CONTROL OF MODULATION NOISE IN MAGNETIC RECORDING TAPE

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ABSTRACT:

Factors in the formulation and manufacture of magnetic tape which contribute to the problem of modulation noise have been defined. The effects of formulation variables (oxide, binder and additive types and proportions) are relatively small. The effects of manufacturing variables, particularly calendering, are very large. Improvements in modulation noise of 12 dB were found when the calendering process was optimized. The best calendering process requires the use of homogeneous compliant rolls instead of the composite type previously used. Infrared transmission microscopy was developed as a useful technique for identifying and controlling the calendering-related modulation noise.

INTRODUCTION:

Tape manufacturers have tended to emphasize increases in signal-to-noise ratio in developing new generations of magnetic tape for audio mastering use. Signal-to-noise ratio has been defined as the range in dB between the weighted noise level and the output at which the signal contains some percent of third harmonic distortion. What was a reasonable development approach in the past is no longer adequate. The current emphasis on multitrack recording, particularly 24-track, and the increased level capability of new tapes have caused modulation noise to become an increasingly more important tape characteristic. Modulation noise on earlier tapes was safely masked by the biassed tape noise and could not be detected easily. Also, if every instrument was not fully isolated in recording, it was difficult to distinguish modulation noise problems in the mix. Finally, the use of relatively wide tracks and long-gap heads with these earlier tapes minimized their modulation noise limitations.

The present recording practice is often to allocate one track to one instrument. That instrument is recorded at a high level regardless of its final intended level in the mix. To accomodate this recording style, many studios are using a 24-track recording format. The new tapes invite the use of significantly higher recording levels because of their low distortion properties. All of these more modern recording practices cause modulation noise to assume greater significance. For instance, the sound of a bass guitar, with its pure vibrational characteristic, is particularly susceptible to being degraded by modulation noise. If it is recorded alone on one track of the narrow 24-track format at an elevated level, the modulation noise of even a very good tape will be noticeable in an isolated playback. Although the bass guitar is usually mixed in at a low level with other instruments, this is not always true, so the potential for degrading the sound quality of the final mix remains. Ultimately, the fact that the modulation noise characteristics of tape now may limit the fidelity of a recording convinced us to undertake this empirical study to understand and control the factors in tape design and manufacturing which cause modulation noise.

DEVELOPMENT OF MEASUREMENT METHOD:

We first measured the modulation noise using the standard dc magnetization methods described by Eldridge (1), Daniel (2), WT 001572 (3) and DIN 45519 (4). These methods were later replaced with a more direct ac method which was both simpler and more accurate. We felt that an ac method as described by Trendell (5), Davidson (6) and Melis (7), would be more closely analogous to the modulation noise problem as it manifests itself in audio program material. We therefore set out to develop a technique to measure the modulation noise side bands in the presence of a single tone frequency which we chose as 1 kHz in accordance with Trendell's findings. By using a spectrum analyzer with a high enough selectivity such as provided by the HP 3590 A or the EMR 1510, we found that the modulation noise could be separated from the signal frequency and measured directly. Both analyzers were used but the final measurements were made on the EMR because of a slightly higher accuracy from a numeric readout with 0.1 dB amplitude resolution. The modulation noise is equally distributed within ± 600 Hz of the signal frequency (1 kHz). In order to provide a number for signal-to-noise comparisons between different tapes, we decided to measure the noise at a single frequency, 800 Hz, in a frequency range of 10 Hz to 2.56 kHz and a band width of 15 Hz per line on the EMR 1510. The modulation noise ratio is therefore defined here as the difference in amplitude between the signal frequency (1 kHz) recorded at 260 nWb/m (3 dB above Ampex Operating Level) and the noise at 800 Hz. (See Fig. 1)

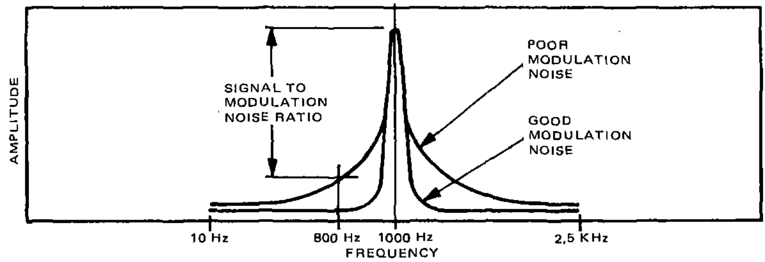


Figure 1. Spectrum Analysis of Modulation Noise

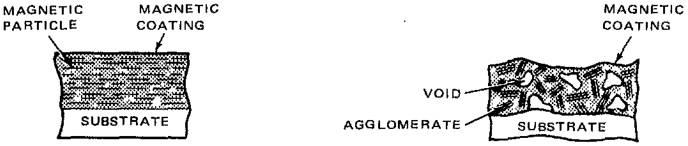
Fig. 2 and Fig. 3 show examples of a good and a bad modulation noise sample as displayed on the CRT of the EMR 1510. All of our measurements were made on an MM-1100, 16 track recorder with standard heads and electronics. Tape speed was 15 ips. Bias was optimized (maximum sensitivity at 1 kHz) for each tape. Dependence of bias and record level on the modulation noise was also verified. Minimum modulation noise occurred at optimum to 1 dB overbias and increased significantly at other bias settings. Modulation noise was directly proportioned to the record level. Listening tests were conducted to confirm the validity of this measurement technique and good qualitative agreement was established. Two listening methods were employed. In one a 40 Hz recording was played back through a 250 Hz high pass filter. The coherant noise was judged to be a measure of the modulation noise. In the other method, an open base guitar line was recorded and listened to. While these methods were useful crosschecks, the quantitative results were much better for evaluation of the experimental samples. However, we determined from the listening tests that a modulation noise ratio of 60 dB or higher was acceptable to a critical listener while lower values were objectionable.

PLAN OF EXPERIMENTS:

We expected to discover effects on modulation noise from both the constituents of the coating and from the way in which the coating and the tape was manufactured. The experimental program was divided into two parts; materials and processes. Each variable of interest was controlled at two or more levels to determine its effect on modulation noise. In discussing the results of the study, each variable will be described in such a way that its possible effect on modulation noise can be visualized. Then the associated experimental data will be presented and discussed. The presentation of the findings is organized, for materials, in the order of the importance of the material,and, for processes, in the order in which they are carried out to make tape.

MATERIALS:

Magnetic tape is composed of a matrix of magnetic particles bonded to each other and to a polyester substrate by a combination of polymers and additives chosen to give a tape the correct physical properties (durability, lubricity, conductivity, etc.). The microscopic point-to-point uniformity of this magnetic particle matrix is directly related to the degree of modulation noise it will exhibit. If each particle is of the same size and is separated from adjacent particles by a constant distance, and if all particles either are aligned perfectly or completely randomized, the minimum of modulation noise will be found. If the particles are clumped together in one region, and if they consistently are oriented first one direction, then another, modulation noise will be very high. Also, if the surface of the tape contacting the heads is rough, or if the interface between the coating and the substrate is uneven, modulation noise will be increased.



A. BEST CASE

B. WORST CASE

Figure 4.

MATERIALS (Continued):

All of these uniformity properties could be affected by the choice of materials, their proportions and their chemical and physical interactions. For this reason we studied the following materials and formulation variables. In each experiment the modulation noise and output properties of the tape samples were measured. This allowed us to be sure that an apparently better tape, according to modulation noise, was not just a poor tradeoff for output deficiencies.

Magnetic Material

The magnetic material in current mastering tapes is almost always the same chemical species (γ Fe_2O_3) but it is synthesized in a wide variety of sizes and length/diameter ratios (acicularity). We studied several of these shape characteristics as well as a zinc-doped magnetite (Fe_3O_4) to see if there was a modulation noise effect. The degree of magnetic orientation for each of these oxide types is also tabulated since this may be more important than the shape factors in controlling the electrical performance properties of tape.

TABLE I

MAGNETIC MATERIAL TYPE

Magnetic Material	Acicularity	Length	Orientability (Br/Bm)	Modulation Noise Ratio (dB)
*A	15/1	0.88	0.84	58.1
B	12/1	0.70	0.82	57.3
C	10/1	0.50	0.76	57.8
D	8/1	0.30	0.79	58.0
E	8/1	0.50	0.78	55.1
F	7/1	0.50	0.73	57.9
50/50 A:E	-	-	0.81	57.1

Note: All samples are gamma ferric oxides except F which is zinc magnetite.

When all processing and other formula conditions are held constant, magnetic particle characteristics have very little effect on modulation noise.

Volume Concentration of Magnetic Material

The magnetic particles in the coating are the only active recording elements of the tape. In audio (analog) recording, an increase in the volume fraction of magnetic material will provide an increase in signal-to-noise ratio. However, we were not certain how modulation noise was being affected by increases in the volume concentration of magnetic oxide. One could visualize severe clumping of particles at too high a volumetric loading and non-uniform distribution of particles occurring when the loading was too low. Tests at three levels of magnetic material volume concentration were conducted.

TABLE II

MAGNETIC MATERIAL VOLUME CONCENTRATION

Volume Concentration (%)	Modulation Noise Ratio (dB)
57	58.0
52	60.1
48	60.0

Very high volume concentration appears to cause a slight increase in modulation noise but, below a critical level (52%), no further improvement in modulation noise was noted as the volume concentration was lowered.

Binder Composition

The polymeric binder components which bond the magnetic material together and adhere it to the polyester substrate are generally classifiable into two groups according to tensile characteristics; 1) tough, rubbery and 2) hard, brittle. Also if the binder is further polymerized in place on the substrate it can be classified as being cross linked, or thermoset. If it has not been so treated it is considered to be thermoplastic. Mechanisms for changes in modulation noise related to these binder properties can be visualized readily. We tested samples representing all four binder system characteristics.

TABLE III

BINDER COMPOSITION

Type	Modulation Noise Ratio (dB)
Tough rubbery - thermoplastic	57.9
Tough rubbery binder modified with hard - brittle binder - thermoplastic	58.0

Type	Modulation Noise Ratio
Tough rubbery - thermoset	57.8
Tough rubbery binder modified with hard - brittle binder - thermoset	57.9

Binder composition appears to have no effect on modulation noise.

Solvent Composition

The solvents used in the magnetic tape coating dissolve the binder components and create a fluid state in the coating so that it can be applied to the substrate film. The solvents are evaporated from the non-volatile components using a forced-air drying tunnel to leave a dry, cohesive magnetic coating adhered to the substrate at the end of the drying phase. The wetting characteristics and relative volatility of the solvents can affect the integrity and smoothness of the applied coating. We varied the drying rate of the solvent blend to determine whether this produced an effect on modulation noise.

TABLE IV

SOLVENT COMPOSITION

Solvent Type	Modulation Noise Ratio (dB)
Slow evaporating rate	57.5
Medium evaporating rate	57.8
Fast evaporating rate	57.5

Solvent composition had no effect on modulation noise.

Base Film: Thickness, Smoothness and Backcoating

The base film or substrate for almost all magnetic tape is polyethylene terephthalate (polyester) film. The thickness and/or roughness of this film could affect the uniformity of the applied magnetic coating. We tested films of nominally 1.0 milli inch (25 microns) and 1.5 milli inch (37 microns) thickness. We compared standard polyester film smoothness with an ultrasmooth film, and we examined the effect of the carbon backcoating on modulation noise.

TABLE V

BASE FILM: THICKNESS, SMOOTHNESS AND BACKCOATING

Type	Modulation Noise Ratio
1.0 mil (25μ)	58.1
1.5 mil (37μ)	58.1
Smooth surface (1.0μ)	59.4
Standard surface (2.5 μ)	58.0
Backcoated	57.8
Not backcoated	59.0

The smooth base film has a slightly beneficial effect on modulation noise. Elimination of the backcoating could improve modulation by 1dB. Base film thickness has no effect.

Antistatic Additive

Carbon black is often incorporated into magnetic tape coatings to control static electricity in the tape. It has the disadvantage that it occupies space in the coating which would be better allocated to magnetic oxide. For this reason, backcoatings, which also dissipate static electricity, are being used increasingly on audio tapes. Nevertheless, carbon, being much smaller in size than the magnetic particle, could have a marked effect on modulation noise because of its size interaction with the other solid components of the coating. Coatings with and without carbon were tested.

TABLE VI

ANTISTATIC ADDITIVES

Condition	Modulation Noise Ratio (dB)
Without carbon	57.8
With carbon	58.0

The inclusion of carbon black does not affect the modulation noise on magnetic tape.

Lubricants

Lubricants are used in magnetic tape coatings to provide a low-friction

Lubricants (Continued)

interface between the heads and the tape surface. If the tape moves erratically over the heads in a slip-stick mode, this introduces a time base error which causes frequency-modulation noise. The question is not whether to use a lubricant but rather what type of lubricant will give the best results. An experiment was conducted to determine the effect of various lubricant types on modulation noise.

TABLE VII

LUBRICANT

Type	Modulation Noise Ratio (dB)
Natural animal oil	56.9
Natural vegetable oil	57.5
Silicone oil	57.2
Stearate lubricant (wax)	57.9

The type of lubricant has a small effect, if any, on modulation noise.

PROCESSES:

Magnetic tape is manufactured in a series of steps which can be roughly separated into three areas; batch preparation, coating and drying, and tape finishing. The coating ingredients are intimately dispersed in a batch milling vessel using either flint pebble or steel ball media. The finished coating resembles a paint or lacquer which is then applied at the appropriate thickness to polyester film in a precision coating machine. The magnetic material in the wet coating is magnetically oriented and then the solvents are evaporated from the coating in a tunnel dryer to provide a tough dry magnetic film on the wide web of polyester. The coated web is then passed between two smooth rolls under high pressure and temperature in an operation known as calendering. Finally the coated web is slit into the tape widths required for the end use and then subjected to an operation known as burnishing, which is a tape cleaning process.

Obviously every one of these processes is capable of affecting the uniformity of the coating or the surface of the tape. A series of experiments was designed to determine which of the tape-making processes contributes most significantly to modulation noise problems.

Batch Preparation

The perfect dispersion of magnetic material can occur only when every particle is separated from every other particle and surrounded by the same amount of binder material. Since magnetic oxide particles are less than one micron in their longest dimension, energy must be expended on a microscopic scale for long periods to eliminate initial particle agglomeration which is a source of modulation noise. Two factors which are known to affect the quality of magnetic oxide dispersions are media type and dispersion time. Both were considered in this study.

1. Media Type

The milling vessel in which the coating ingredients are dispersed is a large cylinder rotating with its long axis horizontal. Along with the ingredients to be dispersed, this milling vessel is filled with a large quantity of flint pebbles or steel ball bearing-like milling media to assist in the process of particle separation. Because of the great difference in density between these two types of media, it was suspected that they might have different modulation noise effects.

TABLE VIII

MEDIA TYPE

Type	Modulation Noise Ratio (dB)
Steel media/steel mill	57.7
Pebble media/porcelain mill	57.5

No effect was noted.

2. Dispersion Time

The huge number of particles which must be dispersed in a coating batch make it difficult to define a precise dispersion end point. The batch must be milled for at least a minimum time or all electrical and magnetic properties of the resulting tape will be sub-standard. We decided to investigate the effect of a major increase in dispersion time.

TABLE IX

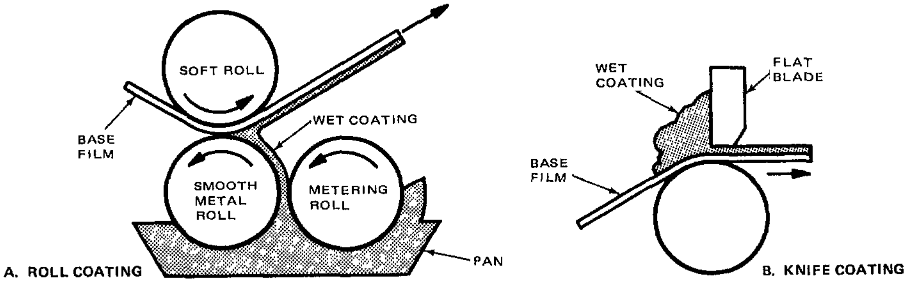
DISPERSION TIME

Time	Modulation Noise Ratio (dB)
48 hours	58.0
96 hours	58.0

Doubling the dispersion time had no beneficial effect on modulation noise.

Coating Method

Several methods are used to coat magnetic tape. Roll coating consists of first applying the correct thickness of wet coating to a very smooth metal roll, and then transferring this coating to the polyester film in an operation like printing. Knife coating consists of positioning a flat blade above the moving polyester film at the exact distance which will allow only the desired thickness of wet coating to pass through.



A. ROLL COATING

B. KNIFE COATING

Figure 5

Because the flow orientation and shear rate effects of these two methods are greatly different, we decided to investigate the effects of both.

TABLE X

COATING APPLICATION

Method	Modulation Noise Ratio (dB)
Roll Coating	58.1
Knife Coating	57.3

The slight improvement shown by roll coating may be a result of the higher shear stresses developed during this coating process.

Coating Viscosity

The viscosity of the wet coating can affect the tendency of the ingredients to separate before application. Shear stress also varies directly with viscosity in any coating operation. Two levels were studied using knife coating.

TABLE XI

VISCOSITY

Viscosity	Modulation Noise Ratio (dB)
4000 cps	58.0
2000 cps	57.9

No significant effect of this viscosity change was seen.

Magnetic Orientation

The freshly-coated polyester film with its still-wet coating is passed through a longitudinal magnetic field so that the magnetic particles are aligned with their long axes in the recording direction. Because of the strong, possibly non-uniform, magnetic fields which are developed, the magnetic material may be redistributed unfavorably in this process. Tape was tested which had been made with (standard), and without magnetic orientation.

TABLE XII

ORIENTATION

Condition	Modulation Noise Ratio (dB)
With	58.0
Without	55.0

The effect of orientation is beneficial, not only on modulation noise, but also on most other electrical properties which are not fully developed unless the particles are correctly aligned.

Calendering Process Conditions

The dry coating emerges from the coating/drying process with a relatively rough surface and it contains microscopic voids. The high-temperature-high-pressure calendering process reforms the coating into a smooth, dense film with improved low-frequency distortion and high-frequency response properties. As the coating passes between the two rolls, it becomes fluid again momentarily, and then assumes its final compressed form. The conditions which exist as the coating passes through this fluid state could easily influence the magnetic uniformity of the finished tape. Temperature, inter-roll loading (nip pressure) and number of calendering stages were studied in this experiment.

TABLE XIII

CALENDERING PROCESS CONDITIONS

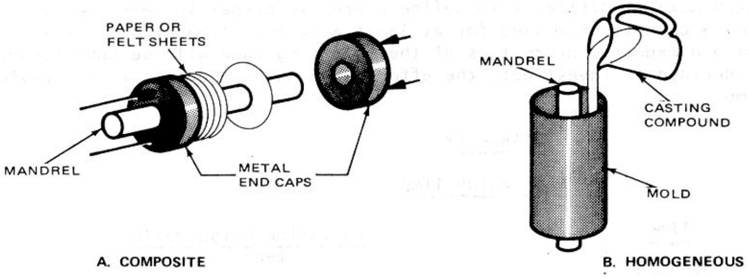
Variable	Level	Modulation Noise Ratio (dB)	15 kHz Sensitivity (dB)
Temperature	200°F	57.8	0.0
	70°F	60.0	-1.8
Pressure	2000 PLI	57.8	0.0
	1000 PLI	58.8	-1.1
Stages	2	57.8	0.0
	4	56.5	+1.3

No beneficial effect was noted in these evaluations. The effect of increasing the degree of calendering through increased temperature or more stages was detrimental. Doubling the pressure at a single temperature had no effect.

Calender Roll Material and Construction

A calender stage employs one very highly-polished chrome-plated roll in conjunction with a relatively more compliant roll. Although classified as compliant, these rolls are "soft" only as compared with metal rolls. The Shore Durometer is used to characterize the hardness of these rolls.

Compliant roll construction can be either composite or homogeneous. The composite roll is fabricated by stacking washer-like sheets of paper or felt material on a cylindrical mandrel, compressing these sheets mechanically, and then turning and finishing the outer diameter of the construction. The homogeneous roll is made by casting a liquid elastomeric compound into a cylindrical configuration around a mandrel and curing it into a solid of desired hardness. Similar surface finishing techniques are carried out on either roll type to achieve the proper runout and smoothness.



A. COMPOSITE

B. HOMOGENEOUS

Figure 6

Various compliant roll hardnesses, and composite and homogeneous constructions were evaluated against a control sample which was not calendered.

TABLE XIV

CALENDERING ROLL CONSTRUCTION

Construction	Hardness (Shore D)	Modulation Noise Ratio (dB)	15kHz Sensitivity (dB)
Composite	90	58.1	0.0
Cast	80	64.8	-0.3
Cast	75	65.7	-0.5
Cast	65	66.9	-0.7
Cast	45	67.0	-1.5
Not Calendered	--	67.0	-2.5

Calender roll construction is found to have major, significant effect on modulation noise. The composite construction, which has been commonly employed for extremely hard compliant rolls, was found to be a major cause of tape non-uniformity. A probable cause for this is the point-to-point hardness variation in the composite roll structure which must then bring about a corresponding density variation in the calendered tape coating. Interestingly, the effect of roll hardness, providing the roll is homogeneous, is small. The non-calendered tape had excellent modulation noise, but, as expected, was also very poor in high-frequency sensitivity, making it an unacceptable alternative.

Roll construction, alone, is capable of eliminating as much as 9.0dB of measured modulation noise from an otherwise properly manufactured tape.

Lag Time - Coating to Calendering

The newly-coated tape is relatively soft; the curing reaction is incomplete. With time, the coating becomes harder. Calendering immediately after coating will have a more profound effect on the coating structure than will calendering after a long delay. The effect of this on modulation noise was investigated.

TABLE XV

LAG TIME - COATING TO CALENDERING (Cast Compliant Roll)

Time	Modulation Noise Ratio (dB)	15 kHz Sensitivity (dB)
0 hours	64.8	0.0
4 hours	66.0	-0.5
8 hours	67.0	-0.5
24 hours	67.1	-0.7
6 days	66.8	-1.3
8 days	67.0	-1.7

A four to eight-hour delay in the coating/calendering interval appears to allow the coating to maintain a stable structure and still be enhanced by the calendering process. Longer delays result in unacceptable losses in short wave length response.

Tape Cleaning

The slit tape is subjected to a cleaning process wherein debris is removed from the coating surface and the edges of the tape. Since this process should reduce the head-to-tape spacing variability caused by surface debris, an improvement in modulation noise was expected when the tape was cleaned. Cleaned and uncleaned tape was tested.

TABLE XVI

TAPE CLEANING

Condition	Modulation Noise Ratio (dB)
Not Burnished	64.1
Rotary Burnished	66.8

The effect of tape cleaning is nearly 3.0 dB improvement in modulation noise.

INFRARED MICROSCOPE INSPECTION:

Attempts were made to verify the hypothesis that composite roll calendering causes oxide density gradients to be formed in the coating. Initially, we tried to inspect the calendered tape using visible light transmission. Without a backcoating, some light can be transmitted through a magnetic tape coating but it is insufficient for microscope illumination. Our associate, Hillard Kahan, suggested that infrared transmission be tried. With the appropriate image converter, this proved to be an excellent means of inspecting the microscopic structure of carbon-free magnetic tape coatings. The intrinsic absorption edge for iron oxides is in the near infrared at about one micron. Also the light scattering caused by the oxide particles is particularly severe unless the wave length of the incident light is significantly greater than the particle size. Infrared light, then, is more readily transmitted and less subject to scattering by the coating than visible light and will reveal coating structure extremely well. Defects such as particle agglomeration, density variations, voids, inclusions and surface asperities are immediately observable as variations in the transmisivity of the tape.

Figures 7 and 8 show the difference in infrared transmission of two tape samples, the first calendered using a homogeneous cast roll construction, the second using a composite roll construction. The difference in point-to-point uniformity is obvious and the measured signal-to-modulation noise ratio for the first sample is 12 dB better than the second. The associated modulation noise spectra are shown above the IR photos as Figures 2 and 3.

ACKNOWLEDGMENTS:

The authors are indebted to Myles Weiner of Wally Heider Recording, Hollywood, California, for convincing us that modulation noise was sufficiently important to warrant a study of this type and to Richard and Iris Sontag of Supersound Inc., Monterey, California, for helping us to confirm our laboratory results in their studio with live music recordings.

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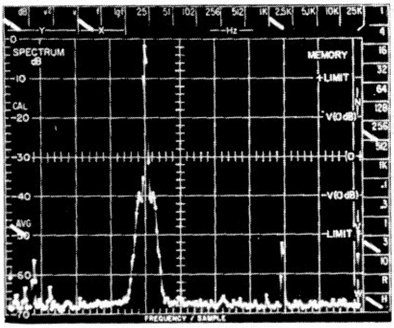

Figure 2. CRT Display of Modulation Noise Spectrum S/MN = 67.0 dB

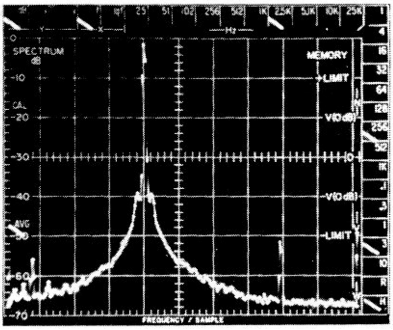

Figure 3. CRT Display of Modulation Noise Spectrum S/MN = 55.1 dB

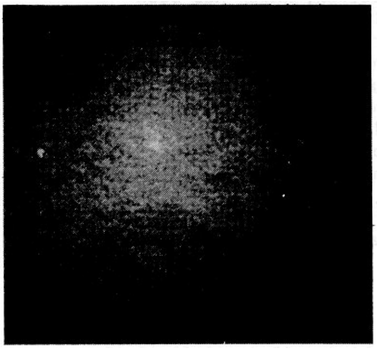

Figure 7. Infrared Transmission Photomicrograph of Sample Calendered with Homogeneous Roll

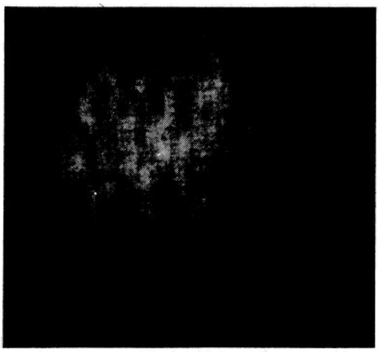

Figure 8. Infrared Transmission Photomicrograph of Sample Calendered with Composite Roll