Excess Spacing Loss with Alfenol-Core and Ferrite-Core Magnetic Tape Reproducing Heads*

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The head core material Alfenol (also called Vacodur) is long wearing, but produces an excess spacing loss, apparently due to a nonmagnetic surface layer of about 0.4 μm that cannot be removed. Ferrite cores sometimes have gap erosion that also causes excess spacing. Because of this, heads with these core materials are not suitable for fundamental measurements. For ordinary sound recording purposes the excess spacing loss is easily compensated when the reproducer response is adjusted by playing a calibration tape.

0 INTRODUCTION

One of the most variable response errors in magnetic reproduction is the reproducing spacing loss, produced when there is a space between the recorded tape and the surface of the reproducing head. Even when the tape seems to be in intimate physical contact with the reproducing head, there may be a space due to the roughness of the head face; due to an air film drawn between the tape and the head face, especially at higher tape speeds; or due to a nonmagnetic "dead layer" on the surface of the head face. It is possible to determine the difference between the spacing loss with one head and that with another head, but it is not possible to determine the *absolute* value of the spacing loss.

The classic material for magnetic recording and reproducing head cores is 4-79 molybdenum permalloy [1]. It is the standard to which all "improved" core materials are compared. For direct recording of audio-frequency analog signals, its major disadvantage is its high wear rate. A number of "wear-resistant" materials have been developed; Appendix 1 gives some comments and references on wear and core materials.

Years of experience with cores of 4-79 molybdenum permalloy have shown that they exhibit a uniform miminum spacing loss when they are properly polished. Some reproducing heads exhibit a greater spacing loss than this minimum, and we will refer to this as excess spacing loss. We will not further consider the possible air film between the tape and the head.

We have found excess spacing loss with two popular long-wearing core materials, namely, ferrites and Alfenol. The problems with ferrite have been reported before, but are sometimes forgotten. The problem with Alfenol has not been reported previously.

Ferrite heads have been used on magnetic tape recorders made by Philips and others. There are two problems with ferrites. First, some ferrites have a "dead layer" on their surface that causes an excess spacing loss. This has been reported by Wada [2] and others. Second—worse from a practical maintenance viewpoint—is that although ferrite cores wear very slowly, some of the ferrites chip and erode in the gap region, causing increased gap length and an effective space between the head and the tape, even though there has been very little wear in the sense of the total amount of material removed from the head face. This problem has been reported by Manquen and Martinson [3], and we commend you to that paper. We also observe with full-track ferrite recording heads that the area of the head face that is under the tape edge can be noticeably worn out and unusable, while the area in the center of the tape is relatively unworn.

Alfenol [4] (also called Vacodur [5]) has been a popular long-wearing core material used for heads on some of the magnetic tape recorders and reproducers man-

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ufactured by Telefunken [6],[1] Studer,[2] and others. We have found that Alfenol has a dead (nonmagnetic) surface layer about 0.4 μm thick that produces a reproducing excess spacing loss at high-frequencies, as shown in Fig. 1. At 20 kHz the loss amounts to 5 dB at a tape speed of 95 mm/s (3.75 in/s), 2.4 dB at 190 mm/s (7.5 in/s), 1.2 dB at 380 mm/s (15 in/s), and 0.6 dB at 760 mm/s (30 in/s). We are unable to remove this layer by the simple kinds of polishing techniques that we have available.

For studio applications at the higher speeds the increased wear life of ferrite and Alfenol is very advantageous, and the small high-frequency loss can be approximately compensated by playing a reproducer calibration tape and adjusting the reproducer's high-frequency equalizer controls for flattest output versus frequency. But ferrite cores and Alfenol cores should not be used in applications that require an accurate fundamental measurement of the wavelength response of the system.

Thus ferrite heads and Alfenol heads are not suitable for calibrating the response of reproducer calibration tapes (also called test tapes, alignment tapes, or standard tapes). This calibration is mainly done by the manufacturers of reproducer calibration tapes, but it is also done sometimes by studio maintenance engineers. They check their equipment and calibration tapes against each other by using a flux-inducing loop to set the reproducer equalization approximately (see Appendix 2) to the standard frequency response [7], then play the calibration tape. If the output of this system is not flat, then something is out of calibration. That something can be excess spacing loss due to a ferrite head or an Alfenol head.

Let me also remind you of the obvious: If a reproducer that is not correctly calibrated is used to calibrate a recorder, then the recordings made subsequently will have a response that is the *inverse* of the *reproducer's* error. You will find some calibration tapes that have a high-frequency boost. It may mean that the manufacturer's reproducer used an Alfenol head or a worn ferrite head, and that the excess spacing loss was not taken into account when the calibration tape was recorded.

1 CALIBRATION TECHNIQUES

In order to make reproducer calibration tapes we must be able to take accurate measurements of the tape flux emanating from recorded tapes. The measurements of tape flux are made by using a reproducing system which is calibrated from first principles, using our knowledge of the theory of magnetic tape recording and reproducing. The various factors that cause a head to deviate from an "ideal" response, and the measurement methods for each, are given in [7, sec. 2.2.3.3 and table 2]. Looking at that table, you will see that there is a measurement method for all of the responses but one—there is no known way to measure the absolute spacing loss. You can measure only the *difference* in spacing loss between two different systems or conditions.

We have calibrated many different reproducing heads of different designs, and usually we find that after we have compensated for the measured frequency response and wavelength response (except for the unknown spacing loss), the heads perform very nearly identically. But occasionally there are discrepancies. Then we look at the shape of the *difference* between the response curves of the two heads.

Frequently that difference has the shape of a reproducing excess spacing loss curve, that is, it is a long gradual slope, with the loss doubling with each octave, as shown in Fig. 1. For example, if there is a spacing loss of 4 dB at 16 kHz, it will be 2 dB at 8 kHz, 1 dB at 4 kHz, 0.5 dB at 2 kHz, 0.25 dB at 1 kHz, and so on. In this case we suspect that we have found the "unknown" spacing loss.

We then repeat all of the measurements to be sure we did not make an error in the calibration. If we find no error, we conclude that the difference must be excess spacing.

2 REPRODUCING SPACING LOSS THEORY

The reproducing spacing loss was first measured experimentally and also computed theoretically by Wallace [8]. The formula for the reproducing spacing loss response is

$$\Phi_s/\Phi_0 = e^{-2\pi s/\lambda}$$

where Φ_s is the flux at wavelength λ when the spacing between head and tape is s; Φ_0 is the flux at wavelength λ when the spacing s is zero; and λ is the wavelength ($\lambda = v/f$, v being the tape velocity and f the frequency). All distances and times are in consistent units, such as spacing and wavelength in meters, tape velocity in me-

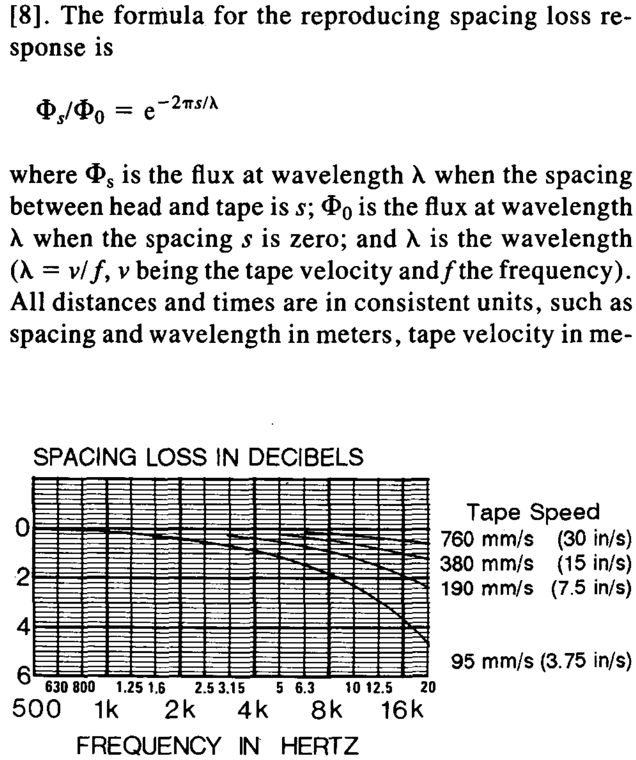

Fig. 1. Calculated reproducing spacing loss produced by 0.4-μm spacing for four different speeds.

[1] Thiemer describes the design and performance of a line of long-life (LL) Telefunken recording and reproducing heads using Vacodur 16 as the core material. These heads have been used on Telefunken recorders and reproducers.

[2] Vacodur heads have been used on the Studer A-80. They are identified as product numbers 1 217 XXX, where XXX represents the particular function (recording or reproducing, tape width, number of tracks, impedance, gap length, etc.).

ters per second, and frequency in hertz.

We can convert this flux ratio to the spacing loss in decibels by using the relationship[3] that spacing loss = $-20 \log(\Phi_s/\Phi_0)$. When we do so, we get the very simple formula

$$\text{spacing loss} = 55s/\lambda \quad [\text{dB}] .$$

The shape of this curve is shown in Fig. 1. We see that the spacing loss doubles with each octave increase in frequency.

Westmijze [9] and Wallace both demonstrated that when you *add* spacers, the loss increases by the theoretical amount. Unfortunately it is not possible to extrapolate back to "zero spacing" because the formula itself is for the ratio of the flux at spacing s to the flux with no spacing. But we have no way to determine the value of the flux with no spacing. Thus Wallace observes that "The problem of determining the magnitude of the loss or in other words the amount of the effective spacing in a practical case is, however, a difficult one. So far, no direct experimental method for its determination has been found."

What you can do is to make a measurement with one spacing, then another measurement with another spacing. Then the level difference at a known wavelength gives the difference in spacings.

Daniel and Axon [10] also studied the problem of calibrating reproducers, and their conclusions are as true today as they were when they published them 40 years ago, in 1953: "As very short wavelengths are approached any effective separation of the head from the recorded medium becomes very important, and great care must be taken in the selection and finishing of heads used for standardization. *No test, other than that of inconsistency, can be established for imperfect contact*, and it can be stated in this connection only that the head finish must be of good quality and the standardization tape must possess a smooth surface, free from large particle projections." (Emphasis added.)

When we suspect a small excess spacing loss, we polish the heads by "playing" a couple of rolls of ordinary blank recording tape. When we suspect a large excess spacing loss, we lap the head face with a fine grade (1-μm grade, then 0.3-μm grade) of 3M imperial aluminum oxide lapping film. These procedures will usually eliminate the excess spacing loss.

3 CORE MATERIALS

The classic material for magnetic recording and reproducing head cores is 4-79 molybdenum permalloy. We have used many different heads made with cores of this material, as fabricated into heads by Studer,[4] Ampex, and Nortronics.

We test both the theory of calibration and for excess spacing loss by the following means. We first compensate each head for its eddy-current loss [7] and gap loss [11], and we make sure that the head face is properly polished and the head is adjusted mechanically for best tape contact. Then, using these different calibrated heads, we measure the flux from the *same recording* over a range of wavelengths and frequencies. We get very consistent results with these different heads—on the order of ±0.4 dB over a range of 1–20 kHz at 190 mm/s (7.5 in/s), which is a wavelength range of 9.5–190 μm. Thus we believe that the theory of calibration is correct, and that, whatever the spacing loss, it is very consistent.

Several materials have been developed which claim to have especially low wear rates. Appendix 1 references some of these. A relatively new (1976) material is wear-resistant HyMu 800, manufactured by Carpenter Steel (Reading, PA, USA). It was developed by Carpenter in conjunction with Nortronics [12], who uses this material in its Duracore heads. Some Studer heads[5] are made from cores of the wear-resistant HyMu 800. When we calibrated these heads as described and compared the responses of these heads to that of the 4-79 molybdenum permalloy heads, we found them to fall within the same error range. In other words, the responses were indistinguishable. Thus we conclude that there was no excess spacing loss.

On the other hand, over the past several years we have become aware of a problem with the low-wear aluminum-iron alloy Alfenol (Vacodur), which has been in use since 1966. If the procedure described in the foregoing is followed using the Alfenol-core heads, the response relative to the molybdenum permalloy core heads follows a spacing loss response, as shown in Fig. 1. It corresponds to an excess spacing of approximately 0.4 μm for a loss at 95-mm/s tape speed of about 5 dB at 20 kHz. We have found this loss consistently with three or four Alfenol-core heads. The loss is sufficiently consistent that we cannot believe that it is a chance occurrence, nor a defect in a particular sample of head. In the case of Alfenol cores, neither of the head-polishing techniques described above reduces the excess spacing loss. (There are other techniques, such as chemical etching and the ion mill used in the photolithography industry, that we have not tried.)

We have discussed possible causes for the excess spacing loss with magnetic head designers. They conclude that the presence of a dead layer on 16% aluminum-iron alloy is not surprising, and that the determination of the exact mechanism is very difficult, but that several mechanisms can be hypothesized, including

[3] Note that a reduction of signal level produces a positive loss. Thus we plot Fig. 1 as an increasing (positive) loss downward, corresponding to a reduced signal level with increased frequency.

[4] Recovac (Vacuumschmelze Hanau's tradename for a material similar to 4-79 permalloy) has been used in some heads for the Studer A-80 recorder. They are identified as product numbers 1 316 XXX.

[5] Wear-resistant HyMu 800 heads have been used on the Studer A-80. They are identified as product numbers 1 317 XXX.

the following three:

1) Aluminum is a very active material. An aluminum oxide (nonmagnetic) layer might form on the head face.

2) There is some segregation of the aluminum from the iron. Bozorth [13, fig. 7-8] shows that aluminum iron becomes nonmagnetic at 17–18% aluminum content.

3) The magnetostriction coefficient of 16% aluminum iron is high. Bozorth shows [13, fig. 13-116] $+ 10 \times 10^{-6}$, as opposed to less than 0.1×10^{-6} for 80% nickel-iron [13, fig. 13-96]. Normal wear pushes the core material past its yield point, and this might cause the formation of a nonmagnetic layer, especially with a material such as Alfenol, which has a large positive coefficient of magnetostriction.

4 CONCLUSION

Long-wear heads are a practical convenience in any application, and may be a necessity in high-wear applications such as tape duplication.

All Alfenol (Vacodur) heads that we have measured have an unremovable dead layer on their surface that produces an excess spacing loss in reproduction which ranges at 20 kHz from about 5 dB at 95-mm/s (3.75-in/s) tape speed to 0.6 dB at 760 mm/s (30 in/s).

Some ferrite heads may have a dead layer. They may also chip and erode, causing unknown short-wavelength losses.

In studio and duplication applications, these excess spacing and other losses can usually be compensated adequately by playing a reproducer calibration tape and adjusting the reproducer for flat output versus frequency.

But neither Alfenol (Vacodur) nor ferrite reproducing heads are suitable for use in the fundamental wavelength-response calibrations that are required for testing or manufacturing the calibration tapes themselves.

5 REFERENCES

[1] O. Kornei, "Structure and Performance of Magnetic Transducer Heads," *J. Audio Eng. Soc.*, vol. 1, pp. 225–231 (1953 July). (See sec. "Core Materials.")

[2] T. Wada, "An Improvement in Ferrite Substrate," *IEEE Trans. Magnetics*, vol. MAG-16, pp. 884–886 (1980 Sept.).

[3] C. D. Manquen and J. Martinson, "Maintenance Procedures for Ferrite Heads," *J. Audio Eng. Soc.*, vol. 27, pp. 881–886 (1979 Nov.).

[4] J. F. Nachman and W. Buehler, "16-Percent Aluminum-Iron Alloy Cold Rolled in the Order–Disorder Temperature Range," *J. Appl. Phys.*, vol. 25, pp. 307–313 (1954 Mar.).

[5] "Vacodur 16," Data Sheet M 009, Vacuumschmelze GmbH, Hanau, Germany (1962 Mar.).

[6] H. Thiemer, "Langlebensdauer-Magnetköpfe in Studioqualität," presented at the 2nd Conference on Magnetic Recording, Budapest (1966).

[7] J. G. McKnight, "Flux and Flux–Frequency Measurements and Standardization in Magnetic Recording," *J. Soc. Motion Picture TV Eng.*, vol. 78, pp. 457–472 (1969 June).

[8] R. L. Wallace, Jr., "The Reproduction of Magnetically Recorded Signals," *Bell Sys. Tech. J.*, vol. 30, pp. 1145–1173 (1951); reprinted in M. Camras, Ed., *Magnetic Tape Recording* (Van Nostrand Reinhold, New York, 1985).

[9] W. K. Westmijze, "Studies on Magnetic Recording," *Philips Res. Rep.*, vol. 8, pp. 148–157, 161–183, 245–269, 343–366 (1953); reprinted in M. Camras, Ed., *Magnetic Tape Recording* (Van Nostrand Reinhold, New York, 1985).

[10] E. D. Daniel and P. E. Axon, "The Reproduction of Signals Recorded on Magnetic Tape," *Proc. IEE*, vol. 100, pt. 3, pp. 157–167 (1953 May).

[11] J. G. McKnight, "Gap-Length Response in Magnetic Reproducers: Calculation, Measurement, and Compensation," presented at the 58th Convention of the Audio Engineering Society, *J. Audio Eng. Soc. (Abstracts)*, vol. 25, p. 1064 (1977 Dec.), preprint 1297. Revised version to be submitted to *J. Audio Eng. Soc.* in 1994.

[12] S. A. Bendson, "New Wear-Resistant Permalloy Material for Magnetic Recording-Head Application," *J. Audio Eng. Soc.*, vol. 24, pp. 562–567 (1976 Sept.).

[13] R. M. Bozorth, *Ferromagnetism* (Van Nostrand, Princeton, NJ, 1951); reprinted by IEEE Press, New York (1993 Aug.).

[14] C. Heck, *Magnetic Materials and Their Applications*, English ed. (Crane, Russak & Co., New York, NY, 1974), chap. 15, "Magnetic Materials for Information Storage"; sec. 15.3.3.2, "Core Materials."

[15] C. D Mee and E. D. Daniel, *Magnetic Recording*, vol. 1, *Technology* (McGraw-Hill, New York, 1987), sec. 4.3, "Head Materials."

[16] F. Jorgensen, *The Complete Handbook of Magnetic Recording*, 3rd ed. (TAB Books, Blue Ridge Summit, PA, 1988), pt. 3, "Magnetic Heads," chap. 7, "Materials for Magnetic Heads."

[17] F. Kalil, Ed., *High-Density Digital Recording*, NASA Ref. Publ. RP-1111 (1985-09) (NASA, Washington, DC). (See app. C for three papers on increased head life.)

[18] J. G. McKnight, "The Frequency Response of Magnetic Recorders for Audio," *J. Audio Eng. Soc.*, vol. 8, pp. 146–153 (1960 July).

[19] J. G. McKnight, "Magnetic Design Theory for Tape Recorder Heads," *J. Audio Eng. Soc.*, vol. 27, pp. 106–120. (See especially sec. 2.4 and fig. 13).

[20] N. H. Yeh and K. N. Yang, "Paradox of Deep Gap Field and Far Field at High Frequencies in a Recording Head," *IEEE Trans. Magnetics*, vol. 29, pp. 3864–3866 (1993 Nov.).

APPENDIX 1
ON WEAR AND CORE MATERIALS

Several materials have been used to manufacture magnetic recording and reproducing heads. The ideal material would have infinite magnetic permeability at all frequencies and throughout the surface and body of the material; would be easy to form mechanically to the desired shape and completely stable (that is, unaffected by stresses of any sort in manufacturing and usage); and would be completely resistant to the wear caused by the tape that continually abrades its surface.

No known material achieves all of these goals. Each has some advantages and some disadvantages compared to the others, but several of the materials have properties that are good enough so that with careful selection of the material for a particular application, one can design the head structure and the manufacturing and testing techniques in such a way as to make commercially useful heads. Reviews of characteristics of several different core materials are given in Heck [14], Mee and Daniel [15], and Jorgensen [16].

Wear of the core by tape abrasion is extremely important from the user's viewpoint. It controls how rapidly the performance of the recorder deteriorates with wear, and this in turn controls the cost of maintenance (how often testing and realignment are necessary, and how often heads must be relapped or replaced). From the designer's viewpoint, achieving low wear may require a tradeoff with some aspects of recording and reproducing performance, as well as the costs of the core material and the fabricating processes.

The AES *Journal Cumulative Index 1953/1980* shows seven papers relating to head wear (improved materials, relapping, wear measurement, and so on). The Tape Head Interface Committee (THIC) publication [17] has a 10-page appendix devoted to increasing the head life.

Unfortunately some of these materials with "improved" wear properties have proven to have their own special problems, as discussed in the body of this paper.

APPENDIX 2
ON THE RESPONSE ERROR FROM A FLUX-INDUCING LOOP

The frequency response of a reproducing head is most accurately measured by playing a constant-wavelength recording at variable speed [18] (but being careful at higher speeds that the tape tension and head wrap are such that an air film is not drawn between the tape and the head).

A simpler measuring technique is to use a flux-inducing loop, but it may not give the correct response at high frequencies. The amount of the error is completely dependent on the head design. It may be quite negligible in the audio band, or it may be several decibels. One cannot tell without all the details on lamination material, thickness, and gap length. This discrepancy has been described in [19] and explained theoretically in [20].

For instance, we have measured a Studer reproducing head, product number 1 317 146 (wear-resistant HyMu 800 core with a 2.5-μm gap length). With this head we found that when the response is flat from a constant-wavelength variable-speed recording, the flux loop response is +0.1 dB at 8 kHz, +0.6 dB at 16 kHz, and +0.9 dB at 20 kHz. In other words, if we had used the flux-loop measurement method instead of the variable-speed method, the response of the reproducing system would have been −0.6 dB at 16 kHz and −0.9 dB at 20 kHz. Thus we say that with the flux-inducing loop we can set the response only approximately.

THE AUTHOR

John G. (Jay) McKnight has been the president of Magnetic Reference Laboratory (MRL) in Mountain View, CA, since 1975. He also develops new products and directs engineering at MRL. He was President of the Audio Engineering Society (AES) for the year 1978/1979, and a member of the Committee on Evaluation of Sound Spectrograms of the National Academy of Sciences (1977 to 1979). In 1973/1974 he was a member of Judge Sirica's Advisory Panel on White House Tapes. From 1972 to 1974 he was a consultant on audio systems and magnetic recording, and Engineering Vice-president of MRL.

From 1952 thru 1972 he worked for Ampex Corp., serving in the magnetic recording research group, the stereo tape division, and the professional audio division. He received his BS in Electrical Engineering from Stanford University in 1952.

He has published over 60 technical papers on the theory and practice of magnetic recording and on audio engineering. At Ampex, in addition to research he also worked on the design of the CinemaScope reproducer system; the Models 350, PR-10, and MR-70; improvements in the high-speed duplication system and operating procedures at the Ampex Music (Stereo Tape)

Division; and developed the Ampex Master Equalization (AME).

He is a Fellow and an Honorary Member of the AES, and recipient of the AES Award; a member of the AES Review Board; and has been a Governor three times and Chairman of the Standards Committee and Chairman of the Publications Policy Committee.

Mr. McKnight has been a member of standards committees on audio engineering and magnetic recording of the AES, ANSI, CCIR, EIA, IEC, IEEE, NAB, RIAA, and SMPTE, and is presently Chairman Emeritus of the AES Standards Committee. He is also a senior member of the IEEE.

His hobbies include hiking and knapsacking, programming in the Forth computer language, and playing viola in an amateur string quartet, in several community orchestras, and in the orchestras of two Gilbert & Sullivan companies.