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Engineering procedures used in the design and construction of a high-speed, multi-channel magnetic tape duplicator are described. The completed duplicator, a common mandrel duplicator in which a single drive motor turns a common capstan shaft at high speeds and moves both master and copy tapes simultaneously, performs satisfactorily yet suggests design modifications for a second-generation machine.

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The Southwest Regional Laboratory decision to use short audio tapes to assist in the training of teachers and supervisors required that multiple copies of a particular instructional audio tape be available. The number of tapes needed was sufficient to necessitate a rapid duplication of the master tape, but it was not enough to warrant contracting the job to a professional high-speed duplicating operation. To provide the Laboratory with the needed facility and at the same time to investigate the tape-duplicating field, a compact magnetic tape-duplicating unit of simple construction was designed and built.

TAPE-DUPLICATING METHODS

Design of a tape duplicator employing one of several duplicating methods was possible.

1. Master and multiple slaves running at normal speed with common start-stop control.
2. Master and multiple slaves running at faster than normal speeds with common control.
3. Direct master-to-copy magnetic transfer recording using a high coercivity master and an environmental flux to ease the transfer.
4. A common mandrel duplicator in which a single drive motor turns a common capstan shaft at high speed and moves both the master and copy tapes simultaneously.

Method 1 is easy to set up provided enough recorders are available. The overall production is low and the results are only as good as the quality of the recorders used. If the slave recorders run off-speed or have noisy bias oscillators, the duplicates will be of varying quality. The large number of components, especially gain controls, reduces the predictability of consistent output.

Method 2 is a faster duplicating method, but requires higher quality recorders if the results are to be adequate. Since all of the audio frequencies will be multiplied by the speed-up ratio, each amplifier must be equalized for the higher frequency band. Ordinary recorders are not designed to satisfy these requirements. A speed-up ratio of 2 to 1 is the usual maximum if reasonable fidelity is to be attained. Speed and bias noise considerations are the same as for Method 1.

Method 3 is attractive because less equipment is involved than in Methods 1 and 2, but it nevertheless has major drawbacks. The maximum level that can be transferred is limited by the coercivity of the master tape. Good frequency response requires intimate contact between the master tape and the print stock. Low overall production can be increased with use of multiple masters but with loss of the minimum-equipment advantage.

Method 4 has a common drive capstan that tends to cancel out speed variations due to power train aberrations or line voltage changes. Since variations in speed are common to both master and copy, they do not affect the quality of the recording. The number of required electronic components is minimal since the one amplifier serves as both playback amplifier and record head driver. Due to high speed-up ratios, the pass band of the combined amplifier is designed specifically to provide proper equalization at the multiplied signal frequencies. Because of these several positive features, Method 4 was chosen for the design task.

DESIGN FEATURES

Speed-up ratio. A speed-up ratio of 8 to 1 was a reasonable compromise between tape handling and productivity. The release speed of the copies was specified to be 3 3/4 inches per second. The duplicator tape speed was therefore 30 i.p.s. (8 x 3 3/4 i.p.s. = 30 i.p.s.).

Duplicator productivity. With a duplicating speed of 30 i.p.s., the running time for a 10-minute release tape will be 1.25 minutes. Loading time will be proportional to the number of copies being made at one pass. Increasing the number of copies to be made at a time will not increase the productivity in a linear fashion. Duplicating time per copy is determined as

$$T_c = \frac{K + NT_1}{N}$$

where

K = running time of duplicator

T_1 = loading time per channel

N = number of channels in use

T_c = time per copy

It was determined that an increase past 10 channels will not significantly increase productivity. Ten was therefore chosen as the optimal number of copies to be produced at one time.

Take-up tension control. An innovative friction drive offering many potential benefits and possibly some pioneering problems was used to provide take-up torque for reels that wind up tape coming from the capstan.

The method was made up of a shaft with 10 rubber tires which fit nicely between the reel flanges and was driven by a common slip clutch and pulley arrangement working off the main drive belt. Restraint was installed for the reels to keep them in position during recording. This was insured by a common roller and a flip down pressure system.

The choice of reel size for this particular duplicator was established by the amount of tape required for 10 minutes at 3 3/4 i.p.s. Although 3-inch reels could have accomodated enough tape, the small-diameter reels would have caused problems on some school recorders. Therefore, even though they were more expensive, it was decided to standardize on 4-inch reels.

Maximum speed at which the take-up reel must turn for a 4-inch reel is calculated as

$$C = 3.1416 \times 1.5 = 5 \text{ inches}$$

$$T = 30 \text{ (i.p.s.)} \times 60 = 1800 \text{ i.p.m.}$$

$$\frac{T}{C} = \frac{1800}{5} = 350 \text{ r.p.m. maximum reel speed}$$

where

C = circumference of the take-up reel hub

T = tape length to be coiled in one minute

With a 4-inch diameter reel and a 1½-inch diameter rubber drive tire, drive wheel speed is

$$\frac{4}{1.5} \times 350 = 930 \text{ r.p.m.}$$

Since the motor is to run at 1800 r.p.m. and will have a pulley diameter of 1½ inches, the reel drive pulley diameter will be

$$\frac{1800}{930} \times 1.5 = 2.9 \text{ inches}$$

The capstan drive system. A capstan drive system must have a high degree of precision if recordings are to be of acceptable fidelity. The capstan shaft must be ground to virtually perfect trueness and it must have enough rigidity to resist deflection. The manufacture of such a shaft requires the ultimate in machine shop technique. A ready made unit satisfying the stringent requirements was found in a Danley precision die guide post. A post with a diameter of 1.25 inches and an overall length of 10 inches was bought off-the-shelf.

Bearing requirements for a capstan are not easily satisfied with ball or roller bearings due to eccentricity. Sheet teflon was therefore used as bearing material, supported with adjustable aluminum housings. The adjustable housings can be set for minimum clearance consistent with acceptable friction. Provision is made for lubricating with a good quality of engine oil. Thickness of the teflon bearing material is .010 inches.

$$\text{Capstan r.p.m.} = \frac{\text{tape length moved per minute}}{\text{capstan circumference}} \quad \frac{30 \times 60}{1.25 \times 3.1416} = 460$$

Capstan drive wheel diameter is found from

$$\text{diameter} = \frac{1800 \text{ (motor speed) } \times 1.5 \text{ (motor pulley diameter)}}{460 \text{ (capstan speed)}} = 5.9 \text{ inches}$$

A crowned cast steel wheel was located that had an outer turned diameter of 6 inches and an inner bore that could be machined to shrink-fit over the capstan shaft. Due to the relatively low capstan speed, it was not considered mandatory to balance the flywheel pulley.

The drive belt for this design had to meet several critical demands:

1. It had to be of seamless construction.

2. It had to be very flexible.

3. The running surface had to develop reliable friction.

4. Oscillating tendency had to be minimal.

All of these specifications were met by using a rubber-covered fabric high-speed grinder belt, procured from a local bearing supply house.

Adequate belt wrap-around was ensured by mounting a ball bearing idler pulley between the take-up pulley and the capstan flywheel.

Adjustment of belt tension was achieved by moving the motor within its slotted mounting pads.

Motor selection. The choice of suitable motors for this application was somewhat limited due to the uniqueness of the task. With 10 pressure rollers and 10 take-up reel slippages to be powered, the torque requirements dictated a substantial power source. Motors designed for tape recorder use are mostly under one-tenth horsepower and obviously are not adequate. Search through a Bodine Electric catalogue revealed a stock design that had all of these necessary features:

1. Synchronous operation at 1800 r.p.m.

2. Capacitor-start/capacitor-run using an extra winding for getting a stationary mass moving.

3. Quiet operation.

4. Ball bearings for resisting the side thrust of a belt drive.

5. Convenient mounting base allowing adjustment of belt tension.

6. One-fourth horsepower continuous rating.

Pressure roller system. Correct pressure of each of the tapes to the drive capstan dictated that a separate roller be used for each of the 11 tapes. Since it was not predictably possible to make 11 rubber wheels of exactly the same size, each of the rollers was mounted on its own spring-loaded arm. The 11 arms hinged around a common shaft made of drill rod and were pressured into position by a common lever system.

Stock rubber rollers of 1-inch diameter were located at a local parts house. These came equipped with a sintered bronze bearing made to fit over a .250-inch diameter steel shaft. The possibility of making the assembly of .250-inch diameter shafts to the pressure arms true enough to eliminate skew did not seem very certain. To make sure that the shafts would be true, the bronze bushings were pressed out and turned. That allowed for a .011-inch clearance for a sheet teflon bearing. With the stationary bushings being of a larger diameter and faced off in the lathe, the result was that no alignment of the pressure rollers was required.

Tape guiding. Accurate positioning of the tape flow past the heads was assured with two adjustable guides for each head. These chrome-plated guides thread onto two transverse threaded rods. One rod precedes each head and one follows. A spring-loaded, felt-covered finger presses each tape into its first guide to ensure contact of the tape to the record gap. The pressure fingers are mounted to the pressure roller arm assembly and are pulled out of the way during loading operations.

Head alignment. It was essential that each of the record head gaps be exactly perpendicular to the tape path in order that the release copies exhibit proper high frequency response.

An azimuth alignment tape was made on an Ampex studio machine known to be in good alignment. Since the recording gap was much wider than a playback gap, it was not possible to use a test frequency as high as would normally be the case. In this instance the azimuth tape was recorded at 10 kilocycles at a speed of 15 i.p.s. When this tape passed over the head at 30 i.p.s., the resultant 20 KHZ was high enough to give a sharp azimuth setting. Each of the heads was connected in turn into an amplifier and then into an oscilloscope. With the alignment tape passing over the head, it was adjusted for maximum output.

Recording bias. Radio frequency bias current is a basic requirement for analog recording on magnetic tape. In a high-speed tape duplicator using a signal pass-band of over 100 KHZ, the bias frequency must be around 500 KHZ to eliminate the possibility of beat phenomena. The wave form must be devoid of harmonics. Enough power must be developed to provide bias current for the 10 record heads. A circuit and components developed by Nortronics Company was used to build the oscillator. Two TO-5 case-size transistors with added heat sinks were connected in a balanced Colpitts arrangement. The resistor in the collector winding aided in maintaining balance.

Capacitors and variable resistors were used to vary the bias current for optimum output. An additional playback head that could be positioned after the record head permitted a ready setting of the bias.

Amplifier. The amplifier used in this application had to perform the following functions:

1. Increase the output voltage of the playback head to the level required for driving the record heads.

2. Correct the frequency response of the playback head output to remove the velocity effect and to reinsert the proper pre-emphasis equalization needed in recording.

3. Accommodate the increased pass band due to the 8 to 1 speed-up ratio.

4. Give a firm source for the recording driver circuits.

Based on favorable experiences with the basic two-stage transistor amplifier using overall A.C. and D.C. feedback, it was decided to use two of these units in cascade. By starting with maximum gain amplifiers and adjusting gain with feedback, a substantial amount of preliminary data collection and theoretical calculations was eliminated.

In line with usual practice, feedback around the first two stages tailored to give an inverse gain versus frequency characteristic was used. This method ensured that the playback head would not be loaded excessively at the higher frequencies, since input impedance increased with feedback. Recording pre-emphasis was added by a passive R-C coupling network to the following two-stage amplifier. The output amplifier had non-frequency selective feedback for overall gain control and source impedance reduction.

A tuned filter was inserted between the amplifier and the recording bus to keep bias frequency signal out of the feedback circuit. Because the recording head was highly inductive, a means had to be found to keep a constant current versus frequency characteristic in the recording circuits. In this case a fixed resistor was provided for each of the 10 recording heads. Bias was inserted into each recording circuit via a variable resistor and a 100 picofarad capacitor. Record level monitoring was provided by a standard volume unit meter with its own bias rejection filter and sensitivity control. Mechanical construction of the amplifier was greatly simplified by using a method developed by the author for this purpose. All components, including transistors, were fastened to an aluminum panel using liquid neoprene. This method was very fast and eliminated vibration problems. All leads were on the same side of the panel as the components, thus simplifying servicing and also reducing the effects of stray capacity. Removal of any component for modification or repair was made by loosening the adhesive with benzine.

Control system. Twenty-four-volt D.C. relays were used to control the drive motor and the two shaded pole motors that handle the master tape.

When the start button is pressed momentarily, RL-1 pulls in and latches thru a holding contact. Simultaneously, RL-2 is pulled in through a silicon diode from the coil of RL-1. These two relays apply power to the drive motor and the master take-up motor. Stop relay RL-3 is photo-electrically controlled through a tape opacity sensor mounted inside the right hand master tape guide.

The tape leader and tail fastened to the master allow more light to pass than does the magnetic tape. While the magnetic tape is passing through the tape guide, there is insufficient light input into phototransistor Q1 to drive power transistor Q2 into the conductive state needed to operate RL-3. Normally closed contacts on RL-3 allow RL-1 to remain pulled in and the drive motor to run.

As soon as the tape tail appears over the tape guide, RL-3 is pulled in and the machine coasts to a stop. During stop, the master take-up and the rewind motors are in series across the A.C. line for dynamic braking purposes. Rewind relay RL-4 is engaged by the momentary switch mounted on the meter case and latches through a set of holding contacts. Rewinding continues until the leader passes the photo sensor and actuates the stop relay.

Current into the sensor exciter lamp is limited by resistors to reduce the possibility of burnout.

A conventional full wave power supply furnishes all D.C. power required by the machine.

Mechanical construction. Aluminum extrusions and plate were used to fabricate the recorder parts. The main support member is a 6061-t6 channel section 8 inches wide and 2½ inches high with a one-quarter inch thick web. The match drilled side plates are made of .100-inch thick 7075-t6 aircraft quality sheet aluminum.

The capstan bearing supports were machined from 2024-t3 stock. Various sizes of extruded tubing were used to make the pressure roller spring carrier and the drop in take up system components. Standard inch-size ball bearings were used for the take-up roller system.

All components were bolted together using aircraft bolts and self locking nuts.

Protective housings for the belt area and the meter case were fabricated from one-eighth inch thick mahogany plywood and finished in wrinkle enamel. Aluminum parts were left natural.

Operation. A sandwich composed of 7-inch reels of magnetic tape and felt-covered wooden spacers is assembled on the five-sixteenths inch diameter supply shaft and fitted onto the machine. Each of the tape ends is threaded across the appropriate head guide path and the pressure arm is lowered into position to hold the tapes into place, but not to lock. A drop of rubber cement is placed on the hub of each 4-inch take-up reel as it is placed into its take up slot. The tape end is touched onto the rubber cement and the reel is rotated by hand to secure the tape to the reel. After all the take-up reels have been dropped into place, the overhead reel roller arm is dropped into place to keep the reels from bouncing. The master tape which has been recorded at 3 3/4 i.p.s. and is wound tail out is placed on the master supply motor shaft and threaded past the playback head and over to the tape-up reel, where it is secured. The pressure roller arm is then levered down into the locked position and the start button is pressed. After the machine has stopped automatically, the pressure arm lock is released by deflecting the release arm. The pressure arm is left just off the lock position in order to keep the tapes in position. The overhead reel roller arm is lifted into the retracted position, and the reels are removed and the tape is parted with a pair of scissors. Since the master was placed on the machine tail out, the copies do not have to be rewound and are ready to be played.

CONCLUSION

While the first model works quite well and produces excellent copies, it would be desirable in a second-generation machine to:

1. Incorporate the same basic drop in loading system for supply reels as well as take-up.

2. Increase the take-up reel system to accomodate up to 7-inch diameter reels.

3. Reduce the number of copy channels to around six.

4. Install stereo heads for increased usage.

5. Place the drive motor in back of the take-up area to give more room for loading.

6. Use thicker teflon sheets in the pressure roller bearings.

All the principal engineering decisions of this effort have proven to be basically correct and no major operational flaws have shown up. Lessons learned on this machine will be reflected in future designs of other duplicators.

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