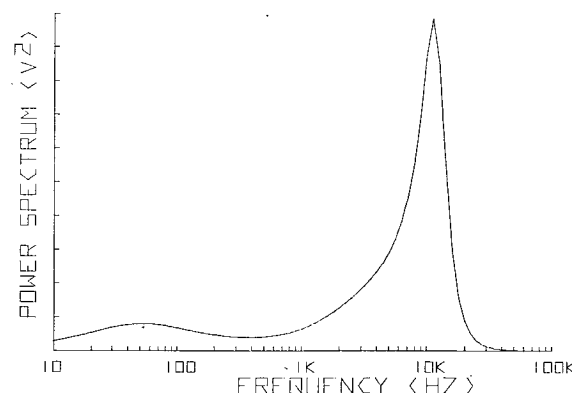


Fig. 8. Power spectrum plot of thermal noise of ADC 27; CL = 250 pF; RIAA weighted.

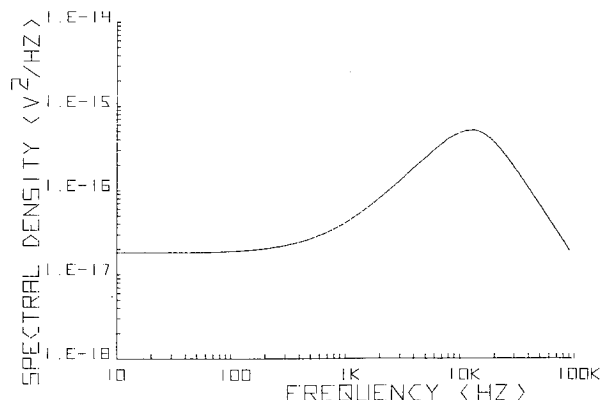


Fig. 9. Spectral density of thermal noise of ADC 27 loaded with 250 pF and 47 k Ω .

Fig. 10 shows the power spectrum plot. The peak is much wider compared to Fig. 6. It is also moved from about 10 kHz to 16–18 kHz. The total rms value is $3.68 \mu\text{V}$, but there is some noise generated over 100 kHz.

The RIAA weighted spectral density is shown in Fig. 11. A comparison between Figs. 11 and 7 shows that there is a difference for frequencies higher than 1 kHz. The corresponding power spectrum is shown in Fig. 12. The peak at 10 kHz still dominates, but the peak at 50 Hz is now more pronounced. Very little noise < 2% is generated above 20 kHz. The total rms value of the thermal noise is $0.77 \mu\text{V}$, which is about 12% less than without the 47-k Ω

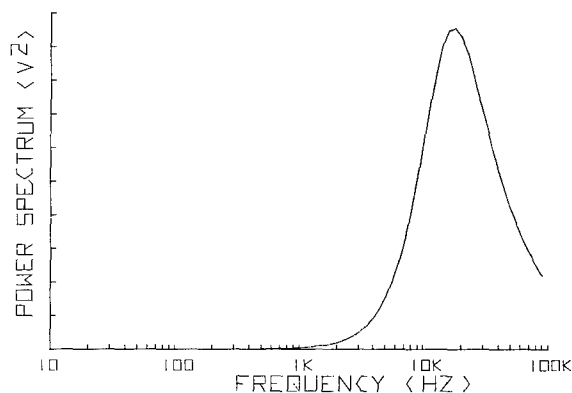


Fig. 10. Power spectrum plot of thermal noise of ADC 27; CL = 250 pF; RL = 47 k Ω .

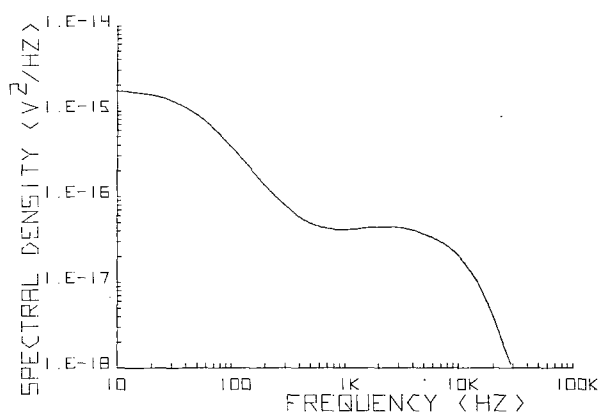


Fig. 11. Spectral density plot of thermal noise of ADC 27; CL = 250 pF; RL = 47 k Ω ; RIAA weighted.

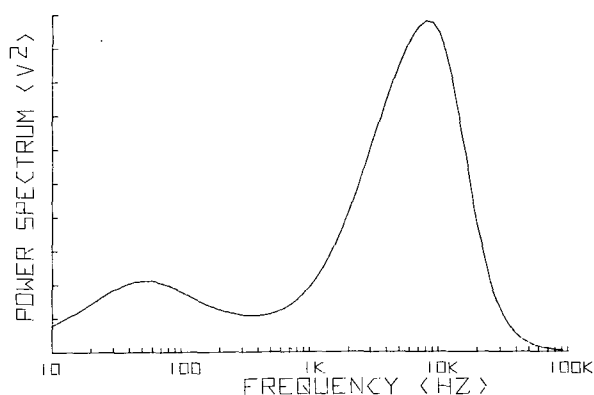


Fig. 12. Power spectrum plot of thermal noise of ADC 27; CL = 250 pF; RL = 47 k Ω ; RIAA weighted.

load resistor. The figure of $0.77 \mu\text{V}$ is of interest because it gives a value for the maximum SNR which can be achieved for a pickup of this type (Audio Dynamics Corporation Model 27). This SNR is 68.2 dB relative to 2 mV/1 kHz.

Subjective Audio Noise Weighting

Audio noise with high-frequency components (1–10 kHz) is often considered to be more annoying than noise with only low-frequency components. To assess the effect of the ear's sensitivity, the thermal noise has been weighted with the *A* curve of IEC standard 268-1 [9]. Fig. 13 shows the spectral density. It is fairly constant from 80 Hz to 5 kHz.

The power spectrum has a peak at about 8 kHz as shown in Fig. 14. In Table II a summary of the results from calculations on two pickups is given. There is only about 1.5 dB difference between the *A*-curve weighted noise and the unweighted noise because most noise is typically generated in the frequency region where the ear is most sensitive.

The SNR figures given in Table II are the best that can be obtained with these pickups with any preamplifier. The 47-k Ω load resistor is included with the pickup because a magnetic pickup is designed to be used together with a load resistance of this value. Even a theoretical ideal amplifier should therefore have a resistive input impedance of 47 k Ω which will contribute to the thermal noise. This is the case

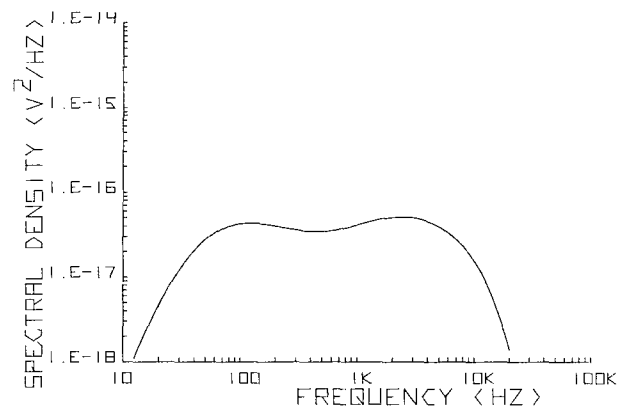


Fig. 13. Spectral density of thermal noise of ADC 27; CL = 250 pF; RL = 47 k Ω ; weighted according to *A* curve of IEC 268-1 and RIAA weighted. Compare with Fig. 11.

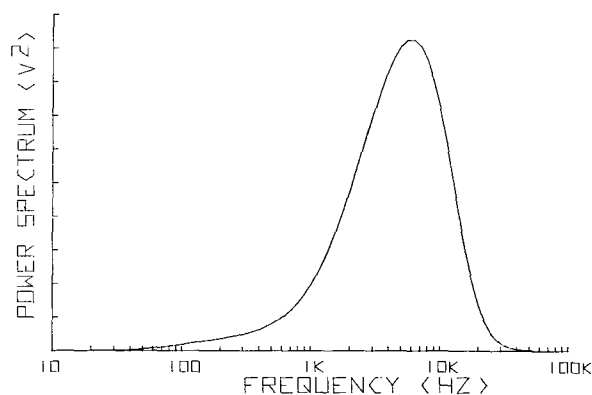


Fig. 14. Power spectrum plot of ADC 27; CL = 250 pF; RL = 47 k Ω ; weighted according to *A* curve of IEC 268-1 and RIAA weighted. Compare with Fig. 12.

whatever internal circuit configuration is used in the amplifier, even if the input resistance is established by a combination of shunt and series feedback.

Capacitance Influence on the Noise Performance

The product $LT \cdot CL$ determines the resonance frequency of the impedance of the pickup. The value of CL can vary within several hundreds of picofarads depending on cable length and input capacitance of the preamplifier. A low value of CL means a large bandwidth which is of advantage for the transient response of the pickup. The influence of CL on the noise performance has been examined for the ADC Model 27 and CL values from 4 to 400 pF, see Fig. 15. The unweighted SNR (bandwidth 10 Hz to 114 kHz) is nearly constant for C values less than 100 pF. However, for values higher than this value, there is a small increase in the SNR figure by 0.3 dB at 400 pF. This is due to the decrease in the impedance level at lower frequencies (see Fig. 4).

The weighted SNR shows an inverse response versus frequency compared to that of the unweighted, and is more dependent on CL . At low values of CL the peak in the frequency spectra lies at frequencies higher than the audible range. With higher CL values the noise frequency spectrum falls in the audible range, and therefore there is a decrease in the SNR figure. A change of CL from 400 to 100 pF will increase the weighted SNR by 0.4 dB.

SNR OF MAGNETIC PICKUP TOGETHER WITH PREAMPLIFIER

The noise sources in an amplifier may be represented by the e_n, i_n parameter model [1]. If the correlation between e_n and i_n is neglected, three noise sources can be identified, (1) thermal noise of the pickup and the 47-k Ω input impedance of the amplifier, (2) noise due to the e_n noise generator, and (3) noise which is caused by i_n with a magnitude determined by the product of i_n and the parallel combination of the impedance of the pickup and the amplifier input impedance.

Fig. 16 shows some examples of e_n and i_n of semiconductors of the type which can be used in a phonograph preamplifier. They are the bipolar transistor 2N 4104, the field effect transistor 2N 4869, and the monolithic operational amplifiers LM 1303, μA 739 and μA 741.

The designer can vary considerably (10 to 100 times) the magnitude of the e_n and i_n of a bipolar transistor. This is done by selecting the value of the bias current. As an example of this the e_n and i_n for the emitter currents of 10 and 100 μA are shown for 2N 4104.

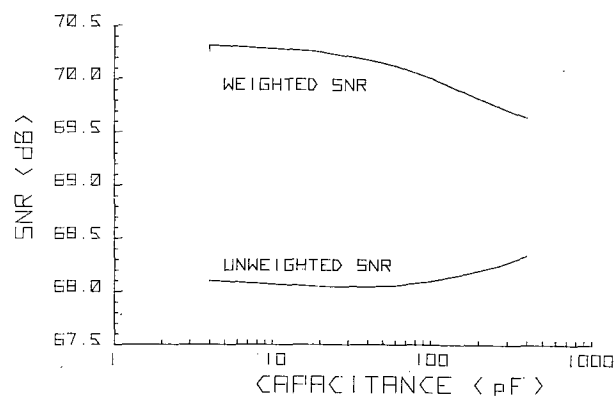
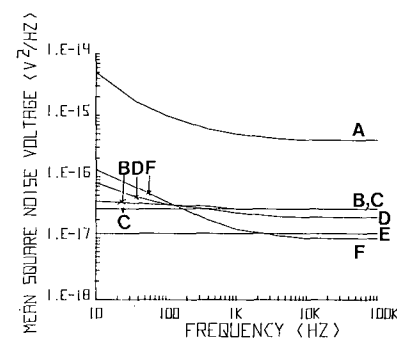
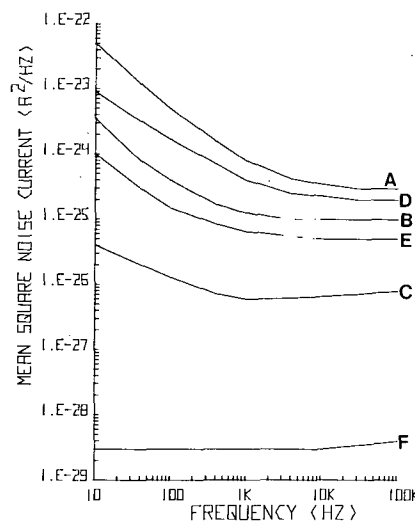


Fig. 15. Influence of load capacitance CL on SNR.



a.



b.

Fig. 16. Example of equivalent noise generators of some semiconductors. A— μA 741; B—LM 1303; C—2N 4104—10 μA ; D— μA 739; E—2N 4104—100 μA ; F—2N 4869. a. Voltage generator e_n . b. Current generator i_n .

Table II. Typical noise performance of two magnetic pickups. Load resistance 47 Ω , load capacitance 250 pF.

Pickup	Unweighted (μV)	NOISE VOLTAGE RIAA Weighted		RIAA and IEC Weighted	
		(μV)	SNR* (dB)	(μV)	SNR* (dB)
A.D.C. 27	3.68	0.774	68.24	0.650	69.76
SHURE M75	3.67	0.709	69.00	0.612	70.28

* Signal-to-noise ratio relative to a signal of 2 mV/1 kHz.

Table III is a summary of the results from an analysis of the noise performance of an idealized amplifier with noise characteristics such as the above-mentioned active devices. It can be concluded from Table III that a device with a low e_n value ($< 2 \times 10^{-17} \text{ V}^2/\text{Hz}$ at 10 kHz) gives the best SNR. This is illustrated both by the 2N 4104 ($-100 \mu\text{A}$) and the 2N 4869. The difference in SNR between the two pickups is about 0.5 dB unweighted and 0.4 dB weighted.

In the above idealized amplifier no considerations were given to the chosen circuit configuration or the passive circuit components. Fig. 17 shows a simplified circuit diagram of a common magnetic pickup phono playback amplifier, RIAA equalized [10]. The circuit has been analyzed to find each single contribution to the total output noise voltage from the different sources such as pickup, passive components, and semiconductors. Of the total output noise voltage, which is $109 \mu\text{V}$ (SNR = 65.28 dB relative to 2 mV/1 kHz),

(1) the pickup together with the 47-k Ω load resistor contributes $78.7 \mu\text{V}$.

(2) the passive circuit components ZF and 1-k Ω resistor contributes $40.7 \mu\text{V}$, and

(3) the monolithic operational amplifier LM 1303 contributes $63.3 \mu\text{V}$.

The pickup is the largest single noise source.

The figures of the passive circuit elements and the LM 1303 could be improved. If the impedance of the circuit elements is decreased 10 times, the thermal noise voltage of them will be decreased by $\sqrt{10}$. To be able to do this, a power stage should be added to the LM 1303. Care should be taken so that it is the thermal noise which is the dominating noise source in the passive components, that is high-quality and low-noise components should be used. If a discrete input stage is added to the LM 1303, for example, a pair of 2N 4104 at a bias current of $100 \mu\text{A}$, the

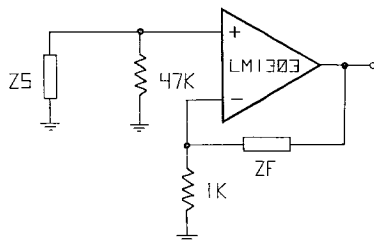


Fig. 17. Simplified circuit diagram of preamplifier for magnetic pickup. ZS represents impedance of pickup and ZF impedance of RIAA feedback network.

monolithic amplifier contribution could be decreased considerably. A summary of some possible improvements is given below:

- (1) pickup and 47 k Ω 78.7 μV (same as above)
- (2) passive circuit 12.9 μV
components
- (3) semiconductors 38.0 μV

Total output noise voltage is $88.3 \mu\text{V}$ (SNR = 67.10 dB relative to 2 mV/1 kHz).

The contribution of the pickup to the total output noise voltage is now more than twice that of the semiconductors.

SUMMARY

By introducing a frequency-dependent loss resistance, the impedance model of the magnetic pickup has been much improved. The actual value of the loss resistance and its frequency dependence has been determined experimentally for two different pickups.

Based on the accurate impedance model, the thermal noise of the pickup has been analyzed. The thermal noise of the magnetic pickup with no resistance load has a very sharp peak in its frequency spectra. The RIAA equalization decreases the rms value of the thermal noise of the pickup about 5 times, but even if the frequency distribution is changed, the peak at about 10 kHz still dominates. The load resistor, usually 47 k Ω , widens this peak. When RIAA weighted, the rms value of the noise is about 12% less than without a load resistor.

If the effect of the ear's sensitivity is considered, about 1.5 dB SNR improvement can be obtained. This relatively small SNR improvement is due to the fact that most thermal noise of a magnetic pickup is generated in the frequency range where the ear is most sensitive.

The theoretical SNR relative to 2 mV/1 kHz of the two magnetic pickups is 68.24 and 69.00 dB when measured and 69.70 and 70.28 dB when weighted according to the IEC 268-1 A curve (load capacitance 250 pF and load resistance 47 k Ω).

It was also found that the value of the load capacitance should be as low as possible. About 0.5-dBA improvement can be obtained if the load capacitance is decreased from 500 to 100 pF.

When considering the magnetic pickup together with an active device, it was found that the device with optimum noise performance with a magnetic pickup should have a low value of equivalent input noise voltage (less than $2 \times 10^{-17} \text{ V}^2/\text{Hz}$). The noise contribution from the mag-

Table III. Noise performance of an idealized amplifier with noise characteristics equal to that of the device indicated and each of two magnetic pickups. Load resistance 47 k Ω , load capacitance 250 pF.

Device	RIAA Weighted SNR* (dB)		RIAA and IEC Weighted SNR* (dB)	
	A.D.C. 27	SHURE M75	A.D.C. 27	SHURE M75
2N 4104 - 100 μA	67.34	67.95	69.19	69.64
2N 4104 - 10 μA	66.49	66.98	68.75	69.14
LM 1303	66.08	66.58	68.49	68.89
2N 4869	65.91	66.31	69.19	69.63
μA 739	65.66	66.08	68.29	68.70
μA 741	54.68	54.73	61.98	62.08

* Signal-to-noise ratio relative to a signal of 2mV/1 kHz.

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netic pickup will dominate in an actual amplifier circuit. Using modern semiconductor devices, it can be as much as twice the noise from the semiconductor.

Attention should thus be placed on the noise performance of the magnetic pickup when considering the overall noise performance of the phonograph system.

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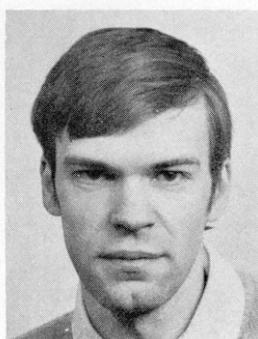
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