VIDEO TAPE RECORDER DESIGN

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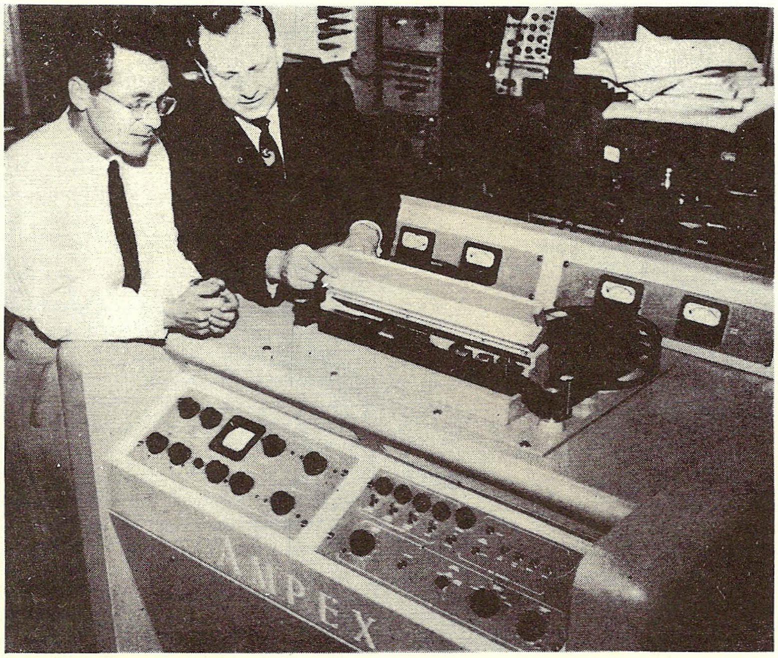
These papers constitute the first technical discussions of the Ampex video tape recording system, presented on October 11, 1956, at the Society's Convention at Los Angeles. Various problems encountered in the development of the recorder are discussed and the steps taken toward solutions are described in detail. These papers were first received on October 23, 1956, and in final form on March 11, 1957, from the authors at Ampex Corp., 934 Charter St., Redwood City, Calif.

Comprehensive Description of the Ampex Video Tape Recorder

By CHARLES P. GINSBURG

The subjects covered in this paper include: the choice of a system approach, the configuration of elements on the top plate, the magnetic pattern on the tape, the video electronics, the control system, principal factors in the response of the overall system, head life and tape life, and a note on splicing and editing.



The Ampex Video Tape Recorder, including the head assembly, being inspected last year by Charles P. Ginsburg, senior project engineer in charge of video development, and Phillip L. Gundy, manager of the audio division of Ampex Corp.

The Choice of a System Approach

In making any comparison among various approaches for recording video on magnetic tape, a fundamental premise can be made which defines the state of the art. This premise concerns the shortest useful recorded wavelength. The recorded wavelength is, of course, equal to the head-to-tape velocity divided by the frequency of the signal. For an audio recorder operating at 15 in./sec, a 15-kc signal has a wavelength of 1 mil, that is, 1/1000 of an inch.

Although in professional audio recording it is possible to obtain excellent results with wavelengths as short as $\frac{1}{2}$ mil, for other applications the shortest useful wavelength might be either greater or less than $\frac{1}{2}$ mil, depending on the application involved. For example, it might be possible to cite some application where only a 20-db signal-to-noise ratio is required, in which case it might be reasonable to reduce the size of the magnetic playback gap to a dimension smaller than the customary $\frac{1}{4}$-mil dimension in order to get an increase in the null frequency, and then to use recorded wavelengths considerably shorter than $\frac{1}{2}$ mil.

On the other hand, some very practical applications of tape recorders have performance requirements so stringent that it is necessary to operate with recorded wavelengths considerably greater than $\frac{1}{2}$ mil. Although some investigators have obtained significant results working with wavelengths as short as $\frac{1}{10}$ mil and even less, we believe that such considerations as life of the equipment, reliability, and ease of manufacture should restrict

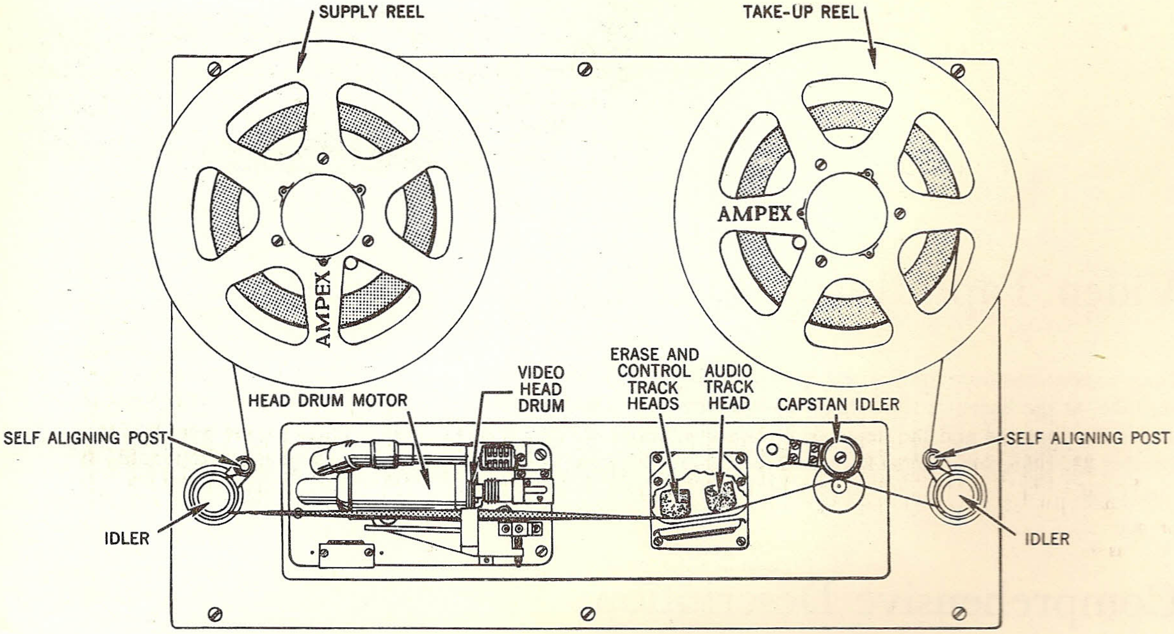


Fig. 1. Top-plate layout.

wavelengths for the video tape recording application to a dimension not less than $\frac{1}{5}$ or $\frac{3}{10}$ mil.

For several years it has been known to those intimately connected with or interested in the extension of the field of magnetic recording into much wider band applications that there are three promising approaches toward the development of a tape recorder for television use. The first and most obvious approach is a brute force method in which the tape is pulled past the magnetic head at a speed sufficiently high so that the recorded wavelength is not greater than, let us say, $\frac{1}{5}$ mil. Thus, to record a 4-mc signal a tape speed of 800 in./sec would be required if one were working with a top information packing density of 5 kc/inch of tape speed. Even with an increase of this packing density to 15 kc/inch, which approaches the greatest packing rate which has been obtained even under laboratory conditions, the required tape speed would still be in excess of 20 ft/sec. The accompanying problems in such a system, which range from the awkwardness of physically handling the reel of tape to the extreme difficulty in obtaining adequate head life, and even of producing the heads in other than laboratory fashion, would indicate that the approach might not be the best for the television application.

The second system is one which uses several channels in a time multiplexing fashion. The essence of such an approach is to sample the information to be recorded by each of the several channels consecutively and thus to reduce the bandpass requirements of each channel by a factor roughly equal to the number of channels employed. The obstacles encountered with this approach lie in the difficulty of maintaining during playback channel-to-channel phase relationships the same as they were during the recording process. This problem is almost exclusively mechanical and is, in the greatest part, due to the very severe effect on phase relations caused by a minute amount of tape skewing.

Again, this problem is intensified as the effort is made to use shorter and shorter wavelengths for the purpose of obtaining reasonable tape speeds. In following a development plan based on this type of approach, investigators have found it necessary to employ rather unique and elaborate correction devices, one example of which is a servo mechanism which varies the inclination of a stack of multiplexing heads, in order to compensate for tape skew. Within the requirements of a system for recording television programs, this approach is workable provided the wavelengths are sufficiently long so that the remaining error with a servo compensation system is tolerable in terms of the reproduced picture. In practice, it turns out that the restriction on permissible shortness of the wavelengths may still run in the order of that corresponding to a packing density of 2 kc/in. of tape speed. This means that in a ten-channel time division multiplexing system with a 4-mc bandpass, a tape speed of 200 in./sec would be required. A considerable amount of work has been done by some investigators along lines that are essentially combinations of the first two methods mentioned, with problems following the trends of both.

The third approach is one which has been pursued in developing the Ampex system. A very high writing speed is obtained by recording transversely across the tape while pulling the tape at a rate dictated by the width of the recorded tracks and the number of these tracks laid down per second. In the Ampex machine four heads are mounted in a drum so that their tips protrude very slightly past the periphery of the drum. The heads are precisely aligned in a rotational direction, so that each head gap is separated from the gap of the adjacent head by 90°. The drum diameter is approximately 2 in. and the rate of rotation is 240 rps, which gives a writing speed of about 1500 in./sec. The tape is 2-in. wide, which means that during the complete sweep of a head transversely across the tape, about 120° of arc are described. The soundtrack is laid down at one edge of the tape by means of a conventional stationary magnetic head, and a control system signal is recorded similarly at the other edge of the tape. The same rotating video heads are used for record and playback.

Configuration of Elements on the Top Plate

Figure 1 shows the top-plate layout. The tape is fed from the supply reel, around the supply idler, past the rotating drum and an assembly of stationary erase, record, and reproduce heads of conventional design, between the capstan and the capstan idler, around the take-up idler and to the supply reel. The stationary erase head for the audio track is located past the rotating drum; it erases the top edge of the tape after the video sweeps have been written on the tape by

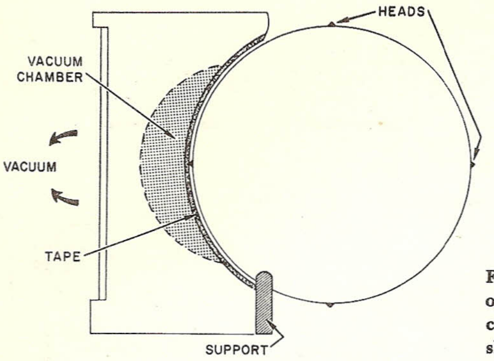
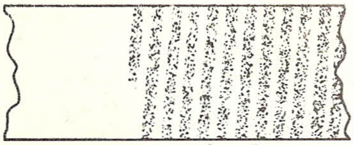
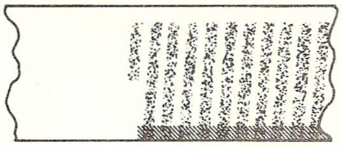


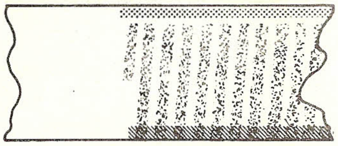
Fig. 2. Cross-sectional view of recording drum, with concave guide and tape shown in operational position.



SIGNAL PATTERN AFTER PASSING VIDEO HEAD DRUM.



SIGNAL PATTERN AFTER PASSING PAIRED AUDIO ERASE AND CONTROL TRACK RECORD HEADS.



SIGNAL PATTERN AFTER PASSING AUDIO RECORD HEAD.

Fig. 3. Magnetic pattern in sequential steps through head assembly.

the rotating video heads. It is unnecessary to erase the lower edge of the tape prior to recording the control signal. For the audio channel as well as for the control channel a combination record/-reproduce head is used. These heads are located as shown in Fig. 1.

Figure 2 shows in cross-section the drum, the tape and the concave guide or shoe which is used to cup the tape around the drum. Vacuum is "pulled" or exhausted from the shoe side of the tape as part of the tape stabilizing means.

The Magnetic Pattern on the Tape

Figure 3 shows the magnetic pattern on the tape at various points. The top sketch shows the magnetic pattern written completely across the tape by the rotating video head. The tracks are only 10 mils wide. The 2-in. tape travels at 15 in./sec, which allows about 5 mils of spacing between adjacent edges of the tracks laid down by the rotating head. The middle sketch shows the magnetic pattern on the tape after passing the audio and control track record/reproduce assembly. During playback, the interference in the control channel due to the incidence of the transverse video tracks does not exceed the required signal-to-noise ratio in the control channel. The tape dimension measured from the edge of the magnetic pattern toward the top of the tape after erasing of audio has occurred, to the top edge of the recorded control channel signal, exceeds by about two television picture lines a length which corresponds to 90° of arc. This means that successive recorded video tracks have an information overlap amounting to about 130 μsec. The purpose of this overlap is to allow during playback a fairly broad interval at any time during which electronic switching can take place. This process will be discussed in detail in the succeeding paper, "Commutation and Switching."

The Video Electronics

Figure 4 is a somewhat simplified block diagram of the complete system. The diagram breaks down into two major parts: the video electronics (certain aspects of which will be covered in much greater detail in companion papers) and the control system. The video signal is fed into the machine at standard level, is amplified, and goes to the modulator. The output of the modulator is fed through a drive amplifier to four separate record output amplifiers and is coupled to the rotating heads through slip rings and brushes. Inasmuch as an extensive discussion of the nature of the modulation system will be presented in the third paper of this group, at this point it might be merely stated that the modulation system records a frequency modulated wave in which the observable effects of amplitude variations of the modulated wave are, within certain limits, undetectable. Within these limits, the only result of failing to achieve during playback 100% registration of the heads on the previously recorded tracks will be a slight increase in the noise level.

In the playback mode the switches associated with the rotating heads are thrown to the preamp position, and thus the head output signals are passed through the respective preamps, and constitute the four input signals to the electronic switcher. The function of the switcher is to pass the output of each preamp only when it should be passed. This is for the purpose of eliminating the additional noise which would exist by transmitting an undesired signal or what is essentially the same thing, a signal at the wrong time. In short, the output of the switcher consists of the consecutive transmission of the signal read off by the individual heads. The signal appearing at the output of the switcher is still the frequency modulated wave. This rf signal is then passed to the demodulating unit which amplifies and clips, and then demodulates the signal. Following detection, the video signal is passed through video amplifiers and appears at the output of the machine in the same form in which it was originally presented at the input.

The Control System

It might appear a most formidable problem to control the heads so that they are in the right place at the right time. Actually, the control system is fairly simple. Sixty-cycle power line frequency is multiplied to 240 c (cycles per second), which is then applied to a power amplifier which drives the drum motor. A light source is focused on a disk mounted on the drum motor shaft. The disk reflects the light to a photoelectric cell. The surface of this disk has 180° of reflecting surface and 180° of nonreflecting surface. Thus, a square wave is generated at the output of the photocell which has a 1:1 correspondence with the rotation of the drum.

This 240-c square wave is passed through a 240-c bandpass filter and is then fed to the control track record electronics and thus written on the lower edge of the tape by the control track head. At the same time the 240-c square wave is divided down to 60-c, the 60-c signal being used to drive the capstan motor power amplifier during the record process. During playback, the drum runs in the same fashion as in record, but the capstan motor is driven under servo control (Fig. 5). The 240 c previously recorded on the tape is read back by the control track head, amplified by the control track playback electronics and constitutes one input to the servo amplifier.

The other input, which is the reference input to the servo amplifier, is the 240-c sine wave derived from the photocell impulses. These two 240-c signals are compared in phase, an error voltage is generated which is a function of the phase difference between the two signals, and this error voltage is applied to a low-pass filter whose output is fed to the grid of a reactance tube. The reactance tube is

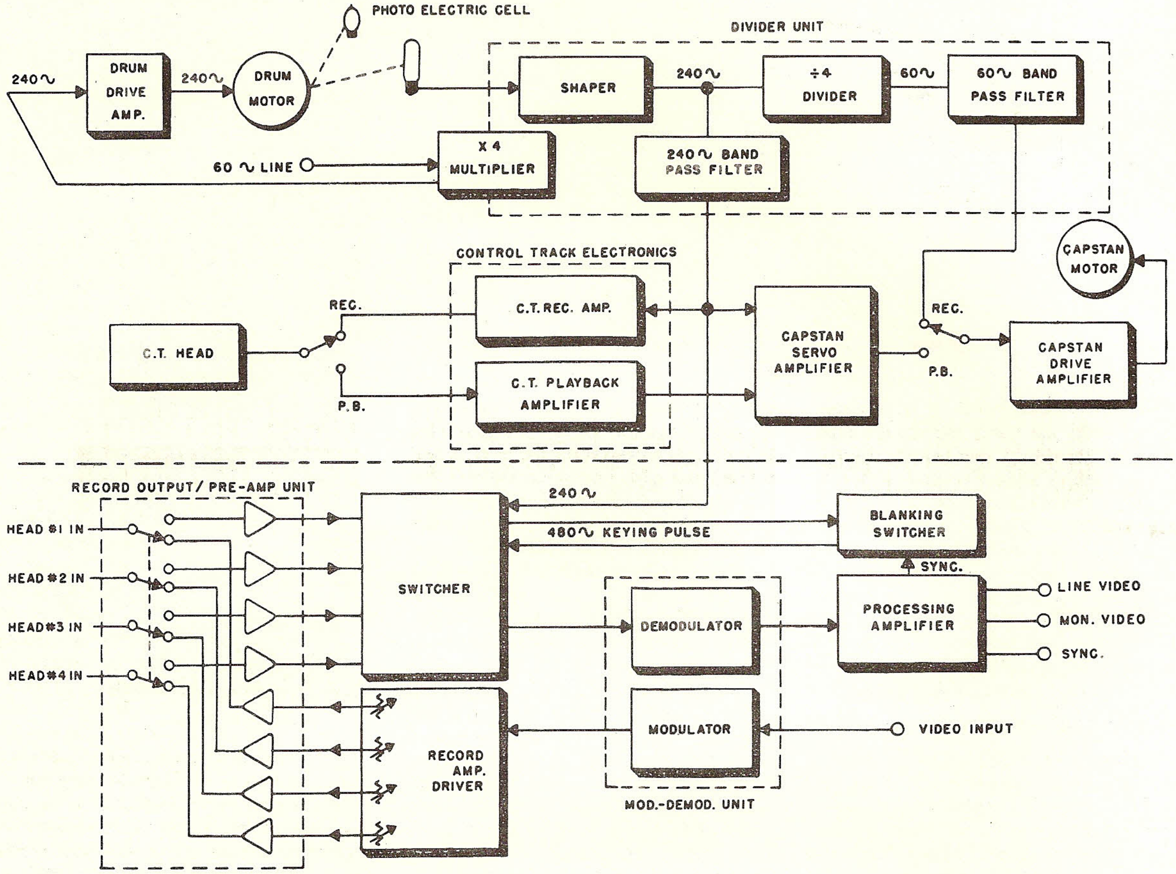


Fig. 4. Simplified block diagram of complete system.

one of the frequency determining elements of a Wien bridge oscillator. Thus, the Wien bridge oscillator frequency, which is nominally 60 c, is controlled by the phase variation between the two 240-c signals. Since it is the output of this oscillator which is applied to the input terminals of the capstan drive amplifier during playback, this method of control insures proper registration during playback of a given head upon the track which it previously recorded. The capstan motor is speeded up when the recorded 240-c signal (and therefore the tape) is lagging behind the photocell 240-c signal, and correspondingly slowed down when it is leading.

Any minor adjustments in tracking which might be desirable because of such factors as time-varying phase changes caused by temperature effects on circuit components, and temperature and humidity effects on the tape length between cylinder and control head, can be made by adjusting a vernier phasing control located on the operating panel of the machine.

Principal Factors in the Response of the System

A detailed and precise analysis of the response of the entire system is extremely complex. Although a direct recording approach, as opposed to a carrier system such as we are using, would have great pitfalls, especially in trying to obtain a very slow tape speed, the direct recording method would be far easier to analyze. We trust that the technical and economic advantages of the particular modulation system used in the Ampex video tape recorder outweigh the burden of having to interpolate, invert, translate and extrapolate certain nonlinear functions in particular elements of the system in an attempt to understand just how to increase horizontal resolution by 40 lines, or to reduce the rise time or overshoot by 20%. Here will merely be described very briefly some of the factors involved in the frequency response or transient response of the system.

The output circuits being used in recording consist of so-called constant current amplifiers. The type of amplifier that is used is a plate-coupled pentode in which the impedance in series between the plate and the B supply is sufficiently large in comparison with the impedance of the head circuit so that the amount of signal current going through the heads is essentially independent of frequency. An important consideration which precludes the possibility of keeping the current through the heads at an absolutely constant amplitude and with linear phase shift is the resonance of the head circuit itself. The inductance of the head windings, in conjunction with the various shunt capacities which couple a particular head winding to various other impedances as well as to ground, gives us a fairly complex network, the principal complexity arising from the existence of antiresonant circuits. An obvious solution to the problem of having the antiresonant frequency within the range of the required bandpass spectrum is to put fewer and fewer turns on the heads. However, there is a real limitation in this direction since a smaller number of turns gives less playback voltage. In a practical solution to this problem we have found it desirable to locate the antiresonant frequency within the range of at least some of the modulation components which are being passed.

Figure 6 gives an indication of the various impedances in the head circuit. Because of the f-m character of the system, it is advantageous to saturate the tape during the recording process. It might be desirable to saturate the tape for all frequencies involved. Since resonance prevents us from having a truly constant output amplifier, one might reach the con-

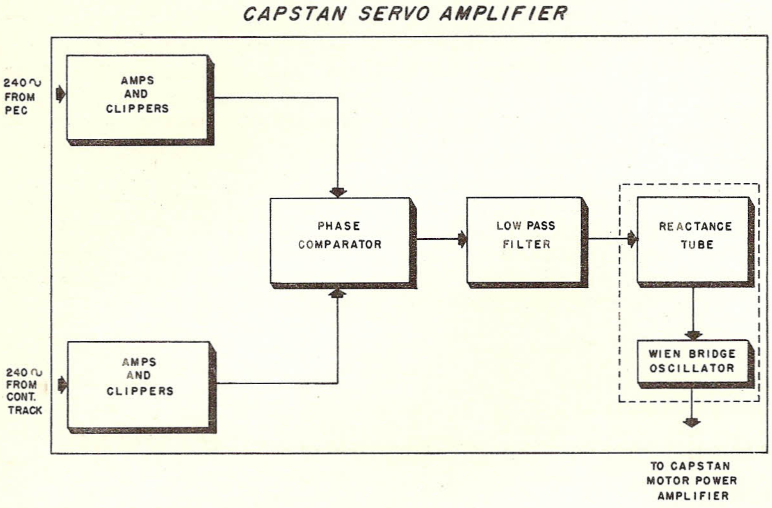


Fig. 5. Block diagram of capstan servo control.

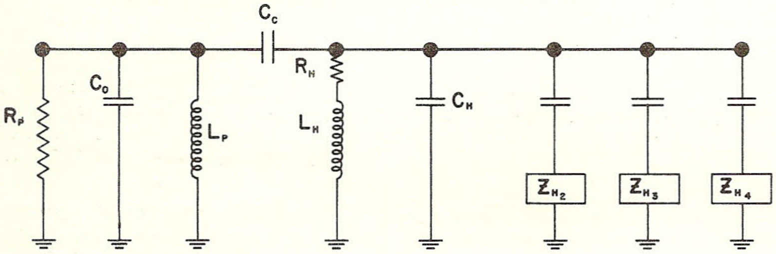


Fig. 6. Equivalent circuit for video head circuit during record.

clusion that the voltage level being delivered to the grid of the output stage could be of sufficiently high value so that the tape would be saturated even by the lowest amplitude current. It turns out that to do this is not as simple as it sounds.

Figure 7 shows a family of curves plotting output playback voltage amplitude (e_0) vs. record current for various wavelengths. At a 2-mil wavelength the output voltage will remain essentially at the maximum, even if a record current considerably in excess of the saturating level is used. At a $\frac{1}{2}$-mil wavelength, however, a very definite current optimum appears, in terms of playback voltage amplitude. In the case of the $\frac{1}{4}$-mil wavelength the curve is even sharper. Thus, unless one considers using very accurate amplitude or phase equalization, or both, the selection of the best possible input voltage to the record amplifier must be determined either by extensive analysis, if the understanding of the overall characteristics of the system justifies this, or by inspection of the reproduced picture.

The phenomenon exhibited in Fig. 7, rather well known to those in the magnetic tape recording industry, is due to self-demagnetization during the record process. The actual wavelength at which the peaking effect occurs in the playback voltage as a function of record current can be changed, within certain limits, by variations in the head design.

Another complicating element in the system is made up of the combination of a 6-db rise per octave of frequency together with a frequency varying attenuation of this characteristic due to core losses in the magnetic head. In view of the many variables, some dependent and some independent, of the type already mentioned, it might be rather interesting to note the results obtained some time ago when measurements were made on a laboratory machine from the input to the record amplifier through the output of the playback preamplifier. The machine had been set up for optimum picture under one given set of conditions. The amplitude vs. frequency curve was flat with no bumps or holes in the region from 750 kc to 6 mc with a gradual taper of about 2 db at 6 mc. However, it should not be concluded that this flat amplitude characteristic gives the desired performance under all conditions.

Head Life and Tape Life

When the engineering model was demonstrated at the NARTB Convention in Chicago in April 1956, we stated that the life of a set of heads was expected to be about 100 hours and that the tape life should be about 100 passes. At the present time we believe that the figures are conservative but do not wish to alter them until laboratory tests as well as field tests have been conducted on the prototype units. As the heads wear in, no degradation occurs in pictures reproduced from the machine. On the contrary, it is likely that some slight improvement in picture quality will be detected during the life of the head. This is due largely to the fact that the amount of shunting in the gap decreases as the head tips are worn down. As the shunting in the gap decreases, the heads become more efficient. It is difficult to say at this time whether or not such improvements will be detectable except by instrumentation.

The beginning of the end for a given head comes when the gap depth is reduced to zero, that is, to a chisel point. As the head continues to wear past this point the gap increases in width and the null frequency, due to gap effect, falls off correspondingly. However, the rate of wear is sufficiently slow so that when this point is reached the head will still be capable of making satisfactory recordings for some hours. The first signs in the reproduced picture of the end of the useful life of a head will be the appearance of a certain characteristic type of noise peculiar to this particular cause. This noise is for some time sufficiently small in its subjective effect on the picture so that for at least several recording and reproduction processes after the milestone has been reached the picture will still be commercially acceptable.

From the tests which have already been conducted it appears that, up to a certain point in the life of the tape, the reproduced picture will show little or no deterioration due to tape wear, and, in fact, in some cases may show an improvement in picture quality with reference to that type of noise denoted as snow. At this point, some deterioration in the picture will appear as an increase in dropouts, which would appear on the picture monitor as occasional short transients. Another type of deterioration which earlier appeared during the course of development of the system was a clogging of the head gap by the oxide or binder after a certain number of plays.

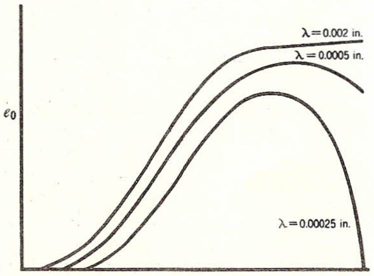


Fig. 7. Family of curves illustrating self-demagnetization effect.

This difficulty has been completely eliminated due primarily to the efforts of the tape people to improve their product for the rotary head video tape application. Unless a tape has been run for several times its recommended life, degradations in the reproduced picture due to tape wear do not affect the gray scale or the resolution.

A Note on Splicing and Editing

The machines now being delivered are to be used for the delay of network programs. They do not have special facilities for performing splicing and editing functions. On the first machine a tape can be cut with a pair of scissors and spliced with splicing tape. If a recording is made over such a splice there will be very little disturbance in the reproduced picture. If such a splice is made after recording, and the tape is then played back, a few seconds will be required for the control system to restabilize itself. We are fully aware of what the television industry wants in terms of splicing, editing and switching facilities in the regular production machines which will be delivered next year. Those machines differ primarily from the prototype run to be delivered this year in the fact that they are interchangeable, that is, any machine will be able to play back a tape made on any other machine. In addition, next year's models will incorporate facilities for splicing, editing and switching which we believe will be completely satisfactory to the industry.

The Modulation System of the Ampex Video Tape Recorder

By CHARLES E. ANDERSON

The modulation system will be considered first as to why such a system is necessary; then as to possible types of modulation; and finally a complete examination of the specific solution is presented.

Why a Modulation System Is Necessary

In an ordinary tape recorder operating in the audio range all of the problems encountered in higher frequency systems are to be found. Let us first examine the low-frequency end of the spectrum. At frequencies much lower than 50-c (cycles per second) the flux recorded on the tape changes very slowly per unit of tape length and the resultant voltage output is very low. If the speed of the tape were increased from a usual $7\frac{1}{2}$ in./sec to 150 in./sec, or an increase by 20, there would be difficulty in reproducing not 50 c but 1000 c. Since an ordinary television signal has frequency components as low as 30 cycles, the resultant reproduction from tape would be poor. The problem is well known and most of the high tape speed, direct recording systems have various ways to overcome the shortcomings.

The high-frequency end of the spectrum is a different situation completely. Here the problem is one of keeping a wavelength on tape greater than the gap of the playback head. This can be done in two ways: either by increasing the tape speed so a wavelength is stretched over a longer section of tape, or by decreasing the gap. Usually both are done. The ultimate in present techniques seems to be a gap stated as capable of producing 20 kc/in. of tape speed, which represents an 0.05-mil effective gap.

From these facts it can be seen that the two requirements are incompatible; but what is to be done? The question we asked ourselves over and over was if we could somehow process the video signal and fit it into the space available. The problem was further complicated by having the signal chopped at approximately a 1000-c rate by the rotating heads used in the Ampex process.

In studying the possibilities we came across unusual and interesting methods other groups had used at various times and in various fields to transmit the video signal. Of the more applicable methods the idea of modulating a carrier seemed most practical. This would solve the problem of low-frequency response but the high end problem would remain. An old rule of thumb that seems to be pretty true is that for reasonably low distortion with simple equipment, the carrier should be at least ten times the highest modulating frequency. This would have meant a carrier of 4 mc × 10, or 40 mc.

Further reflection, however, showed that the nature of a television signal makes it possible to tolerate high orders of a certain type of distortion (caused by the use of too low a carrier frequency) without degrading the picture as observed by the human eye.

[*Editor's Note:* The oral presentation at the Convention benefitted from the projection of two slides which it is not feasible to publish, due to the reduction in size necessary for the *Journal* page and due to the inevitable overall degradation in the processes of photoengraving and printing. The slides showed images respectively integrating and not integrating noise and distortions in successive frames. The image with integration was much more acceptable. It is recognized, of course, that photographic evidence of this kind must be used with great caution.]

It could be seen that the resolution wedge blurred at a frequency approximately 0.8 that of the carrier, demonstrating that very little of the available spectrum space would be lost by employing a modulation system with the low carrier frequency as described, while gaining much in simplifying the low-frequency problem.

Amplitude modulation was tried quite early in the experiments, but it had several disadvantages as far as using it with a rotating head system. Since four heads spaced 90° apart on a drum are used, any variation in head sensitivity or output would give stripes across the picture each of different video level or contrast. This could probably be compensated for by gain controls on a short term basis if it were not for another problem.

Each track is 10 mils wide with 5 mils between tracks. A head on playback is supposed to follow a recorded track exactly, but variations in tape velocity in the direction of tape travel (the 15-in./sec direction) will cause the head at least partially to leave the track thus causing a loss in carrier output. This resulted at the time in an undulating envelope on the carrier of perhaps 4 to 5 db peak-to-peak. Present machines, of course, are much superior in this respect to earlier laboratory models.

What all this means is that an instantaneous AGC system is needed. The problems in such a circuit are many, and the idea of IAGC was dropped after some preliminary thought was given it.

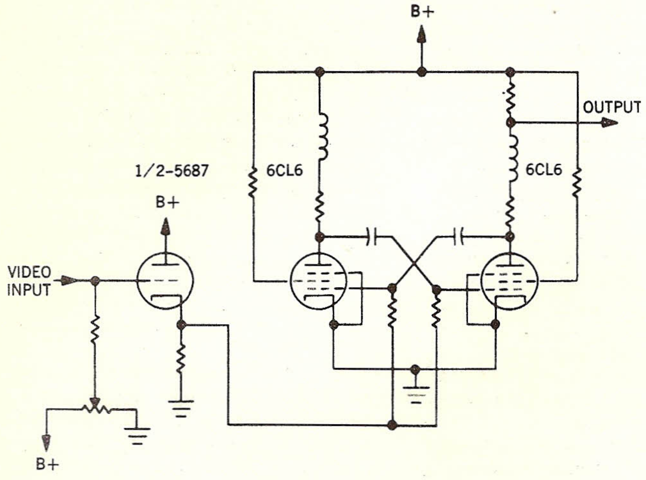


Fig. 1. Simplified schematic of modulator.

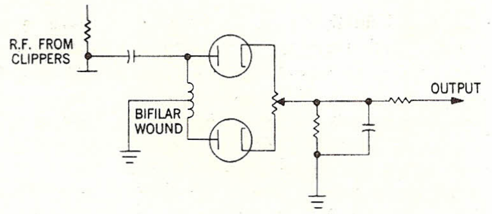


Fig. 2. Simplified schematic of demodulator.

It was recalled at this point that the Federal Communications Commission had conducted some experiments in 1949 to determine the feasibility of transmitting a television image by frequency modulation over existing channels. At that time the FCC was plagued with the co-channel and adjacent channel interference problems, and it was felt that FM might offer a solution. The results were excellent except for the problem of multipath phase distortion. The FCC sent us what data they had, and we resolved to try frequency modulation although several unknowns existed. We could find no mathematical derivation for what happened when the modulation frequency (f_m) approached the carrier frequency F. All the classical derivations* make the assumption that f_m does not approach F. Also, we wanted to violate the condition that $\Delta F << F$, where ΔF represents the derivation from the center frequency F.

Another question was what would happen when FM was transmitted with only one set of side bands.

By keeping β (where $\beta = \Delta F / f_m$) small, only one pair of side bands is generated. If β is 0.1 (meaning that the ratio of modulating frequency to deviation is 10:1), the second pair is only 0.1% of the unmodulated amplitude of the carrier. If β is 0.5, the second pair is still only 3% of the amplitude of the carrier while the first pair has increased to 24% of the unmodulated carrier amplitude. The first pair of sidebands occurs at frequencies $F \pm f_m$, the second pair at $F \pm 2 f_m$.

Further exploration by our associate Harold Walsh, was rewarded by the discovery of a paper published in 1948.† He gave an exact solution to the dominant equation for the case $\Delta F / F < \frac{1}{2}$. Mr. Cambi's resultant exact solution was still cumbersome for dealing with everyday problems; however he made several simplifications that gave an equation sufficiently accurate for most work and at the same time simple. Table I shows the results obtained from Mr. Cambi's equations as well as the more conventional Bessel function distribution. The conditions are:

$$\Delta F = 0.1\ F_c$$

$$f_m = 0.1\ F_c$$

$$\beta = .0.67$$

Table I. Analysis of Sideband Energy Distribution Showing Proximity of Values Calculated by Various Methods.

Spectrum component n	Exact solution (Cambi) I	Approximate solution (Cambi) II	Conventional solution (symmetrical) III
−5			.00003
−4	.00002	.00002	.00056
−3	.00130	.00108	.00673
−2	.02883	.02501	.06001
−1	.28619	.26036	.35333
0	Unity	Unity	Unity
1	.43754	.41007	.35333
2	.11057	.10043	.06001
3	.02157	.01915	.00673
4	.00360	.00314	.00056
5	.00054	.00046	.00003
6	.00007	.00006	
7	.00001		

Column I is the exact solution. Column II is from the approximation and Column III is the usual Bessel function method. Of particular interest is the lopsided distribution and the fact that the example does not include folded lower sideband components.

Table II is the tabulation of sideband components calculated from Mr. Cambi's approximate equations, for a different set of parameters. The parameters were chosen to represent typical values in use in the Ampex system.

$$F = 5\ \text{mc} \qquad \Delta F = 1\ \text{mc}$$

The general drift of the sideband distribution is more exaggerated than in Table I. While the FM in Mr. Cambi's computation assumes sinusoidal transitions, and in the Ampex system is obtained with a multivibrator, this general drift is still illustrative.

In a single sideband transmission of AM we need only transmit enough of the extra sidebands to insure that the filter does not introduce too much phase shift at the carrier frequency. In FM however, one has to think of both sidebands, carrier and instantaneous frequency. The instantaneous frequency is what does the work, and it is created by the sidebands. At least, therefore, either all upper or all lower sidebands must be transmitted, but since ΔF does the work, we must also transmit both its upper and lower excursions. This means that in our case if F = 5 mc, f_m = 4.5 mc, and ΔF = 500 kc, then the system should have a passband extending at least from 5 − 4.5 or 500 kc to 5 + ΔF or 5.5 mc.

Table II. Sideband Energy Analysis Using Simplified Calculation.

Spectrum component	Modulating Frequencies, f_m			
	1 mc/s	2 mc/s	3 mc/s	4 mc/s
A_5	.007			
A_4	.025	.007	.004	.002
A_3	.087	.030	.016	.015
A_2	.264	.118	.068	.068
A_1	.654	.408	.328	.289
A_0	Unity	Unity	Unity	Unity
A_{-1}	.356	.112	.030	.008
A_{-2}	.039	.002	.008	
A_{-3}	.002			

The Factor of Signal-to-Noise

One major item of interest remains that has not been discussed as yet, and that is the question of signal-to-noise. If an AM carrier were used, the signal-to-noise of the detected signal would be roughly the same as that of the carrier and the same as that of a direct recording. With FM, as everyone knows, the situation is quite different, and unfortunately the different situation is not a favorable one. In ordinary FM broadcasting β is quite large and the bulk of the transmitted energy is in sidebands, and the ability to reject noise is superior to AM. As β is decreased, the advantage de-

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* August Hund, *Frequency Modulation* (New York, McGraw-Hill Book Co., 1942), pp. 347–351.

† Enzo Cambi, "Trigonometric components of a frequency-modulated wave," *Proc. IRE, 36:* pp. 42 et seq., Jan. 1948.

creases and finally disappears when the FM sideband energy is less than that in 100% amplitude modulation. Since $\beta = \Delta F/f_m$, in audio FM broadcasting the smallest β possible is 75 kc divided by 15 kc, or 5. In the Ampex video system the deviation is 1 mc and f_m is 4 mc, giving a β of 0.25 and resulting in a wide band signal-to-noise figure inferior to AM. As was previously pointed out, however, FM does solve the low-frequency variations in carrier output that rule out AM, so FM is the more rewarding solution, and adequate effective signal-to-noise ratio can be achieved by additional means.

A Practical System

Up to about 6-mc carriers where the deviation does not exceed 1 mc, a multivibrator type of oscillator whose frequency is changed by applying video directly to its control grids seems to be satisfactory and is certainly the simplest so far as circuitry is concerned. Figure 1 shows the essential parts of the modulator.

Two 6CL6's serve as a multivibrator in which special consideration has been given to reducing the switching time, and the grids of the 6CL6's are driven by the 5687 cathode follower. The output of the multivibrator is amplified by conventional wideband amplifiers and then applied in parallel to the head driving amplifiers which consist of two 815 tubes.

On playback the signal from the switcher is applied to a wideband cascaded clipper and from there to the slope detector shown in Fig. 2.

The last stage of the clippers is coupled to a bifilar wound coil whose center tap is grounded. The coil is made to resonate at a frequency out of the passband and the skirt of the resonance curve is used as an FM to AM translator. The AM is full wave rectified and turned into video by the two diodes. The variable resistor is a balance control to equalize the rectified carrier components of each diode, which balancing reduces the severity of requirements on the output filter (not shown).

The resonant frequency and Q of the coil are carefully chosen for maximum linearity. Linearity has not so far been found a problem with the tape recorder.

Acknowledgment

The author wishes to credit his associate, Harold Walsh, who supplied much of the theoretical help and provided the broad background material that now forms the solid base upon which our methods rest.

Rotary-Head Switching in the Ampex Video Tape Recorder

By RAY M. DOLBY

The problem of commutation and switching for rotary-head tape recorders is not one which dictates a singular solution; rather, in the course of our investigations we have found many approaches feasible, in varying degrees, of course. Our purpose in this paper is to present an indication of what has already been accomplished in the way of a workable product, even if admittedly it is not to be considered the ultimate. However, the present form of the switching scheme may better be understood and appreciated if first a few of the less successful approaches, with their attendant merits as well as pitfalls, are reviewed.

FRANKLY, the fundamental problem is that the Ampex system uses four heads on a rotating drum. Practically, this means that the final r-f output signal is not continuous, but must be synthesized from portions contributed by each of the four rotary heads. In the early stages of the experimentation, switching between the various heads was not employed, nor was it deemed necessary until further information was gathered regarding frequency response, signal-to-noise ratio, and modulation schemes, as well as the mechanical considerations of tape guiding and head tracking on playback. Thus, as shown by Fig. 1, the experiments were made with all four heads wired in a series circuit, from which a common output was obtained.

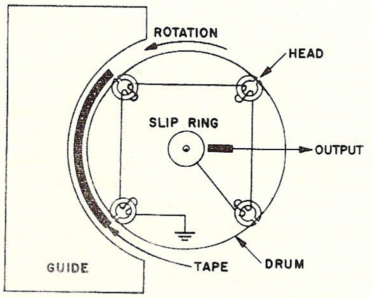

Fig. 1. The basic commutation technique.

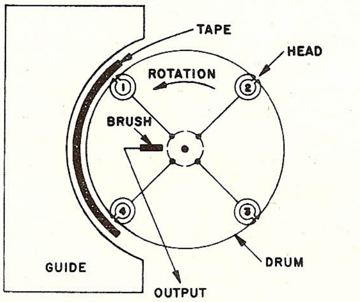

Fig. 2. Mechanical switching system.

With this arrangement there could be no audio track, of course, and also to avoid the use of a control track, a servo system was devised which employed the longitudinal magnetic components of the vertical sweeps on the tape. The radius of the head structure was designed to allow one head to enter the tape just as the previous one was leaving, and it was thought that a substantially continuous output signal could thus be realized. But it did not take long to discover that there was a serious interruption where the entering head began its track, due to tape slapping and to possible cancellations in the carrier signal.

Even before the initial experiments were complete it was obvious that switching the heads during an overlap interval would be imperative if continuity of output signal were to be obtained (Fig. 2). The first reaction might be that a mechanical slip ring switch would suffice; however, a brief arithmetic consideration will show that this is not workable. Specifically, the switching must be done within, let us say, 0.1 μsec, to be consistent with the desired bandpass of the system. A tenth of a microsecond, for a relative head-tape velocity of 1500 in./sec, represents 0.15 mils on the periphery of the drum. A suitable slip ring switch-

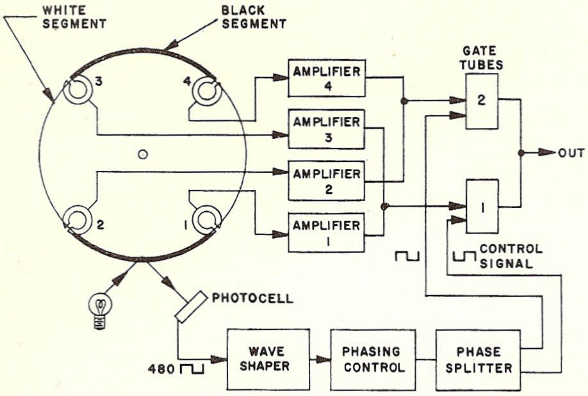

Fig. 3. Electronic switching system.

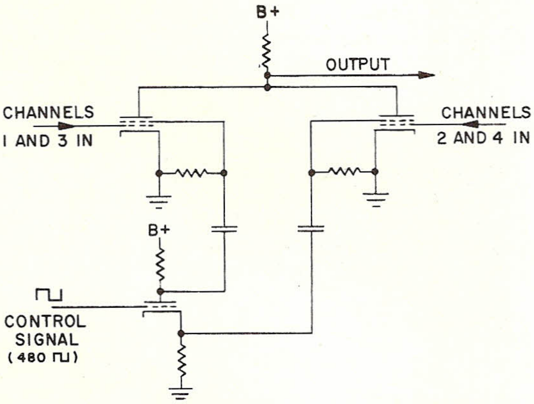

Fig. 4. Basic switching circuitry.

ing assembly would be approximately $\frac{1}{2}$ in. in diameter, for example, which means further that the distance in which the switching should occur must be about 0.04 mil on the periphery of this rotary switch. This is clearly a very difficult thing to achieve with known types of brushes, particularly when these brushes must have the necessary durability for high-speed operation.

The next approach which suggests itself is that of the electronic switch (Fig. 3). Possibly the simplest arrangement in this category would be the ruse of pairing two opposite channels, such as 1 and 3, and 2 and 4, so that it is necessary only to switch between the two paired channels to obtain a continuous output.

Gearing the switching time to the angular position of the wheel can be accomplished in several ways, including the use of magnetic pickups or photocells. Photocells have been found most satisfactory in obtaining the switching signal, as they have the advantage of being insensitive to magnetic fields, which the drum motor supplies in copious quantities. In addition, they also deliver a high output voltage in the order of 10 v peak-to-peak, so that amplifying circuitry following the photocell is relatively simple.

The wheel is painted alternately black and white in four segments. The output of the photoelectric cell will thus be two full square-wave cycles per revolution of the drum, which, in the case of the present speed of 240 rps, amounts to a square-wave output of 480 c (cycles per second). With apertures of the light source and photoelectric cell such that the resulting square wave has a rise time of approximately 100-μsec, a compromise is obtained between rise time and output voltage. The 100-μsec rise time, amounting to about one tenth the duration of a half-cycle, has been found quite satisfactory, since, even though the wave has ultimately a rise time in the order of 0.1 μsec or less, total phase drift can be held to a very few microseconds. Control over the timing of the switching process without resort to the awkward operation of repainting the wheel is obtained with a phasing control.

The controlling 480-c square waves appear in two polarities at the suppressor grids of the gates, which may be tubes such as 6AS6's or 6BN6's. These tubes have characteristics such that the suppressor grid must be positive (relatively) before the tube will conduct the signal applied to the properly biased control grid. The 6AS6 tube has a grid structure similar to that of a standard pentode, with the exception that a pronounced and easily controllable virtual cathode forms between the screen and suppressor grids. In effect, the virtual cathode, suppressor grid, and plate may be treated as a triode section with consequent excellent controlling characteristics by the suppressor grid. The 6BN6 is of different construction, being designed primarily as a limiter, but, like the 6AS6, it has good controlling characteristics due to what we can conveniently call the suppressor grid. Most linear operation has been obtained in both the 6AS6 and the 6BN6 by applying the incoming r-f signal to the control grids, and applying the switching signal to the suppressor grids.

Figure 4 shows typical circuitry. With control grid biases adjusted so that the d-c components of the plate currents will be the same for both tubes, the r-f output of the switcher is taken from the common plate load resistor. This two-channel switcher was acceptable until the signal-to-noise ratio began to be limited by the noise added by the channel opposite from the head actually sweeping the tape. That is, at any given time, signal is being supplied by only one head, whereas noise is being added to the output by two heads. Theoretically, considering wideband noise only, the resulting signal-to-noise ratio of the composite signal should be only 3 db worse than the ideal of having only one legitimate contributor at a time. Practically, however, a greater loss than this is suffered, since in many cases the noise amplitudes may add, as they would with a local powerful AM station being the noise generator (in which case the two noises could add in phase instead of at random).

Another baneful circumstance is that the outputs of all four heads may not be of the same amplitude, making consequent increase in the gain of the low channels necessary. The effect on the screen is that if the gain control on one of the preamplifiers were increased, more noise would appear in the band corresponding to the channel opposite from the one in question. A residual effect of this type is found even with FM recording.

Crosstalk, too, is another effect which plagues the two-channel switcher. The output from the head which is contributing signal may, in the head structure or in the associated wires and commutation means, be capacitively or otherwise introduced into the illegitimate channel. This output may add in irregular and unpredictable phase relation to that from the legitimate channel, to give a distorted resultant.

When it became known that the two-channel switcher was indeed a major contributor of noise to the overall system, a four-channel sequential switcher was devised. The advantages, of course, can be implied from what has been just said about the two-channel switcher; that is, one realizes fully independent control over the effect each channel has on the composite output. In order to accomplish the necessary sequential switching operation, various means could be employed. For instance, a binary count-down scheme could be utilized so that one revolution of the wheel would cause all four switching tubes to be energized sequentially. Another approach might be a triggered sequential multivibrator. However, with the disadvantage of instability, it might be difficult to insure that the heads will switch during the correct 90° interval.

The system which has now been worked out for use in the Ampex recorder overcomes some of the disadvantages of sequential multivibrators or count-down systems. Using a network of coincidence

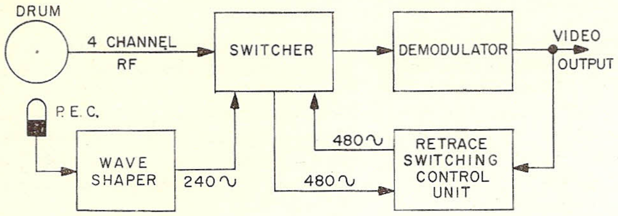

Fig. 6. Retrace switching system.

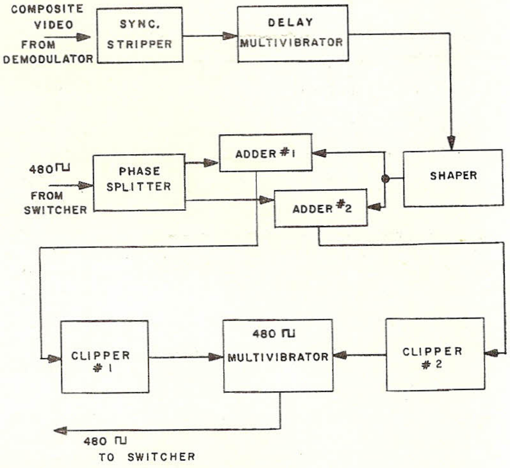

Fig. 7. Retrace switching control unit.

going positive a short time after the r-f signal appears at the control grid of gate 1. The 480-c square wave on the supressor grid, together with the properly biased signal at the control grid of the gate tube, causes the tube to conduct, the resulting r-f signal appearing in the common output circuit of all four gates. It can be seen that at the control grid of gate 2 the r-f signal next appears, waveform D. Waveform J at the suppressor grid of this tube is seen to be going positive shortly after the r-f signal appears on the control grid, and so gate 2 is energized. The reverse phase of the 480-c square wave simultaneously turns off gate 1 so that gate 2 is the only tube conducting. And so the switching goes through its sequence of all four channels and then repeats.

Up to this point there has been nothing introduced in the commutation or switching system, as well as the modulation system, that obligates the video tape recorder to be used in conjunction with a video signal. For example, if the video tape recorder does not have the best signal-to-noise ratio of any audio recorder known to date, it certainly has the flattest frequency response.

Finding the machine to be a rather prodigious audio recorder, we set up an even more interesting and ambitious task. An AM antenna was connected to a wideband preamplifier which was in turn fed to the standard 75-ohm input of the video tape recorder. The recording level was observed on the oscilloscope and adjusted to be the usual 1.4 v. The net consequence of the recording process was that the whole AM band was recorded intact, modulated on the FM carrier. With playback operation as usual, the output was taken from the demodulator 75-ohm output and fed to a standard broadcast receiver. Tuning could be accomplished up and down the band with no difficulty.

Some interesting sidelights came out of this experiment. The wideband tape recorder has a signal-to-noise ratio of about 30 db, by usual methods of video measurement. However, when the AM subcarriers are handled they may be recorded more than 40 db down with respect to peak recording level, and yet the resultant demodulated output after both FM and AM detection will be one which is easily recognizable. Of course, the answer lies in the bandwidth reduction effect which the AM receiver imposes on the signal. In only a 10-kc bandwidth the probability of noise appearing is correspondingly low. Indeed, multiple narrow channel recording is a technique which yet remains to be exploited.

Experiments were carried on for some time with the tape recorder in the form which has been described; however, when the signal-to-noise ratio of the system began to improve due to better electronics, better head construction, as well as smoother tapes, switching transients in the picture became more and more obvious. The spots, occurring in the form of little black and white dots on the screen, come from two causes:

(1) The first, and probably most obvious cause, is that of transients generated in the switcher. For instance, d-c currents in the sequential switching tubes may not be balanced, so that a sharp spike is generated in the r-f output. Also, capacitive coupling between the suppressors and the plates of the gate tubes may transmit some of the switching signal to the output.

(2) A more subtle defect lies in the possible change in carrier phase, switching from one channel to another. Let us say that the phase of the carrier in channel 1 may be 0°. The switch is then made to channel 2, in which the phase may be 180°, so that if a half-cycle is just completed in channel 1, the same half-cycle will again occur in channel 2. Interpreting this phenomenon as a sharp downswing in frequency, the demodulator delivers a black transient to the picture.

In the investigation of this effect, a rather interesting experiment was made. The output of the FM record modulator was fed to the inputs of the four-channel switcher, with the insertion of a variable delay line in one channel. By reducing the delay to zero, the switching transient can be made practically invisible on the screen. However, as the delay in the one channel is introduced, the transient begins to appear in greater magnitude as the delay discrepancy is made larger, until finally after 360° of delay, the transient disappears as would be expected. For a while, serious consideration had been given to the development of a super-fast electronic switch — that is, one which could complete the transition within 0.01 μsec. However, when the phase-shifting phenomenon came to light, it was apparent that a faster switcher would not be the way to effect a net reduction in the observed transients on the screen.

So another tack was made. Using characteristics of the data to be handled, one can reduce obvious defects in the reproduced signal to a minimum. Specifically, the retrace interval of the video waveform can be turned to good advantage by providing a handy camouflage for the switching operation. Unfortunately, however, this cannot be handled by causing the pulses always to be recorded in the same position on the tape — the last pulse in any sweep appearing one-quarter inch from the bottom, for instance. Hunting of the drum in the recording process precludes such a seemingly simple solution.

The electronic artifice finally settled on is shown in Fig. 6. The method can be reduced to a "get ready — go" process which occurs in the retrace switching control unit. The photocell provides the "get ready" information, the sync pulses of the demodulated video output contributing the "go" signal.

Breaking the point marked **X** on Fig. 5, one obtains a 480-c square wave, subsequently sends it to the retrace switching control unit for modification, and then returns it (its offspring, more precisely) to the switcher where this wave performs the usual function of switching the signals.

A supplementary item in the video tape recorder, the retrace switching control unit may be put in and out of the switching operation at will. When tests are being made with sine waves or other

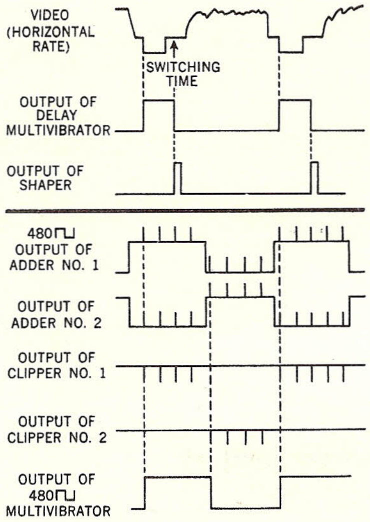

Fig. 8. Waveforms – retrace switching control unit.

nonvideo waveforms, the retrace control is usually out so that switcher is controlled only by the angular position of the drum, and is not related to the character of the signal coming off the tape.

Figure 7 shows in greater detail the operation of the retrace switching control unit. The core of the device is a 480-c multivibrator which is locked by the joint efforts of the photocell signal and the demodulated synchronizing pulses. The philosophy is that after the 480-c incoming signal changes in polarity, the output of the retrace switching control unit will flip over in response to the arrival of the next synchronizing pulse.

Video signal is obtained at standard operating voltage from the demodulator, the signal being amplified and sent to the sync stripper. Locked by these synchronizing pulses, a 15.75-kc multivibrator is used to provide a variable time delay, so that the exact time at which the switching operation occurs can be controlled over certain limits. That is, it has been found optimum to position the switching time so that it occurs on the back porch interval, which, as far as the picture is concerned, places the switching transients on the extreme lefthand side of the screen, just out of the field of view. This must be done with some accuracy, near the middle of the back porch, to prevent the transient from appearing on the retrace line.

Serving another purpose as well, the delay multivibrator, in the event of video signal failure, will continue to send triggering pulses to the 480-c multivibrator so that continuous output is obtained from the retrace switching control unit regardless of the nature of the incoming signal, video or otherwise. For example, if a synchronizing pulse should be missing from the train coming off the tape, and it is time for the switcher to move to the next head, the unit will wait an apportioned time and, with no synchronizing pulse in sight, will flip to the next channel of its own volition, resulting in no loss in signal from the tape. The output of the delay multivibrator is fed to a wave shaper, after which the pulses are added to two polarities of the 480-c signal. The two composite signals are introduced to clippers one and two, the outputs of which synchronize the 480-c multivibrator. The output from this multivibrator is injected back onto the main switching unit and is used to control the switching operation itself.

Figure 8 will clarify the exact nature of these wave-shaping operations. The top waveform is that of the horizontal rate of the standard video signal. The second waveform is the output of the delay multivibrator. The trailing edge of this output wave is differentiated and, as indicated in the third waveform, is the signal which ultimately controls the exact switching time. The two 480-c outputs of the adders are seen in the fourth and fifth waveforms. With the pulses derived from the synchronizing pulses superimposed on these waves, these signals are then fed to their respective clippers, emerging as bursts of triggering pulses. Of this series of negative-going pulses, approximately 2 μsec long, only the first is effective in locking the 480-c multivibrator. The multivibrator is synchronized in such a manner as to deliver to the output a signal always of the same polarity as that which has come in, except that the leading and trailing edges jump back and forth in discrete time steps of one line.

To illustrate the timing of various events, approximately 18 television picture lines are recorded per sweep, the net overlap on the tape from one channel to another being about two lines. Thus, the most desirable timing of the "get ready" signal, derived from the photocell, would be for its polarity change to occur one-half line after the overlap period starts. Then, after the readiness signal has arrived, the 480-c multivibrator is conditioned to accept the next synchronizing pulse which should come from the tape. This means that the switching operation conceivably could occur anywhere between one-half line and one and one-half lines after the beginning of the overlap interval. With a guard time of one-half line at the beginning and end of the overlap period, drift or maladjustment in the switching circuitry can be accommodated.

Subjective improvement of overall picture quality due to the use of the retrace switching control unit has been found to be fairly great, since no longer are the usual black and white specks due to the switching operation seen randomly coursing across the screen. Transition from one head to another through the use of the device is invisible.

Undoubtedly, more clever means of performing the whole switching operation can and will be contrived, but up to this time the devices of gearing the transition to the angular position of the rotary drum, as well as to the timing of the synchronizing pulses coming from the tape, have appeared to give satisfactory results.

Discussion

Leonard A. Herzig (*Prestoseal Mfg. Corp.*): Referring to the diagram of the 240-cycle interlock and your references about recording across the tape and then cutting out from 120° down to 90°, is there a special interlock on the reproduction end, one that allows the heads to be on for only 90° and on the recording end for 120°?

Mr. Ginsburg: No. During recording all heads are being fed current continuously. The amount of video-track information left on the tape after the tape has passed the control track and audio heads is slightly more than what has been written during 100° of arc. This leaves enough information overlap for the switching process which is accomplished during playback between consecutive head outputs. This will be covered in detail in a later paper.

Mr. Herzig: Is the width of the track 10 mils?

Mr. Ginsburg: It's approximately 10 mils.

Mr. Herzig: And the angulation of the track, actually, as it appears on the tape, is approximately what?

Mr. Ginsburg: Very small, since the tape travels 15 mils in 1 msec and the drum, during this time, is tracing out a path about 100 times this distance.

D. McCroskey (*American Broadcasting Co., Burbank, Calif.*): It isn't quite clear how you maintain perfect tracking on the playback process. Is it a function of the control system?

Mr. Ginsburg: We do not have to maintain perfect registration of the heads on the tracks. One of the principal reasons for using the special type of frequency modulation system employed is to make it unnecessary to have perfect registration during playback. Within limits which are met quite easily with this machine, the effect of tracking error is essentially undetectable. Several decibels of variation in amplitude of the r-f playback signal due to failure of the heads to register properly on the recorded tracks will result merely in the loss of signal-to-noise ratio. Very roughly, there is about a 1:1 correspondence between attenuation in db of the r-f amplitude due to tracking error and loss in signal-to-noise ratio as measured in the video output of the machine. A 20% tracking error would mean that the head is in its proper position with respect to the recorded track within 2 mils.

Mr. McCroskey: Does the spacing act as a guard band, then, to eliminate tracking two strips at once?

Mr. Ginsburg: Yes, we have to allow enough space so that the head can get as far off the track as it can get, still being able to make a satisfactory picture with respect to signal-to-noise ratio and at the same time not pick up the information on the next track.

Anon.: As to the ability of your system to make prints and, if you do make prints or duplicates from the original, what is the degradation?

Mr. Ginsburg: The degradation is extremely small. Nothing is lost in gray scale or in resolution. The only degradation that would occur would be in noise, but the degradation is small.

Don Wald (*Univ. S. Calif.*): This wheel that you describe, is that for black-and-white video? And, if so, what type of applications do you have to make for color? Do you have to increase the number of wheels or number of heads on the wheel?

Mr. Ginsburg: We're going to take, I believe, the same attitude with regard to talking about our color TV recording as we have taken in the past with regard to the development of the monochrome system. We aren't going to say anything about it until we have it finished.