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by

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A DIGITAL INTERMITTENT DATA FLOW MAGNETIC TAPE RECORDING SYSTEM

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July, 1963

ABSTRACT

A unique mechanical drive system with associated transistorized circuitry has been developed to allow digital recording on magnetic tape at varying data flow rates. The present system records on command at rates up to 40 characters per second with a packing density of 200 characters per inch. The output is on half-inch magnetic tape in a format compatible with conventional playback equipment.

The system provides a direct link between the slow and intermittent outputs of data acquisition equipment and the high-speed input devices of data reduction equipment. The tape transport could also be modified to record or read magnetic tape at either intermittent or continuous rates. Speeds up to 120 characters per second in the intermittent mode are possible.

INTRODUCTION

The new magnetic tape recorder described in this paper records digital data at slow or intermittent (character-by-character) rates in the format of computer systems now in use. The requirement for magnetic-tape compatibility with a specified computer complex imposes rigid tolerances on bit location, spacing, allowable tape skew, and tape guidance. Minute and precise tape motion is required for character-by-character recording, and the random nature of the repetition rate necessitates very short and constant start and stop times. These requirements introduce severe mechanical specifications for the tape transport.

Conventional tape transports meet spacing tolerances by moving tape at a constant velocity and recording at evenly spaced intervals. Thus, conventional tape drive mechanisms are not usable in a character-by-character recording mode. The tape transport described in this paper uses a mechanical drive system which operates on command, indexing the tape one character space after each character is written. Although the device described here was designed specifically to meet format requirements of the IBM 705 and 7090 computers at the Sandia Corporation data center, the basic design is flexible and adaptable to other format specifications.

This recorder makes possible digital magnetic tape output from slow and intermittent rate data

acquisition systems, providing a direct link between these systems and the high-speed input equipment of large data processing systems.

The tape transport could be further developed to record or read magnetic tape at either intermittent or continuous rates.

BACKGROUND

The wide use of magnetic tape for high-speed data entry into digital computers has created a need for improved recording of the output from low-speed data acquisition equipment. Until now, no recording medium existed which was well adapted to both very high speeds and intermittent low speeds.

In earlier systems, punched cards and punched paper tape equipment achieved general usage for recording at rates not suited to conventional magnetic tape recorders. Although punched records offer advantages in certain applications, they are not ideal for high-speed entry into large computer systems, nor are they suited, as magnetic tape is, to compact storage.

Commonly, data from punched cards is converted to magnetic tape before bulk processing. This is expensive and time-consuming, and it increases probability of errors not contained in the original data. An alternate method bypasses punched records by magnetic tape-recording

FIG. 1. ALTERNATE METHODS OF PREPARING INTERMITTENTLY ACQUIRED DATA FOR HIGH-SPEED PROCESSING

FIG. 2. MAGNETIC TAPE FORMAT

bursts of data from buffer memories. The intermittent data flow tape recorder simply and economically provides a direct magnetic tape output for low-speed systems (Fig. 1). It can replace or operate in parallel with such equipment as card punches, tape punches, and electric typewriters.

MECHANICAL FEATURES OF THE TAPE TRANSPORT

TAPE FORMAT REQUIREMENTS

A typical magnetic tape format is shown in Fig. 2. Four different control gaps between characters are necessary to conform to this format: 0.75-inch end-of-record gap, 3.75-inch end-of-file gap, 0.023-inch longitudinal check-group gap, and 0.005-inch character spacing. The longitudinal check-group gap can be produced, within the allowable tolerance, by advancing the tape for five

consecutive character space steps. Similarly, the end-of-file gap can be produced by five consecutive end-of-record steps. The tape deck must therefore be capable of automatically advancing the tape, on command, in steps of two different lengths (0.005 and 0.75 inch).

TAPE TRANSPORT FEATURES

A partially assembled Automatic Programming And Recording system (APAR) is shown in Fig. 3, with tape transport mounted for output recording. The tape storage system will not be described since it is a conventional type. The tape deck is shown removed from the panel in Fig. 4. A closed-loop tape system is used to minimize tape slippage and to isolate the effect of tape tension transients during the stepping cycle. A neoprene rubber with a hardness of 65 to 70 durometer was molded onto the pinch roller shells. These rollers are self-centering between the

FIG. 3. MAGNETIC TAPE TRANSPORT
FOR RECORDING APAR OUTPUT

capstan and the adjacent idler. A fine straight knurl was placed around the periphery of the capstan on each side of the tape path. The pinch rollers engage with this area and also pinch the tape against the capstan and idler. Uniform character spacings on the tape are obtained with this roller arrangement even with a relatively large fluctuation in tape tension external to the closed loop. Two adjustable flanged rollers are used to guide the tape past the recording head. These rollers are the only means of controlling the distance from the face plate to the control edge of the tape, since guiding the tape within a closed loop is ineffective. For this reason, all the rollers which mount to the face plate have close concentricity and squareness tolerances. A tape tension device is provided inside the closed loop to maintain a small and uniform air gap between the recording head and the tape. Any change in this air gap will cause a change in flux strength on the tape, resulting in noise during playback.

The tape-stepping unit which produces the 0.005-inch character spacing and 0.75-inch end-of-record gap is shown in Fig. 5. A unique mechanical drive system known as a "Harmonic Drive," is used to produce the 0.005-inch tape spacing. Original work on this type of gear system was done by C. W. Musser of United Shoe Machinery Corporation. A harmonic gear drive consists of three major parts (Fig. 6) -- a ring gear with internal teeth mating with a flexible gear having external teeth, and a wave generator. There are fewer teeth on the flexible gear than on

FIG. 4. TAPE DECK

the ring gear. The wave generator forces the flexible gear into the form of an ellipse, causing it to mesh with the ring gear at diametrically opposite points. As the wave generator is rotated with the ring gear held fixed, a traveling deflection wave is propagated in the flexible gear. If the generator is rotated clockwise at a constant angular velocity, the flexible gear will roll counterclockwise at a much-reduced constant angular velocity. The teeth which are in full mesh are stationary, and act as splines. Movement of the flexible driven member is confined to the area where the teeth are disengaged. Each rotation of the wave generator moves the flexible gear a distance equal to the tooth differential between the two gears.

There are 96 teeth on the flexible member and 100 teeth on the ring gear, resulting in a 24-to-1 reduction. For a more detailed description of this type of drive, refer to the work performed by Musser (Ref. 1). A harmonic gear system was chosen for this application because of the following advantages over conventional gear drives:

Large Percentage of Teeth in Contact -- Every tooth on each gear will come into contact with mating teeth approximately twice for each

FIG. 5. STEPPING UNIT

FIG. 6. HARMONIC GEAR DRIVE

revolution of the wave generator. Because of the large number of teeth in engagement at any one time, wear is distributed over all the teeth and the effects of errors in individual tooth shape and placement are not as pronounced as in conventional gears.

Adjustable Freedom from Backlash -- Backlash has been removed by slightly increasing the deflection of the flexible gear. Spring loading the system in this way assures freedom from backlash later, when high spots on the teeth wear away. As a result, the character spacings on the tape are accurately repetitive.

Quiet Operation -- Freedom from backlash, large percentage of teeth in contact, low pitchline velocity, and low tooth contact pressures produce quiet operation.

Counterbalanced Forces -- All forces within this gear system are counterbalanced. This facilitates mounting of the mating components.

An exploded view of the character spacing mechanism is shown in Fig. 7. The triangular, constant diameter cam is driven at a constant speed of 2400 rpm, causing the yoke cam follower to oscillate about the capstan shaft. A pin, attached to the cam follower, is normally kept from engagement with the ratchet by a compression spring. The pin oscillates with the cam follower over a range of 17.5 degrees with a sinusoidal acceleration and deceleration for each half-cycle. Cam follower dynamic characteristics are presented in the Appendix. The pin dwells at each extremity of travel for approximately one-sixth of one revolution of the drive pulley, allowing time for disengagement or engagement with the flat-faced teeth of the ratchet. The ratchet is an integral part of the wave generator and has 24 equally-spaced teeth and the same number of notches around its periphery. A detent mates with these notches, providing a positive location for each of the 24 stationary positions. The detent is pivoted on a revolvable eccentric, permitting angular adjustment of the stationary position of the ratchet with relation to the dwell position of the pin. The total reduction from the input shaft to the capstan is 576 to 1, resulting in a 0.005-inch (one character space) arc length advancement of the periphery of the capstan for each cycle during which the flying pin engages with the ratchet. To obtain the

FIG. 7. CHARACTER SPACING MECHANISM

0.023-inch parity check-group gap, the pin is cycled through insertion and withdrawal from the ratchet five consecutive times.

Push-pull electromagnets (Fig. 7) insert and withdraw the flying pin. Clapper flux is transferred from one magnet to the other during the operating cycle and, therefore, the clapper flux level changes only slightly. The clapper in this design is of solid material because eddy-current losses resulting from this small flux change do not impair magnet response.

FIG. 8. TAPE STEPPING MECHANISM
(0.75 AND 3.75 INCH)

The mechanism which generates the 0.75-inch end-of-record gap is shown in Fig. 8. The pinion gear, which is in mesh with the ring gear, is attached to a single-revolution clutch output. Clutch input is coupled to the output by energizing a solenoid which releases a stop pawl from its mating tooth. This allows a helical spring, attached to the input, to grip the output shaft, causing the clutch to turn as a unit. The stop pawl stops the clutch output shaft after one revolution. The inertia of the system causes the helical spring to

wind up and increase in diameter until the stop spring engages with its mating tooth, allowing the input shaft to turn freely. To obtain the 3.75-inch end-of-file gap, the clutch is actuated five consecutive times. The ratchet is held fixed by the detent while the clutch is energized; therefore, the capstan will rotate at a slightly higher angular velocity than the ring gear. This relative motion of the capstan with respect to the ring gear was compensated in the pinion gear design. At completion of the end-of-record and end-of-file gaps, the ratchet is advanced five consecutive steps to assure that all slack is out of the drive system before writing on the tape. Although the clutch has an anti-backlash feature, any slack from wear of gear teeth will be reflected in the first character space after the 0.75 and 3.75 inch gaps. This slack will disappear after the wave generator has been revolved slightly before recording, since it will drive the ring gear in reverse until it is securely held by the pinion gear. To accomplish this, each end-of-record and end-of-file gap is followed by five character spaces before a new record is begun. Synchronization of the driving circuitry with the mechanism is done by two photodiodes, a light source, and a timing disc which is attached to the drive pulley (Fig. 9). The pulse from one of these diodes is used to indicate the position of the cam follower so that the pin can be inserted and withdrawn from the ratchet at the proper time. The output from the other photodiode indicates the proper time to write on the tape.

A small magnetic pickup is used as a character-space checking device. An electrical pulse is generated each time one of the 24 notches of the ratchet passes it, corresponding to one character-space advancement of the tape. The single-revolution clutch operation is checked by a microswitch. The contacts of this switch close

FIG. 9. ELECTRICAL-TO-MECHANICAL SYNCHRONIZATION

and open for each revolution of the pinion gear. A similar switch is used to indicate the position of the pinch rollers. If a proper output signal is not received from each of these three checking devices, the recording process is inhibited and an error-indicating light on the control panel is energized.

MAGNETIC WRITING MODE

The tape motion of this device presents no unusual problems in magnetic recording. In fact, several advantages result from writing when the tape is stationary. These advantages are:

1. Inexpensive low-speed semiconductor circuitry can be used because low repetition rates are involved.
2. Writing at rest can be performed easily in either the serial or parallel mode.
3. Flux polarity is reversed in a minimum longitudinal distance on the tape. This results in maximizing $d\phi/dt$, the rate of flux change, when the tape is played back with continuous motion. Thus, the playback output and signal-to-noise ratio are maximized with respect to the writing technique.

The transport is not well adapted to recording in the RZ (return-to-zero) or RB (return-to-bias) modes (Fig. 10). An RZ or RB pulse applied to the writing head will write on stationary tape with its leading edge and immediately erase with its trailing edge, so that no bit appears on the tape. If the RZ or RB recording mode is used, special provisions must be made to return the pulse to zero after the tape has moved a fraction of the total character spacing. In NRZI (non-return-to-zero, invert) recording, a "one" bit is identified by a reversal of flux polarity in a tape channel. A "zero" bit is indicated by no change in polarity. The NRZI recording mode is readily achieved when

the tape is stationary during the writing portion of the cycle. The NRZI mode is employed for magnetic tapes used with IBM 705 and 7000 computers.

FIG. 10. FLUX PATTERN FOR SEQUENCE OF BITS FOR THREE RECORDING METHODS

Conventional digital recording heads are well-suited for use with this transport. Each channel is driven by a complementing bistable multivibrator and amplifiers (Fig. 11) so that flux polarity reverses each time the multivibrator is complemented. The "clear" input to the multivibrator is used in writing the longitudinal parity check, which will be explained later.

ELECTRICAL FEATURES OF RECORDING SYSTEM

The tape recorder electronic circuitry (Fig. 12) provides for writing on the tape and controlling various mechanical functions to produce

FIG. 11. RECORDING HEAD AND DRIVERS

FIG. 12. RECORDING SYSTEM CIRCUITRY

output tapes with the desired format. Additional electronic circuitry is required to adapt the recorder to any specific data acquisition system. The transport, as described in this paper, performs the following functions on command:

TAPE MOTION

Character Space -- The character space (Fig. 2) is the longitudinal distance between adjacent characters on the tape. This tape motion is initiated by energizing an electromagnet at the correct time in the mechanical cycle. This electromagnet engages the flying pin with the ratchet, thus coupling the drive from the input cam to the capstan.

The pin is retracted and held after each step by a second electromagnet. Proper timing for stepping pin insertion and retraction is achieved by synchronizing these actions with the leading and trailing edges of the advance pulse. After each character is written, the tape is moved forward one character-space and is stopped for the writing of the next character.

End-of-Record Gap -- The end-of-record gap is the length of tape left blank after each data record in the format of Fig. 2. This gap is 0.75 inch in

length and is initiated by the solenoid controlling the single-revolution clutch. The end-of-record gap requires two rotations of the timing disk for completion, and the system must be inhibited during this time to prevent writing while the tape is in motion. The required delay is obtained using a counter and gated pulses from the timing disk.

After each single-revolution clutch operation, the character-space mechanism is operated five consecutive times to take up slack in the mechanism before starting a new record.

RETURN SIGNALS FROM TAPE DECK

Mark and Advance Pulses -- The mark pulse and advance pulse are the basic timing references for the recording system. They must occur at fixed times in each mechanical cycle, and are generated by angular displacement of the input cam shaft. Metallic contacts were ruled out for this application because of the very large number of operations required in the lifetime of the device. Use of a slotted rotating disk, light source, and photodiodes (Fig. 9) to generate these pulses eliminates problems of electrical contact noise, wear, and mechanical vibrations which often result from use of mechanical switches.

The repetition rate of these pulses is equal to the maximum repetition rate of the character-space stepping mechanism. The signals are generated to meet the following requirements:

1. The leading edge of the advance pulse occurs in each cycle at that time when the stepping mechanism must be actuated to advance the tape during that cycle.
2. The duration of the advance pulse is equal to the time required to advance the tape one character-space. The flying pin must be retracted on the trailing edge of the advance pulse to end the power stroke.
3. The mark pulse occurs a short time after the trailing edge of the advance pulse. This brief delay assures that mechanical vibration resulting from stepping the tape will be damped out before the mark pulse occurs, leaving the tape stationary under the recording head. Writing on the tape is synchronized with the mark pulse.
4. In addition to their primary functions, the mark and advance pulses are used to generate time delays needed in the end-of-record and end-of-file sequences which will be described later.

Check Pulses -- Check pulses indicate that the tape has been stepped, and are thus generated by mechanical motion of some critical part. An inhibiting circuit is set when a signal occurs to initiate tape motion. This lights a panel light and prevents the system from operating on new information until the proper check pulse is received. The inhibiting circuit is then reset. If the transport failed to advance the tape on command, no check pulse would occur. Thus, operation would cease and a panel light would indicate the failure.

The character-space stepping mechanism, which operates each time a character is recorded, requires a check-pulse system which will be reliable for many operations. A magnetic pickup (Fig. 9) is used to check character-space stepping by generating a pulse whenever a ratchet notch moves past the sensing element. One notch is moved past the magnetic pickup each time the tape is stepped, and the resulting pulse is amplified and used to reset the inhibiting circuitry.

The single-revolution clutch operates only at the end of a data record or data file, so that its total number of operations is only a fraction of the total number executed by the character-space stepping mechanism. The lifetime requirements on the single-revolution clutch check are thus less rigid. Since the magnitudes of mechanical motion involved are ample, a microswitch is used to check this operation. The same inhibiting circuit is used with both character-space and single-revolution clutch checks.

Timer Pulses -- A timer is required in the tape transport because of the following problem. Once a tape record is begun it is not desirable to release the pinch rollers (Fig. 4) before the end of the record, since releasing these rollers may result in unwanted motion of the tape. Since it is impractical to relocate the tape properly for continuation, the record would be permanently damaged. Because the recording is intermittent, the capstan might remain stationary for long periods between characters, allowing flats to form on the hard rubber pinch rollers. Although temporary and self-correcting in normal operation, these flats can distort length of steps. Thus, the capstan should not be stationary for very long periods. The timer and its circuitry produce a pulse, record a special character, and step the capstan after each 20-second interval during which no data is recorded. Gating circuitry prevents the timer from stepping the capstan if a data character has been written during the previous timer cycle. The special character is ignored when the tape is played back.

Generation of Tape Format (Fig. 2) -- A primary objective of the recorder design is to provide an output tape format suitable for direct entry into an existing data-reduction system. This requires proper lateral positioning of bits, proper tape guiding, and accurate spacing between characters as well as certain parity check bits, special spacings and characters, and sequences of these actions. The following will be discussed in terms of an acceptable format for the IBM 729 tape transport and 7090 computer at the Sandia Corporation data center:

1. Lateral parity check
2. Longitudinal parity check
3. End-of-record sequence
4. End-of-file sequence

Lateral Parity Check -- Parity checks are redundant bits included in the tape record as checks against bit dropout. The format used here requires that lateral parity be odd, meaning that each character is formed with an odd number of "one" bits. Since no provision is made in the data acquisition equipment for parity-checking, it must be done through the tape recorder circuitry. The code appearing at the recorder input is Elecom 120A, a six-level binary-coded decimal code. These levels are sampled for each character recorded, and a "one" bit in the seventh level is added when required for odd parity.

Longitudinal Parity Check -- The format requires even longitudinal parity, meaning that each tape channel in a complete record must contain an even number of "one" bits. Therefore, a longitudinal

parity-check character is written at the end of each record. This character is written by placing a "one" bit in each channel having an odd total of "ones" and a "zero" bit in each channel containing an even total of "ones". Bistable multivibrators drive the writing heads in the NRZI mode (Fig. 11). Before each new data record is begun, these multivibrators are in their cleared state. A "one" bit is written by complementing the corresponding multivibrator, thus reversing the flux polarity in that channel. The longitudinal parity check (the final character in each record) is formed by resetting all multivibrators to their initial cleared state, leaving each channel containing an even number of "one" bits.

End-of-Record Sequence -- The data record is a collection of data to be treated or processed as a group. The end of a record is identified by a special sequence of spaces and a parity check. This sequence (Fig. 2) follows the final character in each record and consists of 0.023 inch of blank tape, the longitudinal parity check, and 0.75 inch of blank tape, in that order.

This sequence, performed by the tape transport, is achieved through sequential switching circuitry as follows:

1. A special code character signifying end-of-record appears at the output of the acquisition system and is recognized by the recorder circuitry. When this character is recognized, the acquisition system is disabled and the remainder of the sequence proceeds automatically.

2. Five character spaces (0.023 ± 0.005 inches) are indexed past the head without writing on the tape, forming the longitudinal check group gap.

3. The multivibrators driving the writing heads are reset to their initial state, writing the longitudinal parity check.

4. The single-revolution clutch is actuated, moving 0.75 inch of tape past the head without writing. This forms the end-of-record gap.

5. Five character spaces are indexed past the head, removing slack and leaving the transport ready to begin the next record. The data acquisition system is then enabled to proceed with the next record.

End-of-File Sequence -- The file is a group of data records on the same reel of magnetic tape. The end-of-file sequence is used to identify the end of a file on playback. This sequence proceeds as follows:

1. Recognition of a special end-of-file character from the data acquisition system disables

the system and begins the switching sequence.

2. Five character spaces are indexed past the head without writing.

3. Longitudinal parity check is written.

4. The single-revolution clutch is actuated five times in succession, moving 3.75 inches of blank tape past the head.

5. The tape mark, a special code character generated by the recorder circuitry, is written on the tape.

6. The end-of-record sequence is then repeated, providing a longitudinal parity check on the tape mark.

As mentioned, the end-of-record and end-of-file sequences can be initiated by special code characters on the output lines of the data acquisition system. Provision is also made for manually initiating end-of-record and end-of-file sequences in the event that (1) the data acquisition system is not programmable to allow entry of the special characters, or (2) some failure of the acquisition equipment prevents completion of the program. Manual record and file terminations are accomplished by control panel switches which start the switching sequences.

MODIFICATION REQUIRED FOR A CHARACTER-BY-CHARACTER READ-WRITE TAPE TRANSPORT

The proposed scheme of reading and recording data intermittently on magnetic tape is shown in Fig. 13. The same tape deck is shown, except that, replacing the cam, cam follower, electromagnets and associated parts, a printed-circuit motor is used as the input to the harmonic gear reduction drive to the capstan. A motor and control circuit have been designed recently for this application. (Ref. 2).

To operate the tape deck in a character-by-character recording mode, two switches (Fig. 13) are placed in the RECORD position. The first character of a record is placed on the stationary tape. An advance command is then applied to the stepping control.

To rotate the motor armature a distance of one character spacing at the capstan periphery, a bistable flip-flop is set to apply the proper DC voltage on the control input line at point 1 (Fig. 13). The motor immediately accelerates to a terminal speed determined by the control-voltage level and consistent with a bit density of 200 characters per inch. Armature motion continues until a read pulse from the pickup senses passage of a position

FIG. 13. METHOD OF RECORDING OR READING MAGNETIC TAPE
IN AN INTERMITTENT OR CONTINUOUS MODE (REF. 2)

point on the wave generator which is a little less than the 0.005-inch advancement of the capstan periphery. This pulse clears the stepping control flip-flop and resets the voltage at point 1 to zero. The armature stops and the cycle is completed.

Character spacings within a ± 0.0005 -inch tolerance should be produced easily, since a 24-to-1 reduction exists between motor output shaft and capstan. Armature indexing accuracy could be ± 1 degree and yet produce character spacings within the above tolerance. End-of-record and end-of-file gaps are generated easily by applying the appropriate amplitude and duration of signal to the control line. The direction of tape motion may be reversed by changing the polarity of all control voltages.

To avoid oscillations in successive stepped positions, the capstan must attain its steady-state terminal velocity during each cycle before a stop signal is received. This allows the acceleration and deceleration transients to complete themselves so each step will not be a function of the immediately preceding displacement (Ref. 2). Therefore, it appears that a conservative estimate for the maximum stepping rate would be approximately 120 steps per second. The only part directly coupled to the armature shaft is the wave generator, made of magnesium for low inertia. Small steel studs around the periphery of this part would serve as position pickup points.

Reading a digital record, character-by-character, is done by connecting the stop command to the "read" amplifiers through an "OR" gate. There are seven channels across the tape and reading a bit on any one will initiate the stop. When end-of-record or end-of-file gaps are encountered, the tape continues to move uniformly through the gap until the next character is read. Readout always occurs while the tape moves at its maximum running or slewing velocity. Fluctuation in the stepping rate or variations in time between steps would have no effect on operation.

At present, commercial character-by-character tape readers do not exist. Stepping motors cannot be used, since they provide no way of obtaining or maintaining registration between the character spacings and capstan motion. With the equipment described in this paper, it is feasible to have the option of recording or reading data in a character-by-character mode or in a continuous flow mode using the same tape deck.

CONCLUSIONS

Preliminary testing of the recording system has shown the various spacings to be well within tolerances. The tests included measurement of the critical dimensions on tape records and

extensive checking of tape records on the IBM 7090 computer.

This recording system is adaptable to many applications in which data acquired at low speed is intended to be processed at high speed. The system has the following advantages:

1. It allows interlinking of high and low speed systems without buffering or translation between them, thereby increasing reliability and saving time and expense.

2. It can be operated in parallel with electric typewriters, card punches, and paper tape punches.

3. It can replace card and paper tape punches in certain applications, reducing system noise and providing a reusable, high packing density recording medium.

4. It could provide, with additional development effort, the capability of recording or reading data in a character-by-character mode or in a continuous flow mode, using the same tape deck.

In conclusion, this new recording system has proven advantages which can streamline the flow of information in many applications.

APPENDIX

RING GEAR AND FLEXIBLE GEAR TOOTH FORMS (REF. 3)

ϕ = Ring gear tooth pressure angle

ϕ_f = Flexible gear tooth pressure angle

P = Circular pitch

N = Number of lobes on wave generator = 2

h = Height of harmonic wave

β = Tooth spacing angle

n = Number of teeth on ring gear = 100

n_f = Number of teeth on flexible gear = 96

d = Pitch diameter of ring gear = 1.042 inches

d_f = Pitch diameter of flexible gear = 1.000 inch

RING GEAR INTERNAL TOOTH FORM

$$\phi = \tan^{-1} \frac{1.091}{N} = \tan^{-1} 0.5455 = 28^\circ 37'$$

$$\beta = \frac{360^\circ}{n} = \frac{360^\circ}{100} = 3^\circ 36'$$

$$\begin{aligned} \text{Ring gear tooth space angle} &= 2\phi - \beta = 57^\circ 14' \\ &- 3^\circ 36' = 53^\circ 38' \end{aligned}$$

$$P = \frac{\pi d}{n} = \frac{3.1417 \times 1.042}{100} = 0.0327 \text{ inch}$$

NOTE: The formula for determining ring gear tooth space (9/16 P) was modified to equal 8/16 P in order to increase the contact area between the mating teeth.

$$8/16 P = 8/16 \times 0.0327 = 0.016 \text{ inch}$$

NOTE: The diameter between two 0.018-inch diameter gear measuring wires was calculated to be equal to 1.016 inches; however, to remove all backlash from the system this dimension was changed to 1.014 inches.

FLEXIBLE GEAR TOOTH FORM

$$h = \frac{d - d_f}{2} = \frac{1.042 - 1.000}{2} = 0.021 \text{ inch}$$

$$\begin{aligned} \phi_f &= \phi + \tan^{-1} \left(0.458 \frac{hN}{d/2} \right) \\ &= 28^\circ 37' + \tan^{-1} \frac{(0.458 \times 0.021 \times 2)}{1.042/2} \\ &= 28^\circ 37' + \tan^{-1} 0.0369 = 28^\circ 37' + 2^\circ 7' \\ &= 30^\circ 44' \end{aligned}$$

$$\text{Flexible gear tooth space angle} = 2\phi_f = 61^\circ 28'$$

The diameter over two 0.018-inch-diameter gear measuring wires was calculated to be equal to 1.022 inches.

NOTE: The flexible gear was fabricated from a homogenized 17-4 PH corrosion-resistant steel forging. After machining, it was age-hardened to condition H-900 and tempered to Rockwell 40 to 48 C. A vapor blast was used to remove heat-treat discoloration.

WAVE GENERATOR ELLIPSE SHAPE

d_f = Circular bore diameter of flexible gear
 = 0.953 inch
 a = Major radius of ellipse
 b = Minor radius of ellipse
 h = Height of harmonic wave = 0.021 inch
 s = Circumference of ellipse

$$a = \frac{d_f}{2} + h = \frac{0.953}{2} + 0.021 = 0.4975 \text{ inch}$$

$$s = (a + b) \pi \left[1 + \frac{1}{4} \left(\frac{a - b}{a + b} \right)^2 + \frac{1}{64} \left(\frac{a - b}{a + b} \right)^4 + \dots \right]$$

Setting the above equation equal to the circumference of the circular bore of the flexible gear and using an electronic computer, the minor radius (b) was determined to be:

$$b = 0.4550 \text{ inch}$$

The locations for eight ball bearings placed at 45-degree intervals on the wave generator were determined by using the equation for an ellipse

$$\left(\frac{X^2}{a^2} + \frac{Y^2}{b^2} = 1 \right).$$

These bearings were located very accurately to avoid either overstressing the flexible gear or introducing backlash into the system.

CAM FOLLOWER MOTION IN TERMS OF CAM SHAFT INPUT

CAM AND CAM FOLLOWER

EQUIVALENT LINKAGE (EXCLUDING DWELL)

β = Angular displacement of flying pin
 (8°45' maximum each side of centerline)
 θ = Angular rotation of cam ($\theta' = \theta \pm 30^\circ$)
 a = Distance between pivot points of cam and cam follower

β in terms of θ' and constants a , x , and r ;

$$\beta = \gamma - \alpha$$

$$\rho^2 = r^2 + a^2 - 2ar \cos \theta'$$

$$r \sin \theta' = \rho \sin \gamma$$

$$\rho^2 = r^2 \frac{\sin^2 \theta'}{\sin^2 \gamma}$$

$$\rho = \frac{x}{\sin \alpha}$$

$$\alpha = \sin^{-1} \frac{x}{\rho} = \sin^{-1} \frac{x}{\sqrt{r^2 + a^2 - 2ar \cos \theta'}}$$

$$r^2 \frac{\sin^2 \theta'}{\sin^2 \gamma} = r^2 + a^2 - 2ar \cos \theta'$$

$$\sin \gamma = \frac{r \sin \theta'}{\sqrt{a^2 + r^2 - 2ar \cos \theta'}}$$

$$\beta = \gamma - \alpha$$

$$\beta = \sin^{-1} \left(\frac{r \sin \theta'}{\sqrt{a^2 + r^2 - 2ar \cos \theta'}} \right)$$

$$- \sin^{-1} \left(\frac{x}{\sqrt{a^2 + r^2 - 2ar \cos \theta'}} \right)$$

NOTES: 1. Because of the limitations of the equivalent linkage, an inversion takes place when the centerline of the cam coincides with the centerline of the two pivot points, necessitating the substitution of $(\theta \pm 30^\circ)$ for θ' .

2. The total action can be expressed in 180 degrees of cam rotation, since the cam and follower are symmetrical.

α_f = Angular acceleration of follower (rad/sec^2)

A characteristic of sinusoidal motion is that when

ω_f = maximum, $\alpha_f = 0$ and when $\omega_f = 0$,

α_f maximum = $-\omega_f^2$ maximum.

Two acceleration peaks are present:

$(89.7)^2 \text{ rad/sec}^2$ at $\theta = \pm 52.5$ degrees, and

$(52.3)^2 \text{ rad/sec}^2$ at $\theta = \pm 112.5$ degrees.

VELOCITIES AND ACCELERATIONS

Peak velocities are attained at 0 and 180-degree rotation of the cam or at the two over-center positions. At these positions the points of equal linear velocity are at $a \pm r \cos 30^\circ$ degrees with reference to the pivot point of the follower.

Velocity relationships:

ω_c = Angular velocity of cam (rad/sec)

ω_f = Angular velocity of follower (rad/sec)

At 40 rps ($\omega_c = 251 \text{ rad/sec}$),

$a = 0.500 \text{ inch}$,

$r = 0.152 \text{ inch}$

$$\omega_f = \frac{\omega_c r \cos 30^\circ}{a \pm r \cos 30^\circ}$$

$$= 52.3, 89.7 \text{ rad/sec}$$

CAM AND CAM FOLLOWER

TABLE IA. CAM FOLLOWER DYNAMIC CHARACTERISTICS

θ'	$180-\theta'$	$\cos \theta'$	Q	$\sin \theta'$	$\frac{r \sin \theta'}{Q^*}$	γ	χ/Q^*	α	β
82.5		0.13053	0.5037	0.99144	0.2992	17° 25'	0.1507	8° 40'	8° 45'
75		0.25882	0.4840	0.96593	0.3033	17° 39'	0.1570	9° 2'	8° 37'
60		0.5000	0.4440	0.86603	0.2965	17° 15'	0.1712	9° 52'	7° 23'
45		0.70711	0.4070	0.70711	0.2641	15° 19'	0.1867	10° 46'	4° 33'
30		0.86603	0.3762	0.50000	0.2020	11° 39'	0.2020	11° 39'	0
45		0.70711	0.4070	0.70711	0.2641	15° 19'	0.1867	10° 46'	4° 33'
60		0.50000	0.4440	0.86603	0.2965	17° 15'	0.1712	9° 52'	7° 23'
75		0.25882	0.4840	0.96593	0.3033	17° 39'	0.1570	9° 2'	8° 37'
82.5		0.13053	0.5037	0.99144	0.2992	17° 25'	0.1507	8° 40'	8° 45'
120	60	-0.5000	0.5911	0.86603	0.2227	12° 52'	0.1286	7° 23'	5° 29'
135	45	-0.70711	0.6164	0.70711	0.1744	10° 3'	0.1233	7° 5'	2° 58'
150	30	-0.86603	0.6361	0.50000	0.1195	6° 52'	0.1195	6° 52'	0
135	45	-0.70711	0.6164	0.70711	0.1744	10° 3'	0.1233	7° 5'	2° 58'
120	60	-0.5000	0.5911	0.86603	0.2227	12° 52'	0.1286	7° 23'	5° 29'
105	75	-0.25882	0.5590	0.96593	0.2626	15° 13'	0.1360	7° 49'	7° 24'
90	90	0	0.5243	1	0.2904	16° 53'	0.1452	8° 21'	8° 32'
82.5		0.13053	0.5037	0.99144	0.2992	17° 25'	0.1507	8° 40'	8° 45'

* NOTE: $\beta = \gamma - \alpha = \sin^{-1} \left(\frac{r \sin \theta'}{\sqrt{a^2 + r^2 - 2ar \cos \theta'}} \right) - \sin^{-1} \left(\frac{\chi}{\sqrt{a^2 + r^2 - 2ar \cos \theta'}} \right)$

$Q = \sqrt{a^2 + r^2 - 2ar \cos \theta'}$ where $r = 0.152$ inch, $a = 0.500$ inch,

$\chi = 0.076$ inch, and $\theta' = \theta \pm 30^\circ$.

CAM FOLLOWER DYNAMIC CHARACTERISTICS

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