Figure 19 shows a test circuit used to determine induced grid noise. The thermal noise frequency response is modified by the interelectrode capacitances. C_{gp} is the "cold" plate-grid capacitance, and C_{gc} is the "cold" grid-cathode capacitance. If C_{gc} were infinite (shunted by a large external capacitor) the only noise would be shot noise (and $1/f$ noise) and the tube would have full amplification. If C_{gc} is not large compared with C_{gp} feedback will result from plate to grid. The amount of feedback is $1-\beta A$, where

$$\beta=\frac{(1/j\omega C_{gc})}{(1/j\omega C_{gc})+(1/j\omega C_{gp})}=\frac{C_{gp}}{C_{gp}+C_{gc}}.$$

Since the input impedance is capacitive, $C_{gc}+(1+A)C_{gp}$, it is possible to measure the equivalent noise resistance of the induced grid noise by measuring the noise frequency response.

An RCA Nuvistor 7586 was connected as shown in Fig. 19. Plate voltage was 30 V and the grid could be switched between a 25 Megohm resistor to ground, ground directly and open circuit. The cathode potential was monitored to ensure constant dc operating conditions in all three cases.

Figure 19 shows the noise frequency response with open grid, with a 25 Megohm source resistor and with the grid shorted to ground. The open grid and 25 Megohm curves exhibit 6 db/oct slopes with a 12 db level difference. Using the formulas derived in Section 2 of the Thermal Noise section, we find that there is a 24 db difference (16 times) in noise resistance; in other words, the equivalent noise resistance, R_{eq} due to induced grid noise is approximately 16×25 Megohm $=400$ Megohm. It is also interesting to note that due to the shorting out of the negative feedback from the tube capacitance, the noise at 20 kc *increased* 11 db when the floating grid was shorted to ground.

Barkhausen Noise

Magnetic materials with crystalline structure, whether iron, nickel, cobalt or others, consist of small units called "domains." Each domain is a small magnet, magnetized to saturation in one direction. The domains are separated by walls which provide the shift in direction of magnetization. If the material is "unmagnetized," the sizes of the differently oriented domains are distributed evenly and form closed magnetic flux paths inside the material. If an external field is applied, the following will happen, according to D. A. Bell:[16] *1.* The domains oriented approximately parallel to the outside magnetizing field will grow in size, moving the walls outwards at the expense of the domains oriented in other directions. *2.* This growth is fast and reversible until it meets a discontinuity, an impurity in the material or an irregularity in the crystalline structure. The wall movement will stop at this place until enough energy is present to overcome the disturbance. The resulting sudden jump in magnetization when the disturbance is overcome, damped only by eddy currents in the material, constitutes the Barkhausen noise. Once a Barkhausen jump has occurred the situation is irreversible for small signal levels at this particular place in the crystal. This hysteresis effect is negligible at very low signal levels where there is complete reversibility. *3.* All the domains are now oriented in the same direction, but not quite in the direction of the applied field, because they are held back by the crystalline structure (anisotropy). The last domain movement possible is that of bringing their orientation in exact accordance with the applied field. No further Barkhausen jumps are possible, and the process is reversible and noise-free.

Example 10. What is the order of magnitude of induction in a tape reproducing head?

A full track ¼-in. tape recorded to saturation may supply a flux of 600-800 milliMaxwell. With a head efficiency of 75%, about 500 mMx will go through the major volume of the laminations. If the cross-sectional area of the pole pieces is 0.2 cm^2, the induction is 0.5 Maxwells/0.2 cm^2 $=$ 2.5 Gauss. Small local volumes near the pole tips will have a higher flux line concentration, but the major volume, exhibiting the major number of possible Barkhausen jumps, will have a flux concentration of approximately 2.5 Gauss. The saturation induction of a good head material is 6000 to 7000 Gauss, depending upon lamination thickness. Since even the induction from a saturated tape is very small compared to this head material saturation induction, the Barkhausen noise is very low, even at tape saturation. At tape noise levels it will be practically nonexistent.

NOISE IN A REPRODUCING SYSTEM

The different noise sources mentioned in the previous sections were considered in the design of the head and preamplifier of the Ampex MR-70 master recorder. Nuvistors were preferred over transistors because of their inherently high input impedance and low equivalent input noise resistance, and also because of their high reliability and low $1/f$ noise. The MR-70 plays ¼-in., ½-in. and 1-in. tapes, and a multitude of head combinations can be used. The heads are all low-impedance, approximately 17 mH, and a step-up transformer is used in the amplifier. The eddy current losses and copper losses in the head depend

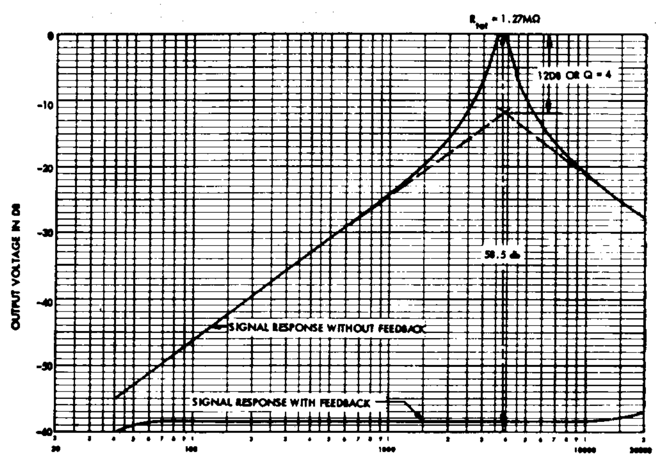

Fig. 20. Signal output voltage *vs* frequency with and without negative feedback for the MR-70 playback head.

upon the number and type of laminations, the number of turns on the head and the winding space.

The following data for a ¼-in. full track head will give a quantitative picture of the noise contributions in the MR-70 playback system:

Head: $L = 17$ mH, dc resistance $r = 1$ ohm, equivalent parallel resistance $R = 1500$ ohm when resonated at 3.7 kc with a low loss capacitor.

Transformer: $L_{sec} = 80$ H, $r_{prl} = 0.75$ ohm, $r_{sec} = 850$ ohm $R_{sec} = 22$ Megohm at 2 kc; turns ratio 1:30.

The total dc resistance r_{tot} of the head and transformer combination, referred to the secondary, is then $30^2 \times (1 + 0.75) + 850 = 2425$ ohm. The total parallel resistance R_{tot} of the head and transformer combination, referred to the secondary, is $30^2 \times 1500 = 1.35$ Megohm in parallel with 22 Megohm $= 1.27$ Megohm.

The difference in noise voltage between r_{tot} and R_{tot} should therefore be $\sqrt{[(1.27 \times 10^6)/2425]} = 22.9$ or 27 db, which is confirmed by measurement (see Fig. 21). The total inductance of the head and transformer combination referred to the secondary is: $30^2 \times 17\text{ mH} = 15.3$ H in parallel with $80\text{ H} = 12.9$ H. The Q at head resonance is

$$R_{tot}/\omega_0 L = (1.27 \times 10^6)/(2\pi \times 3700 \times 12.9) = 4.2,$$

which is confirmed in Fig. 20. The equivalent input noise resistance R_{eq} is 800 to 1000 ohm as shown by the dotted line in Fig. 21, which falls below the head noise curve. The measured signal curve (Fig. 20) and noise curve (Fig. 21)

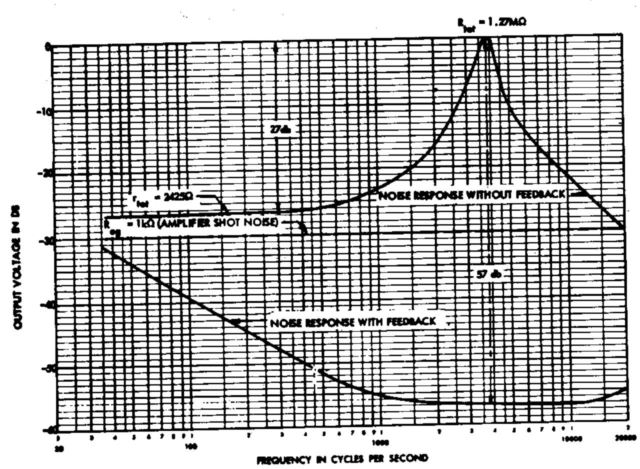

FIG. 21. Noise output voltage *vs* frequency with and without negative feedback for the MR-70 playback head.

are seen to be similar in shape except at low frequencies; this results in a constant signal-to-noise ratio at mid- and high-frequencies but a reduced one at low-frequencies. The low-frequency deterioration is due to the dc resistance r_{tot} or the equivalent input noise resistance R_{eq}, whichever is larger. Figure 21 shows the dc resistance r_{tot} to be the largest in the case of the MR-70, so that the amplifier noise is masked by thermal head noise from dc to 20 kc (assuming amplifier $1/f$ noise never rears its ugly head).

The curves in Fig. 20 are measured with constant flux in the head. This is not a practical condition because, at economical tape speeds (e.g., 7½ and 15 ips), the tape flux is constant at low- and mid-frequencies only, and decreases at high frequencies. This flux loss at low speeds is compensated for by increasing the high frequency amplification in the recording as well as the reproducing amplifiers, thereby introducing a deterioration of both the signal handling capabilities and the noise level. A high tape speed (30 ips) is available in the MR-70 to minimize this deterioration.

When the flux in the head is constant, its time derivative ($d\emptyset/dt$) will rise 6 db/ oct with frequency (see Fig. 22).

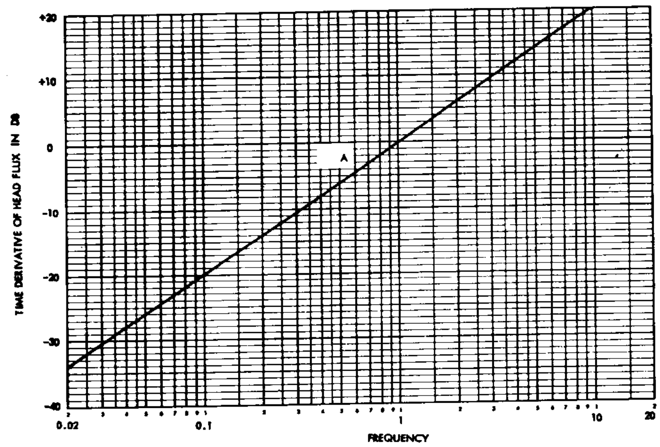

FIG. 22. Time derivative ($d\emptyset/dt$) of the (constant) head flux *vs* frequency.

The head circuit shown in Fig. 6, which actually constitutes a low-pass filter (its response is shown in Fig. 23), will modify this 6 db/oct curve. Figure 24 shows the resulting voltage output from the head with the parallel resistance R as parameter.

With low values of R it is possible to obtain a flat output voltage frequency response in a desired bandwidth for con-

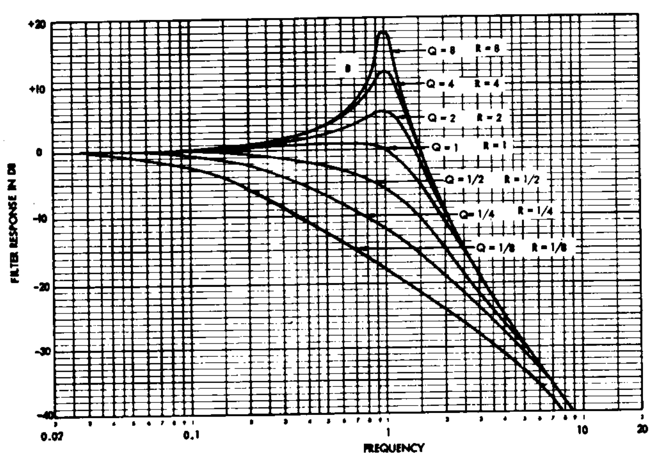

FIG. 23. Filter response of the electrical head circuit shown in Fig. 6 with R as parameter.

stant flux in the head. A low value of R, however, will drastically reduce the signal-to-noise ratio, as described above in the Thermal Noise Section and displayed in Fig. 12. By using negative feedback, however, a "noise free" resistance can be generated to provide the necessary damping without adding significantly to the noise.

A three-stage amplifier is used in the MR-70 (grounded cathode, grounded plate, grounded grid) with low phase shift. Total amplification is 62 db. A 2.7 Megohm feedback resistor is connected from the plate of the last stage directly to the effective head (secondary of input transformer), resulting in 58.5 db damping at the head resonance frequency. Because the head resonance curve has long 6 db/oct slopes with constant phase shift and the amplifier has wideband response, there is no danger of instability.

Negative feedback is also used in the disc recording field

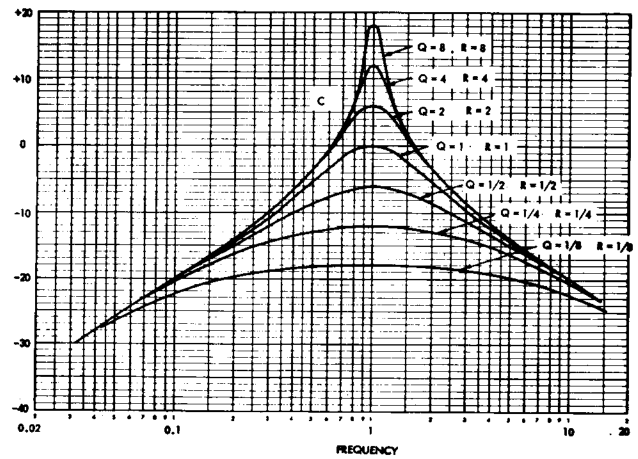

FIG. 24. Resulting head output voltage, with R as parameter, for the head circuit shown in Fig. 6.

where moving coil cutting heads, mechanically resonating near the middle of the audio frequency band, are equalized to a flat velocity frequency response.

Because of the resulting flat voltage frequency response from the head, there is no danger of excessive CCIF intermodulation distortion[17] which results if a passive equalization follows a source of distortion (tube or transistor).

Since the feedback is applied directly to the head, the feedback resistor will load the head slightly and add thermal noise. With a 2.7 Megohm feedback resistor and a head resonant impedance of 1.27 Megohm, the resulting impedance is 860 kilohm. This will reduce the signal by 3 db and the noise by 1.5 db, and result in a net reduction of the signal-to-noise ratio of 1.5 db.

Figures 20 and 21 confirm this. If a regular resistor had been used to achieve the 58.5 db damping, the signal-to-noise would have been reduced by $58.5/2 = 29.3$ db!

ACKNOWLEDGMENT

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APPENDIX

Noise-Producing Real Part of Head Impedance *vs* Frequency

The impedance of the circuit in Fig. 6 is given by

$$Z = \frac{\{[j\omega L(1/j\omega C)]/[j\omega L + (1/j\omega C)]\}R}{\{[j\omega L(1/j\omega C)]/[j\omega L + (1/j\omega C)]\} + R}$$

$$= \frac{j\omega LR}{j\omega L + R[1-(\omega/\omega_0)^2]}$$

$$= \frac{j\omega LR\{R[1-(\omega/\omega_0)^2] - j\omega L\}}{R^2[1-(\omega/\omega_0)^2]^2 + \omega^2 L^2}$$

where $\omega_0{}^2 = 1/LC$.

The real part of Z is:

$$a = \omega^2 L^2 R / \{R^2[1-(\omega/\omega_0)^2]^2 + \omega^2 L^2\}.$$

At resonance ($\omega = \omega_0$): $a = R$.

Above resonance ($\omega >> \omega_0$):

$$a = \frac{\omega^2 L^2 R}{R^2(\omega/\omega_0)^4 + \omega^2 L^2} \sim \frac{L^2 R}{(\omega^2 R^2/\omega_0{}^4) + L^2} \sim \frac{L^2 \omega_0{}^4}{R\omega^2}$$

for $\omega^2 R^2/\omega_0{}^4 >> L^2$,

which represents a 12 db/oct decreasing slope.

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2. When the noise power is divided by the bandwidth, the result is approximately equal to the "spectral noise density." Spectral noise density is defined as the noise per cps of bandwidth, as measured in an infinitesimally small bandwidth ΔB; that is, *spectral noise density* = (*noise within* ΔB)/ΔB. The term "spectral noise density" is not used here for two reasons: *1.* Most of the data was taken in 6 cps wide bands, and not reduced to the "per cps" form; and 2, the term "noise frequency response" seems more descriptive for the purposes of this paper.

3. F. E. Terman and T. M. Pettit, *Electronic Measurements*, (McGraw-Hill Book Co., Inc., New York, 1952), Second Edition, Sec. 812, pp. 354-355.

4. This excludes parametric amplifiers and magnetic amplifiers, for instance.

5. E. G. Nielsen, "Behavior of Noise Figure in Junction Transistors," *Proc. IRE*, 957 (1957).

6. D. A. Bell, *Electrical Noise*, (D. Van Nostrand Co., Inc., New York, 1960), Chapter 11, p. 247.

7. *Ibid*., Chapter 5, pp. 96, 130.

8. *Ibid*., Chapter 8, p. 151.

9. *Ibid*., Chapter 10, p. 210.

10. *Ibid*., Chapter 10, p. 212.

11. *Ibid*., Chapter 8, pp. 163-164.

12. *Ibid*., Chapter 8, p. 151.

13. L. Blaser, "The Design of Low Noise, High Input Impedance Amplifiers," *The Solid State Journal*, 21 (July, 1961).

14. A. Stansbury, "Measuring Resistor Current Noise," *Electronic Equipment Engineering*, 17 (June, 1961).

15. C. J. Bakker, "Fluctuations and Electron Inertia," *Physica* **8**, 23 (1941).

16. D. A. Bell, *op. cit*., Chapter 13, p. 279.

17. If two high frequency tones, for example 5000 cps and 5050 cps, of similar amplitude are played back simultaneously through an amplifier stage, a 50 cps difference tone will be produced. If the difference tone amounts to, say 0.2% of the 5000 cps tone, it will then be boosted approximately 30 db by the (50 μsec) passive playback equalization to $31.6 \times 0.2 \sim 6\%$, which is a considerable increase in distortion. Program material of dominant percussive content will tend to sound muddy under these conditions because of the boosted low-frequency distortion products.

The values $R = 130$ kilohm, $f_0 = 50$ kc, $f = 200$ kc and $L = 0.5$ H from Fig. 13 yield

$$\omega^2 R^2/\omega_0^4 \sim 2.7 >> L^2 = 0.25.$$

Below resonance ($\omega << \omega_0$):

$$a = \frac{\omega^2 L^2 R}{R^2 + \omega^2 L^2} \sim \frac{1}{(R/\omega^2 L^2) + (1/R)} \sim \frac{\omega^2 L^2}{R}$$

for

$$R/\omega^2 L^2 >> 1/R,$$

which represents a 12 db/oct increasing slope.

The values $R = 130$ kilohm, $f = 10$ kc and $L = 0.5$ H from Fig. 13 yield:

$$R/\omega^2 L^2 = 1.3 \times 10^{-4} >> 1/R = 7.7 \times 10^{-6}.$$

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Erling P. Skov was graduated from the Technical University of Denmark in 1951, receiving his M.S. degree in electrical engineering. From 1951-1956 he was a research and development engineer at Linnet and Laursen, Inc., in Copenhagen. In 1956 he joined the engineering staff of Fairchild Recording Equipment Corporation in New York, where he worked on stereo disk cutting systems, stereo playback cartridges, turntables and associated amplifiers and filters. He became engineer-in-charge of professional products engineering at Fairchild in July 1960, but joined Ampex Corporation in December of the same year. He designed the Ampex FM Multiplex adapter and has mostly worked on the design of low noise tape playback systems and the problems in recording on magnetic sheets. He became staff engineer in 1964 and is currently serving as project engineer on the Ampex spot announcer.

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