



(43) International Publication Date
23 December 2009 (23.12.2009)

(51) International Patent Classification:
G11B 15/00 (2006.01)

(21) International Application Number:
PCT/IB2009/052577

(22) International Filing Date:
17 June 2009 (17.06.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
08104461.2 18 June 2008 (18.06.2008) EP

(71) Applicant (for all designated States except US): INTERNATIONAL BUSINESS MACHINES CORPORATION [US/US]; New Orchard Road, Armonk, New York 10504 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **CHERUBINI, Giovanni** [CH/CH]; IBM Research GmbH, Zurich Research Laboratory, Saeumerstrasse 4, CH-8803 Rueschlikon (CH). **JELITTO, Jens** [DE/CH]; IBM Research GmbH, Zurich Research Laboratory, Saeumerstrasse 4, CH-8803 Rueschlikon (CH). **LANTZ, Mark A.** [CA/CH]; IBM Research GmbH, Zurich Research Laboratory, Saeumerstrasse 4, CH-8803 Rueschlikon (CH).

(74) Agents: **Toleti, Martin** et al.; IBM Research GmbH, Intellectual Property Law, Saeumerstrasse 4, CH-8803 Rueschlikon (CH).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: SERVO CONTROL IN TAPE DRIVES

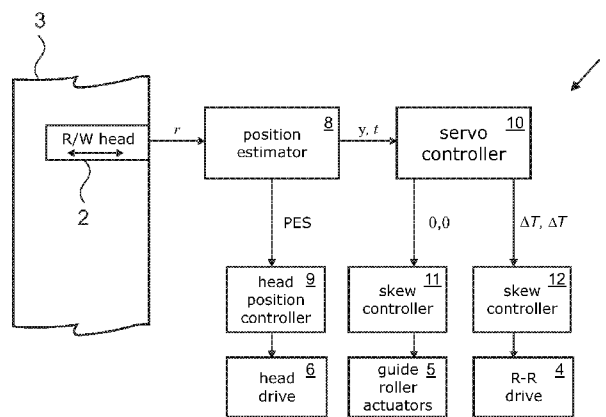
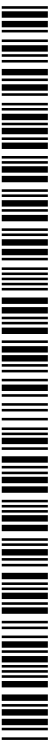


Fig. 2

(57) Abstract: Servo control methods and apparatus are provided for a tape drive (1) where a read/write head (2) reads and writes data on magnetic tape (3) with at least one servo track for providing transversal position information. At least two servo readers (S) are associated with the read/write head (2), each arranged for reading a said servo track during read/write operations. The servo readers (S) are operative concurrently to generate respective servo read signals (r). A position estimator (8) processes each servo read signal (r) to generate a series of position values, corresponding to respective time instants, indicative of transversal position of the associated servo reader (S). A servo controller (10) calculates from the position values and time instants a skew value (θ), indicative of tape skew relative to the read/write head (2), and a tension variation value (ΔT) indicative of variation of tape tension from a reference value. The servo controller (10) is adapted to account for cross-coupling between tape skew and tension variation in the joint calculation of the skew and tension variation values. Where three servo readers (S) are operative concurrently, the servo controller (10) can be adapted to account for time dependency of tape skew and tension variation and to calculate respective time derivatives ($\dot{\theta}$, $\dot{\Delta T}$) for the skew and tension variation values (θ , ΔT). The calculated values can then be used to make compensatory adjustments to tape tension and tape skew relative to the read/write head (2).



WO 2009/153740 A2

Published:

- *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

SERVO CONTROL IN TAPE DRIVES

This invention relates generally to servo control in tape drives. Servo control methods and apparatus are provided for use with magnetic tape having one or more servo tracks providing transversal position information during read/write operations.

In recent years, the capacity and performance of tape storage systems has increased considerably, and the potential for further growth appears to be substantial. In order to achieve higher cartridge capacities and improved performance, advances in several technical areas are necessary. Areal density increase, i.e. increase in linear and/or track density is key to achieving higher storage capacities. In the former case, the distance between adjacent bit cells decreases, leading to an increase in intersymbol-interference. Higher track density implies narrower track width, narrower read/write heads and closer head spacing, leading to losses in signal-to-noise ratio. Also, issues of intertrack-interference become critical. Reliable servomechanisms for controlling the tape transport and tape/head positioning systems, such as reel-to-reel and track-following servomechanisms, are therefore key to achieving best overall drive performance.

Tape storage systems typically use dedicated servo tracks recorded alongside the data tracks on the tape to provide positional information for use by the servo control system. In linear tape open (LTO) tape drive systems for example, the timing-based servo (TBS) format has been adopted as a standard. The TBS system defines a format for the servo pattern recorded in the servo tracks and is detailed in Standard ECMA-319, "Data interchange on 12.7 mm 384-track magnetic tape cartridges – Ultrium-1 format," June 2001, pp. 48 to 56. The TBS servo pattern, described in more detail below, has a frame format comprising magnetic transitions defining a series of stripes with two different azimuthal slopes. During read/write operations, the transversal position of the read/write head can be derived from the relative timing of pulses generated by a narrow servo reader head reading the stripe pattern. TBS patterns also allow the encoding of additional longitudinal position information without affecting the generation of the transversal position error signal (PES). This is obtained by shifting transitions (stripes) in the servo pattern from their nominal pattern position in the longitudinal direction of the tape.

In accordance with the LTO standard, servo tracks are recorded in servo bands which extend on either side of each of several data bands spaced transversely across the tape. Different servo readers can be arranged for reading servo tracks in different bands concurrently during read/write operations, thus providing more information to the servo

control system. For example, in current IBM tape systems there are four servo readers arranged on two modules of the read/write head as illustrated in Figure 1 of the accompanying drawings. Each of the left and right head modules shown schematically here has two servo readers S, one above and one below a line of alternating read and write elements, labeled R and W respectively, only partially shown in the figure. The two servo readers S on each module are thus arranged for reading respective servo tracks on either side of the current data band. This modular head arrangement allows reading and writing in both directions of tape travel, with writing always being performed by the leading module. As alternate tracks are written by the write elements W of the leading module, the two servo readers of that module are active, and the read elements of the trailing module are used to verify the written data. For a read operation in a given direction of tape travel, the two servo readers of the module with active read elements are operative. Thus, two servo readers on one of the two modules are active at all times during read/write operations. A transversal position-error signal (PES) can be derived from the servo read signal from each of the two active readers S. In particular, an estimate of the transversal position of a given reader S (relative to a desired or nominal position, typically the servo track centre line) can be derived from the servo read signal for each frame of the TBS servo pattern. Reading of successive servo frames by reader S results in a series of transversal position estimates for time instants corresponding to reading of respective servo frames. The resulting position-error signal is used together with tape speed and LPOS information derived from the servo pattern for track-following and reel-to-reel servo control functions.

Among the main impairments adversely affecting the performance of track following and reel-to-reel servomechanisms, as well as the quality of readback signals in data channels, are the dynamic skew and the variation of tape tension. Dynamic skew arises whenever the head does not remain perfectly perpendicular relative to the direction in which the tape moves. Tape skewing with respect to the head during tape motion tends to produce increasing loss of signal as frequency rises as well as readback-signal frequency fluctuations. These cannot easily be tracked by the phase-lock loops that are usually implemented in detection systems. Moreover, tape skewing introduces delays in the data channels that have to be estimated and compensated for. When operating in the steady state velocity mode, variations of tape tension around the nominal value, also called once-arounds, are induced by the reel eccentricities. In tape transport, this problem is particularly serious when the reel rotation frequencies are near the resonance frequency determined by the tape path. Tape tension errors affect the position error signal and hence the performance of track following servo.

The adverse effects of dynamic skew and tension variation are well acknowledged and understood, and various approaches have been proposed to estimate these quantities to improve drive operation. For example, US Patent No. 6,563,659 discloses a system for estimating changes in tape tension based on detected changes in distance between two transversely spaced servo bands. The changes in distance are determined from position-error signals derived for two servo read elements reading respective servo bands. A system described in US Patent No. 6,934,108 measures changes in tension based on changes in longitudinal tape length, and in particular changes in longitudinal distance between two known points in the servo pattern read by a servo read head. Tape reel motor torque is then adjusted accordingly. US Patent No. 4,062,047 describes test equipment for separately measuring read head skew and write head skew in a tape recording system. Read head skew is determined by reading a reference tape, and write head skew is determined by reading a pattern written by the write head using a properly-aligned read head. In both cases, the skew estimates are based on time differences between corresponding peaks of identical timing signals recorded in two transversely spaced tracks read by respective read heads. US Patent No. 6,430,008 senses tape skew based on timing differences between signals from two transversely-spaced servo read elements reading respective servo tracks, with tape head positioning being controlled accordingly. US Patent No. 6,724,559 discloses a similar system in which the detected skew is corrected either by rotating the tape head or by tilting rollers in the tape path. While these techniques make some manner of provision for one or other of tape skew and tension variation, an improved system would be highly desirable for the reasons discussed earlier.

One aspect of the present invention provides servo apparatus for a tape drive having a read/write head for reading and writing data on magnetic tape with at least one servo track for providing transversal position information. The apparatus comprises:

at least two servo readers associated with the read/write head, each arranged for reading a said servo track during read/write operations, the servo readers being operative concurrently to generate respective servo read signals;

a position estimator for processing each servo read signal to generate a series of position values, corresponding to respective time instants, indicative of transversal position of the associated servo reader; and

a servo controller for calculating from said position values and time instants a skew value, indicative of tape skew relative to the read/write head, and a tension variation value indicative of variation of tape tension from a reference value, the servo controller being

adapted to account for cross-coupling between tape skew and tension variation in calculating the skew and tension variation values.

Servo control apparatus embodying this invention thus uses values indicative of transversal position of each of two or more servo readers, and timings associated with these position values, to estimate both tape skew and tension variation jointly during read/write operations. Moreover, not only are values for both quantities calculated in operation, the calculation also takes account of cross-coupling between tape skew and tension variation, i.e. the effect of one quantity on the other. This offers exceptional efficiency in servo control functions, allowing corrections for both tape skew and tension variations to be made at the same time, and to a high degree of accuracy, during normal read/write operations. By using the transversal position values and associated timings, this joint estimation of skew and tension variation can be performed based on read signals from any two servo readers operating concurrently, whether reading the same or different servo tracks. Embodiments of the invention thus enable implementation of highly efficient servo control systems, based on joint estimation of tape skew and tension variation, without requiring addition of costly tension and position sensors.

The servo readers are most conveniently mounted on the read/write head, as exemplified in the Figure 1 construction, so as to read the servo tracks during read/write operations. In the example of Figure 1, the joint estimation process could be based on read signals from any pair of servo readers S operated concurrently.

The position estimator may be adapted to process TBS servo read signals. In this case, the series of position values for each servo reader can be the transversal position estimates derived from successive frames of the TBS servo pattern as described above. Each position estimate then corresponds to a time instant at which the respective servo frame is read by the servo reader. In general, of course, other servo patterns might be employed for providing transversal position information. The position values may thus depend in a variety of ways on transversal position of the servo reader, each position value being associated with a particular time instant for which that value is deemed generated, such that the position value is in some manner indicative of transversal position of the servo reader at that time instant.

While alternatives can be envisaged, the servo controller may calculate the skew and tension variation values from each set of position measurements, one for each servo reader, and their corresponding time instants. These values may be fed back via control signals in closed loop servo systems to effect appropriate dynamic adjustments in the drive system. In particular, the servo apparatus may include a tension adjustment mechanism for adjusting

tape tension in dependence on the tension variation value, and a skew adjustment mechanism for adjusting tape skew relative to the read/write head in dependence on said skew value. In some embodiments, the servo controller may generate the skew and tension variation values by processing values produced from several successive sets of position measurements, e.g. by averaging or filtering for smoothing purposes, the processed values then being used in the servo control operations. Embodiments can also be envisaged where the position values and time instants (in particular differences between time instants) are processed in some way, e.g. averaged or smoothed over several measurements, and the processed values used by the servo controller to calculate the skew and tension variation values.

Preferred embodiments include at least three servo readers arranged for reading at least two servo tracks and operative concurrently to generate respective servo read signals. In a particularly convenient arrangement, the three servo readers comprise a pair arranged for reading a first servo track and a third arranged for reading a different servo track spaced transversely across the tape from the first servo track. In these embodiments, the three servo readers could be used in two pairs to produce two sets of skew and tension variation values which could then be averaged for greater accuracy. However, as an additional feature in particularly preferred embodiments, where three servo readers operate concurrently the servo controller can be adapted to account for time dependency of tape skew and tension variation in calculating the skew and tension variation values, and may calculate respective time derivatives for the skew and tension variation values. The time derivative values can also be fed back in control signals for refining the dynamic adjustment of tape tension and skew. These embodiments offer an exceptional combination of accuracy and efficiency in servo control systems.

A second aspect of the invention provides a tape drive comprising: a read/write head for reading and writing data on magnetic tape having at least one servo track for providing transversal position information; a drive system for effecting movement of the tape relative to the read/write head; and servo apparatus according to the first aspect of the invention.

A third aspect of the invention provides a servo control method for a tape drive having a read/write head for reading and writing data on magnetic tape with at least one servo track for providing transversal position information. The method comprises:

during read/write operations, reading at least one said servo track concurrently with at least two servo readers associated with the read/write head to generate respective servo read signals;

processing each servo read signal to generate a series of position values, corresponding to respective time instants, indicative of transversal position of the associated servo reader; and

calculating from said position values and time instants a skew value, indicative of tape skew relative to the read/write head, and a tension variation value indicative of variation of tape tension from a reference value, the calculation of the skew and tension variation values accounting for cross-coupling between tape skew and tension variation.

In general, where features are described herein with reference to an embodiment of one aspect of the invention, corresponding features may be provided in embodiments of another aspect of the invention.

Preferred embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings in which:

Figure 1 illustrates a modular read/write head used in existing tape drives;

Figure 2 is a schematic illustration of a tape drive embodying the invention;

Figure 3 is an enlarged view of the read/write head, illustrating the effect of tape skew, in the Figure 2 drive;

Figure 4 illustrates the TBS frame format for LTO servo patterns;

Figure 5 shows exemplary timing differences between signals from four servo readers on the read/write head; and

Figure 6 is a diagram of the read/write head geometry indicating effects of tape skew and tension variation on position and timing measurements.

Figure 2 is a simplified schematic of a tape drive 1 illustrating the main elements involved in implementing servo control functions embodying the invention. The tape drive 1 has a read/write head 2 for reading and writing data on magnetic tape 3. A drive system effects relative movement of the tape 3 and head 2 during read/write operations, conveying the tape past the head and controlling positioning of the head transversally across the width of the tape. Specifically, a reel-to-reel (R-R) drive mechanism 4 comprises motors for driving the tape reels (not shown), allowing the tape to be transported in either direction between a supply reel and a take-up reel. During this process, guide rollers (not shown) in the tape path control movement of the tape past the head. In this embodiment, these rollers can be tilted by operation of actuators 5, providing active tape guidance to counter tape skew as discussed below. A head drive mechanism 6 effects transversal movement of the read/write head 2 for initial alignment and track following during read/write operations.

The read/write head 2 of drive 1 is substantially identical to that described above with reference to Figure 1, having four servo readers S arranged on two modules with alternating read/write elements as shown in that figure. In contrast to the earlier system, however, all four servo readers S are active concurrently in operation of the present embodiment. During read/write operations, each servo reader S outputs a servo read signal r to a position estimator 8, only one signal r being indicated in the Figure 2 for simplicity. Position estimator 8 processes three of the four servo read signals r in generally known manner to produce a position error signal (PES) for the corresponding servo reader S. This process will be described in more detail below. In this embodiment, the fourth servo read signal is effectively a spare signal, being used in the event of failure of one of the other three servo readers. In the present example, position estimator 8 averages the three position error signals to produce an average PES signal which is fed back to a head position controller 9. This supplies an appropriate control signal to head drive 6 so that the head 2 is moved transversally to correct for positional errors.

In position estimator 8, the succession of transversal position estimates y derived in producing the position error signal for each servo reader S, and the time instants t to which these estimates correspond as discussed further below, are output to a servo controller 10. The servo controller processes the y, t values for the three servo readers S to calculate a skew value θ , a time derivative θ' of the skew value, a tension variation value ΔT , and a time derivative $\Delta T'$ of the tension variation value. The skew value θ constitutes an estimate of the skew angle of tape 3 relative to read/write head 2. This is illustrated in the enlarged view of Figure 3 which shows the skew angle θ defined in accordance with convention here as the azimuth angle between the normal to the head and the direction of tape motion. The tension variation value ΔT is an estimate of the deviation of the tape tension acting along the length of the tape from a reference value, here a predetermined desired or nominal value. The time derivatives θ' and $\Delta T'$ represent estimates of the rate of change of skew angle and tension variation respectively. The joint calculation of these values by servo controller 10 will be described in more detail below. The values of θ and θ' calculated from successive sets of y, t values are supplied by servo controller 10 to a skew adjustment mechanism. This comprises a skew controller 11 controlling guide roller actuators 5. Skew controller 11 supplies control signals based on the received values of θ and θ' to actuators 5 so as to tilt the guide rollers in the tape path to counter tape skew. Similarly, the values of ΔT and $\Delta T'$ calculated from successive sets of y, t values are supplied by servo controller 10 to a tension adjustment

mechanism. This comprises a tension controller 12 controlling reel-to-reel drive 4. Tension controller 12 supplies control signals based on the received values of ΔT and $\Delta T'$ to the reel motors to adjust the motor torque to counter tension variations. (In practice, the reel-to-reel drive 4 typically also operates under servo control dependent on tape velocity and LPOS information derived from the servo pattern as mentioned earlier, though these control operations are independent of the tension control servo and need not be discussed further here). Servo controller 10, skew controller 11 and tension controller 12 are conveniently implemented by digital circuitry, though in general these components could be implemented in hardware or software or a combination thereof, and suitable implementations will be apparent to those skilled in the art from the description herein.

During read/write operation of head 2, the upper and lower pairs of servo readers S read respective servo tracks on either side of the current data band on tape 3. In this example we assume that drive 1 is LTO-compliant and position estimator 8 is adapted to process TBS servo read signals. The TBS servo pattern frame format is illustrated in Figure 4. Each servo frame corresponds to one 200- μm period of the LTO servo pattern and consists of four servo bursts labeled A, B, C and D. The A and B bursts have 5 servo stripes whereas the C and D bursts have 4 stripes. The servo stripes consist of two transitions in magnetization that are 2.1 μm apart and are written at an azimuth angle of $\pm \pi/30$ radians (6 degrees). The servo stripes within a servo burst are spaced at a distance of 5 μm from each other. The difference in azimuth angles of the servo bursts means that the relative times at which a servo reader reads the first stripe of the A and B bursts depend on the transversal (y) position of the reader relative to the servo band centerline shown in the figure. In particular, the time difference between reading of the corresponding stripes of the A and B bursts changes with distance from the centerline. In contrast, the time difference between reading corresponding stripes of the A and C bursts is independent of y -position. Hence, a ratio of the A-B time difference to the A-C time difference provides a direct indication of transversal position of the servo reader relative to its desired position at the centerline. This ratio is independent of tape velocity v_T . The A-C time difference, however, is velocity-dependent and can be used to estimate the tape velocity v_T . Thus, as each servo reader S traverses frames of the servo pattern, a series of estimates y of the transversal position of that reader is generated as the position error signal PES for that reader. Each position value y in the series corresponds to a time instant t at which the corresponding frame of the servo pattern is read. For the four servo readers S on head 2, the relative timings at which these read servo frames depends on the geometry of the head, the servo frame length, and any offset between servo patterns in the two servo tracks, as

well as the effects of tape skew and tension variations. The read signals from the four servo readers, labeled a, b, c and d in Figure 3, may thus be offset in time as illustrated schematically in Figure 5. The illustrated time offsets Δt_{a-c} and Δt_{a-b} , together with the y-position estimates for the servo readers, form the basis of the calculations performed by servo controller 10 as will now be explained with reference to Figure 6.

Figure 6 shows an abstraction of the geometry of head 2 indicating the effects of skew and tension variation on various measurements. In this figure:

θ is the variation of azimuth angle due to tape skew;

$\Delta \ell_L$ is the change of tape length in the longitudinal direction due to tension variation ΔT ;

10 $\Delta \ell_T$ is the change of tape length in the transversal direction due to tension variation ΔT ;

Δy_u is the difference in position measured by servo reader c relative to the transversal position measured by servo reader a;

Δy_ℓ is the difference in position measured by servo reader d relative to the transversal position measured by servo reader b; and

15 v_T is the tape velocity.

With reference to this diagram, the equations of tape transport mechanics give:

$$\Delta \ell_L \approx \frac{\Delta T / k_T}{\ell_p} d_{a-c} \quad (1)$$

where ΔT is the deviation of the applied tension from the nominal value, k_T is the tape spring constant, and ℓ_p is the tape-path length. Assuming elastic behavior of the tape, for a length of tape equal to the width w , and tape thickness u , in the longitudinal direction the change in length for a variation of the applied tension is given by

$$\Delta \ell_w \approx \frac{w \Delta T}{w u E}$$

where E denotes the Young's modulus of the tape. Therefore the tape spring constant can be expressed as

$$25 \quad k_T = \frac{w u E}{\ell_p} \quad (2)$$

Consequently, for a length of tape equal to the distance d_{a-c} between two servo readers having the same transversal position on different modules of the head,

$$\Delta \ell_L \approx \frac{\Delta T}{u E} \frac{d_{a-c}}{w} \quad (3)$$

Observing (3) and recalling Hooke's law, the change in tape length in the transversal direction due to the deviation of the applied tension from the nominal value, and evaluated relative to one of the four data bands on a tape with the current LTO format, is expressed as

$$\Delta \ell_T \approx -v \frac{\Delta T}{4uE} \quad (4)$$

5 where v denotes the Poisson's ratio of the tape.

Recalling the head geometry and the servo format definition, introducing $d_{nom} = \text{mod}(d_{a-c}, 200 \mu\text{m})$, and $t_{nom} = d_{rel}/v_T$, where d_{rel} is the relative displacement in the longitudinal direction between servo patterns in adjacent servo bands, it is possible to establish the timing relationships of servo channel signals. In particular, four equations for the joint estimates of the skew value θ , the tension variation ΔT , and their respective time derivatives θ' and $\Delta T'$ can be derived as follows.

1. Considering the pair of servo readers a and b (or alternatively reader pair c and d), the azimuth θ can be expressed as

$$15 \quad \theta = \arctan\left(\frac{\Delta x}{d_{a-b}}\right) \approx \frac{\Delta x}{d_{a-b}} \quad (5)$$

where the function $\arctan(x)$ is approximated by its argument (x), assuming small values of x .

Assuming without loss of generality that in the absence of skew and tension variation the servo channels a and b are expected to produce estimates of the lateral servo reader position (y-estimates) at the time instants t_b and t_a , respectively, with $t_b - t_a = t_{nom}$, the segment Δx corresponds to the distance that the tape travels in the time interval $t_b - t_a - t_{nom}$, given by

$$20 \quad \Delta x_1 \approx v_T (t_b - t_a - t_{nom}) \quad (6)$$

corrected by the variation of tape length due to the variation of tension. Recalling (3), and observing that the variation of the tension ΔT in the considered interval is $\Delta T'(t_b - t_a)$, the correction term is given by

$$25 \quad \Delta x_2 \approx \frac{d_{a-c}}{w} \frac{\Delta T + \Delta T'(t_b - t_a)}{uE} \quad (7)$$

By substituting $\Delta x = \Delta x_1 - \Delta x_2$ into (5), and observing that the variation of azimuth in the considered interval is $\theta'(t_b - t_a)$, one gets

$$\theta \approx \frac{v_T}{d_{a-b}} \left[(t_b - t_a) \left(1 - \frac{d_{a-c}}{w} \frac{\Delta T'}{uE v_T} \right) - t_{nom} - \frac{d_{a-c}}{w} \frac{\Delta T}{uE v_T} \right] - \theta'(t_b - t_a) \quad (8)$$

2. Considering the pair of servo readers a and c (or alternatively reader pair b and d), the azimuth θ can also be expressed as

$$\theta = \arctan\left(\frac{\Delta y_u}{d_{a-c}}\right) \approx \frac{\Delta y_u}{d_{a-c}} \quad (9)$$

Denoting by $y_c(t_c)$ and $y_a(t_a)$ the y -estimates produced at the time instants t_c and t_a ,

5 respectively, and observing

$$\Delta y_u \approx y_c(t_c) - y_a(t_a) \quad (10)$$

one gets

$$\theta \approx \frac{y_c(t_c) - y_a(t_a)}{d_{a-c}} - \theta'(t_c - t_a) \quad (11)$$

10 3. Consider now the pair of servo readers a and c (or alternatively reader pair b and d).

Assuming without loss of generality that in the absence of skew and tension variation the

servo channels a and c are expected to produce y -estimates at the time instants t_c and t_a ,

respectively, with $t_c - t_a = d_{nom} / v_T$, the change in tape length for a variation of the applied

tension corresponds to the distance that the tape travels in the time interval $t_c - t_a - d_{nom} / v_T$,

15 given by

$$\Delta \ell_1 \approx v_T(t_c - t_a) - d_{nom} \quad (12)$$

corrected by the variation of traveled distance due to the azimuth error, that is approximated

as

$$\Delta \ell_2 \approx d_{a-c}(\theta + (t_c - t_a)\theta') \quad (13)$$

20 Observing (1) and (3), the change in tape length for a variation of the applied tension can be expressed as

$$\Delta \ell_L = \Delta \ell_1 - \Delta \ell_2 \approx d_{a-c} \left(\frac{\Delta T}{k_T \ell_p} + \frac{\Delta T'(t_c - t_a)}{wuE} \right) \quad (14)$$

By recalling the expression of the tape-path spring constant (2), substituting (12) and (13)

into (14), and rearranging terms, one gets

$$25 \quad \Delta T \approx \frac{wuE}{d_{a-c}} [v_T(t_c - t_a) - d_{nom} - d_{a-c}\theta - d_{a-c}(t_c - t_a)\theta'] - \Delta T'(t_c - t_a) \quad (15)$$

4. Consider now the pair of servo readers a and b (or alternatively pair c and d). The change in tape length in the transversal direction, which is due to the deviation of the applied tension from the nominal value and is evaluated relative to one of the four data bands on a tape with

the current LTO format, can be expressed as the difference in the y -estimates that are produced by the servo channels a and b at the time instants t_a and t_b , respectively, given by

$$\Delta \ell_3 \approx y_a(t_a) - y_b(t_b) \quad (16)$$

corrected by the variation in distance in the transversal direction between adjacent servo

5 bands that is due to skew, that is approximated as

$$\Delta \ell_4 \approx d_{a-b}(\theta + (t_b - t_a)\theta') \quad (17)$$

Observing (4), the change in tape length in the transversal direction for a variation of the applied tension can thus be expressed as

$$\Delta \ell_T = \Delta \ell_3 - \Delta \ell_4 \approx -v \frac{\Delta T + \Delta T'(t_b - t_a)}{4uE} \quad (18)$$

10 By substituting (12) and (13) into (14) and rearranging terms, one gets

$$\Delta T \approx \frac{4uE}{v} [y_b(t_b) - y_a(t_a) + d_{a-b}\theta + d_{a-b}(t_b - t_a)\theta'] + \Delta T'(t_b - t_a) \quad (19)$$

It will be seen that each of derivations 1 to 4 in the foregoing analysis provides a formula for skew or tension variation which accounts for both cross-coupling between these quantities, i.e. the effect of one on the other, and time dependency of the quantities, the latter having an effect on measurements due to the timing offsets between read signals from different servo readers. (Note that in derivation 2 the effect of tension variation on the position estimates $y_c(t_c)$ and $y_a(t_a)$ effectively cancels out since the difference between these values is used in the formula for θ). The four equations (8), (11), (15), (19) yielded by this analysis can be solved for the four variables θ , θ' , ΔT , and $\Delta T'$. In this embodiment, the solutions to these equations are used by servo controller 10 to calculate values of θ , θ' , ΔT , and $\Delta T'$ for each set of three y , t value-pairs output by position estimator 8 for the three servo readers for which these values are derived. The resulting values are output to controllers 11 and 12 for effecting adjustments to the tape transport system to compensate for skew and tension variations as described above. In particular, to compensate for dynamic skew, the skew controller 11 generates control signals for the guide roller actuators 5 to tilt the rollers in the tape path to correct for the angle of skew. This can be done in generally known manner as will be apparent to those skilled in the art. The estimated derivative θ' is preferably used in a state-space based realization of the control system, as the derivative θ' can be expressed as a linear combination of the state variables describing the dynamics of the physical plant being controlled. By way of example, a state-space based control system for controlling tilting rollers is described in "Control of Lateral Motion in Moving Webs", Yerashunas et al., IEEE

Transactions on Control Systems Technology, Vol. 11, No. 5, September 2003. Similarly, to compensate for tension variation from a nominal value, the tension controller 12 generates control signals for the motors of the reel-to-reel system to adjust the motor torque and hence the tape tension. Again this can be done in generally known manner, one particular example being discussed in “Controller Development for a Prototype High-Speed Low-Tension Tape Transport”, Mathur et al., IEEE Transactions on Control Systems Technology, Vol. 6, No. 4, July 1998. As in the case of dynamic skew compensation, the estimated derivative $\Delta T'$ is preferably used in a state-space based realization of the reel-to-reel control system. In determining the reel-to-reel drive control signals, the tension controller 12 could adjust for the fact that changes in the distance between the servo bands can also result from creep effects or due to the swelling or shrinking of the tape as it absorbs or expels water as the ambient humidity changes. These effects, however, occur on a much longer time scale than the typical “once-around” tension variations discussed above, and therefore only interfere with the estimation of the steady state tension and not estimation of dynamic tension variations, i.e., the AC component of the tension. The control signal supplied to drive mechanism 4 could therefore be based on an absolute tension value obtained using the known or estimated motor torque constants and reel radii to generate the desired nominal tape tension (as is currently done for tension control), with the estimated dynamic tension variation used to generate an AC correction term. This correction term would have a maximum amplitude that is limited to the range of typical maximum tension excursion due to once around reel eccentricities, corresponding to about +/- 20% of the nominal tension.

It will be seen that the foregoing provides a highly efficient servo control system for tape drive 1 using joint estimation of dynamic skew and tension variation, and accounting for cross-coupling and time-dependent effects, based on concurrent operation of three servo readers S during read/write operations. The signal from the fourth servo reader provides enough redundancy to enable the generation of the estimates even in the case of failure of one of the servo readers. Overall, therefore, the embodiment described provides a simple, robust and highly accurate servo control system.

While one preferred embodiment has been described above, various alternatives and modifications can be envisaged. For example, different adjustment mechanisms for correcting for skew or tension variation can be employed in other embodiments. To counter skew effects, instead of adjusting tape positioning via roller actuators 5, a head-skew actuator may be employed to adjust the position of head 2 so that the head is kept perpendicular to the

direction of tape motion. Tensioning bars, rollers, etc. could also be employed for adjusting tape tension rather than adjusting the tape reel motor torque as described above.

The fourth servo reader need not be operative concurrently with the other three, but could be activated only when required. Alternatively, this fourth signal could be employed to
5 generate a second set of estimates, which could be used to improve the quality of the estimates by averaging in servo controller 10. In addition, individual estimates for θ , θ' , ΔT , and $\Delta T'$ may be averaged over a number of successive calculations, or other filtering operations may be employed in servo controller 10 to reduce the standard deviation of the estimates supplied to controllers 11, 12. Such filtering operations can be performed in
10 generally known manner as will be apparent to those skilled in the art. Embodiments can also be envisaged in which the position values y and the corresponding time measurements (in particular differences between time instants) are averaged or filtered over several measurements, the resulting values then being used by the servo controller to calculate the skew and tension variation values. In simplified embodiments, the effects of time dependency
15 of θ and ΔT may not be taken into account so that only values for θ and ΔT , and not their time derivatives, are calculated by the servo controller. The necessary modifications to the formulae derived above will be apparent to those skilled in the art for this situation. In such embodiments, any two servo readers S operated concurrently will be sufficient for the necessary calculations, the remaining servo read signals offering redundancy in the case of
20 failure or being used to increase accuracy as described above. It will of course be appreciated that many other changes and modifications can be made to the exemplary embodiments described without departing from the scope of the invention.

CLAIMS

1. Servo apparatus for a tape drive (1) having a read/write head (2) for reading and writing data on magnetic tape (3) with at least one servo track for providing transversal
5 position information, the apparatus comprising:
 - at least two servo readers (S) associated with the read/write head (2), each arranged for reading a said servo track during read/write operations, the servo readers (S) being operative concurrently to generate respective servo read signals (r);
 - 10 a position estimator (8) for processing each servo read signal (r) to generate a series of position values, corresponding to respective time instants, indicative of transversal position of the associated servo reader (S); and
 - a servo controller (10) for calculating from said position values and time instants a skew value (θ), indicative of tape skew relative to the read/write head (2), and a tension variation value (ΔT) indicative of variation of tape tension from a reference value, the servo
15 controller (10) being adapted to account for cross-coupling between tape skew and tension variation in calculating the skew and tension variation values.
2. Apparatus as claimed in claim 1 wherein the servo readers comprise a pair of servo readers (S) arranged for reading the same servo track.
20
3. Apparatus as claimed in claim 1 or claim 2 wherein the servo readers comprise a pair of servo readers (S) arranged for reading different servo tracks spaced transversely across the tape (3).
- 25 4. Apparatus as claimed in any preceding claim including at least three servo readers (S) arranged for reading at least two servo tracks and operative concurrently to generate respective servo read signals (r).
5. Apparatus as claimed in claim 4 wherein the three servo readers (S) comprise a pair
30 arranged for reading a first servo track and a third arranged for reading a different servo track spaced transversely across the tape (3) from the first servo track.
6. Apparatus as claimed in claim 5 including a fourth servo reader (S) arranged for reading said different servo track.

7. Apparatus as claimed in any one of claims 4 to 6 wherein the servo controller (10) is further adapted to account for time dependency of tape skew and tension variation in calculating the skew and tension variation values (θ , ΔT), and to calculate respective time derivatives (θ' , $\Delta T'$) for the skew and tension variation values.
8. Apparatus as claimed in any preceding claim including a tension adjustment mechanism (12, 4) for adjusting tape tension in dependence on said tension variation value (ΔT), and a skew adjustment mechanism (11, 5) for adjusting tape skew relative to the read/write head in dependence on said skew value (θ).
9. Apparatus as claimed in claim 7 and claim 8 wherein the tension adjustment mechanism (12, 4) is adapted to adjust tape tension in dependence on said tension variation value (ΔT) and said time derivative ($\Delta T'$) therefor, and the skew adjustment mechanism (11, 5) is adapted to adjust tape skew in dependence on said skew value (θ) and said time derivative (θ') therefor.
10. Apparatus as claimed in any preceding claim wherein the position estimator (8) is adapted to process TBS servo read signals to generate said position values.
11. A tape drive (1) comprising:
a read/write head (2) for reading and writing data on magnetic tape (3) having at least one servo track for providing transversal position information;
a drive system (4, 5, 6) for effecting movement of the tape (3) relative to the read/write head (2); and
servo apparatus as claimed in claim 8 or claim 9.
12. A servo control method for a tape drive (1) having a read/write head (2) for reading and writing data on magnetic tape (3) with at least one servo track for providing transversal position information, the method comprising:
during read/write operations, reading at least one said servo track concurrently with at least two servo readers (S) associated with the read/write head (2) to generate respective servo read signals (r);

processing each servo read signal (r) to generate a series of position values, corresponding to respective time instants, indicative of transversal position of the associated servo reader (S); and

5 calculating from said position values and time instants a skew value (θ), indicative of tape skew relative to the read/write head (2), and a tension variation value (ΔT) indicative of variation of tape tension from a reference value, the calculation of the skew and tension variation values accounting for cross-coupling between tape skew and tension variation.

13. A method as claimed in claim 12 including concurrently reading a first servo track
10 with a pair of servo readers (S) and a different servo track, spaced transversely across the tape from the first servo track, with a third servo reader (S) to generate respective servo read signals (r).

14. A method as claimed in claim 12 or claim 13 including adjusting tape tension in
15 dependence on said tension variation value (ΔT), and adjusting tape skew relative to the read/write head (2) in dependence on said skew value (θ).

15. A method as claimed in claim 12 or claim 13 wherein the calculation of the skew and
20 tension variation values accounts for time dependency of tape skew and tension variation, the method including:

calculating respective time derivatives (θ' , $\Delta T'$) for the skew and tension variation values (θ , ΔT);

adjusting tape tension in dependence on said tension variation value (ΔT) and said time derivative ($\Delta T'$) therefor; and

25 adjusting tape skew relative to the read/write head (2) in dependence on said skew value (θ) and said time derivative (θ') therefor.

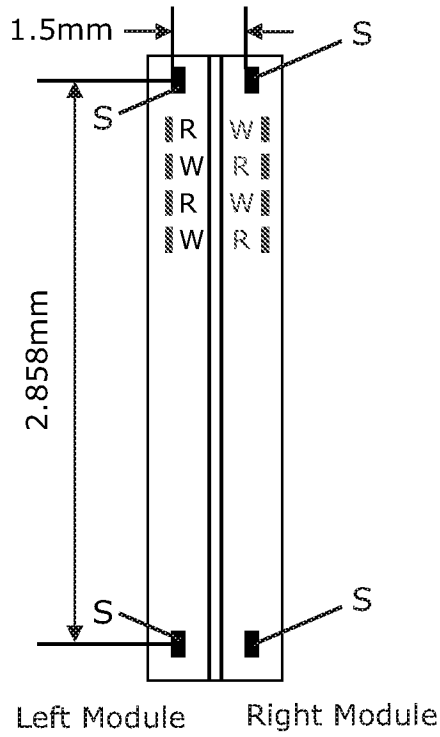


Fig. 1

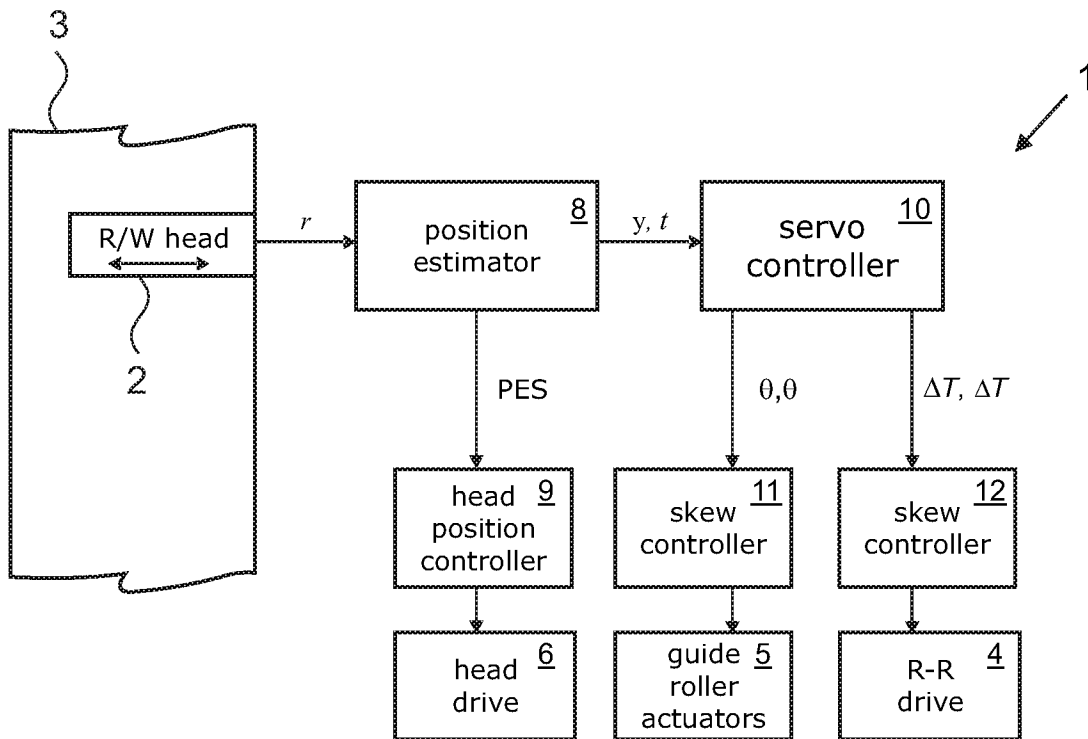


Fig. 2

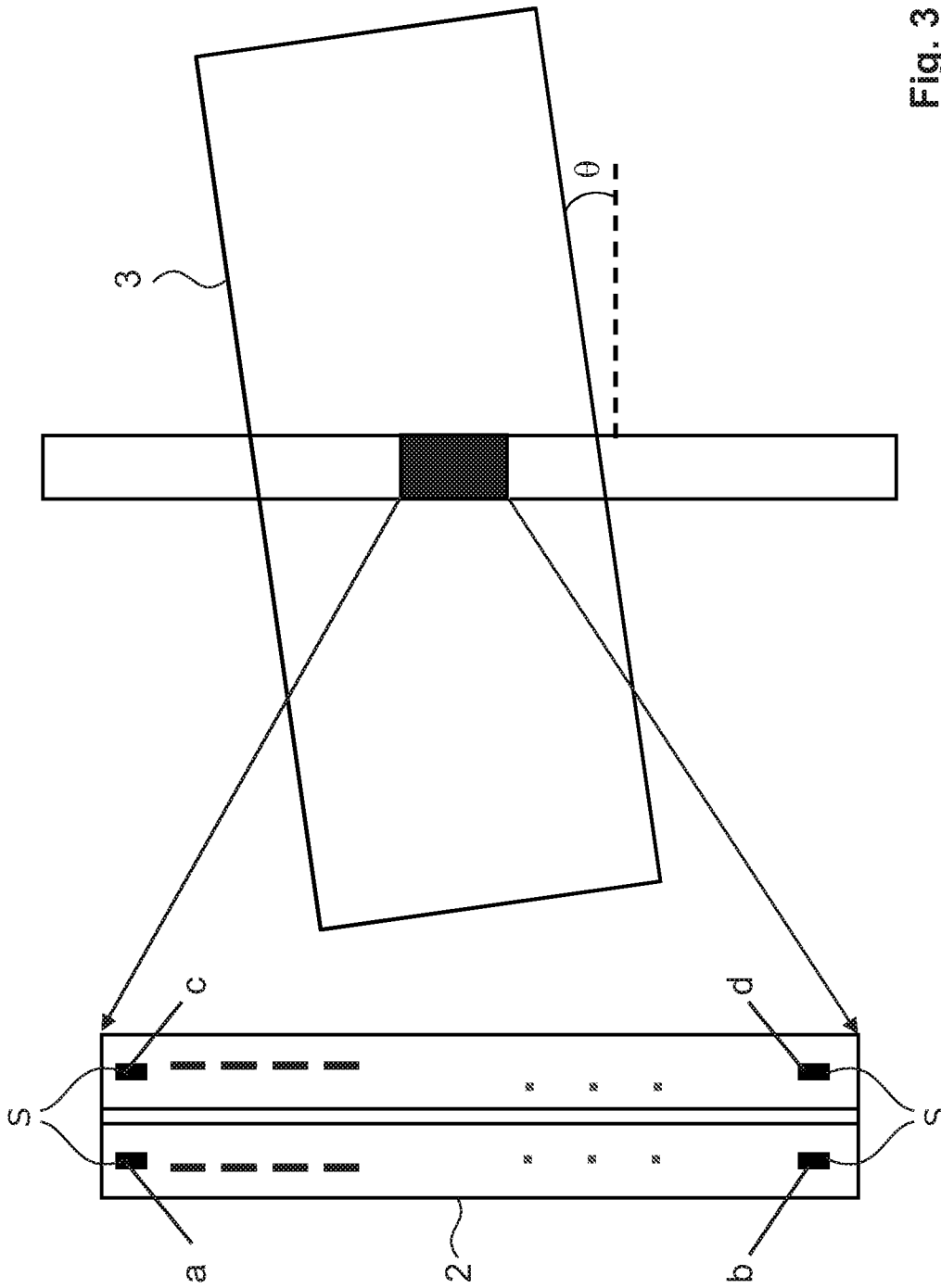


Fig. 3

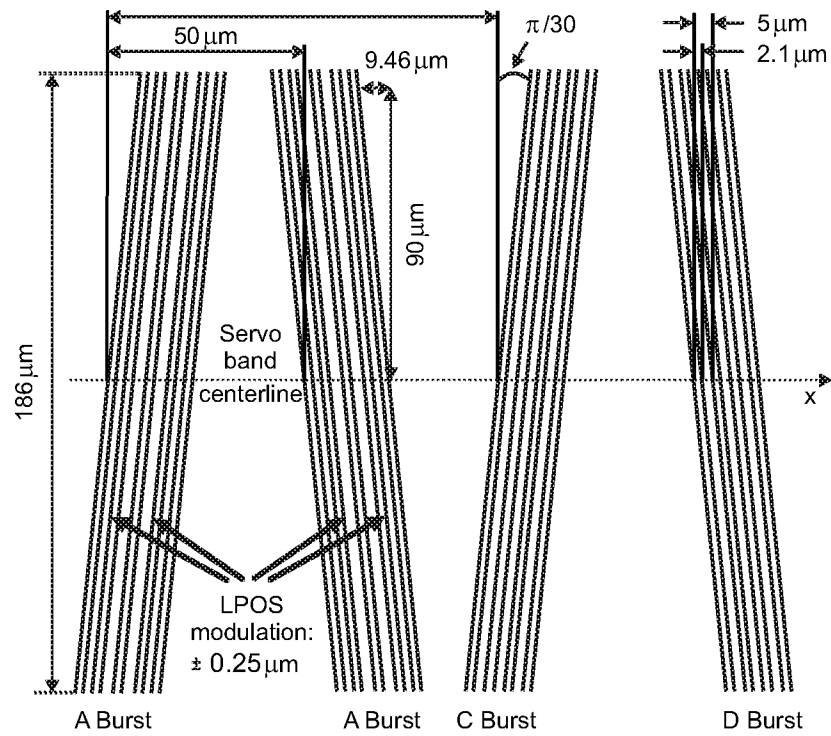


Fig. 4

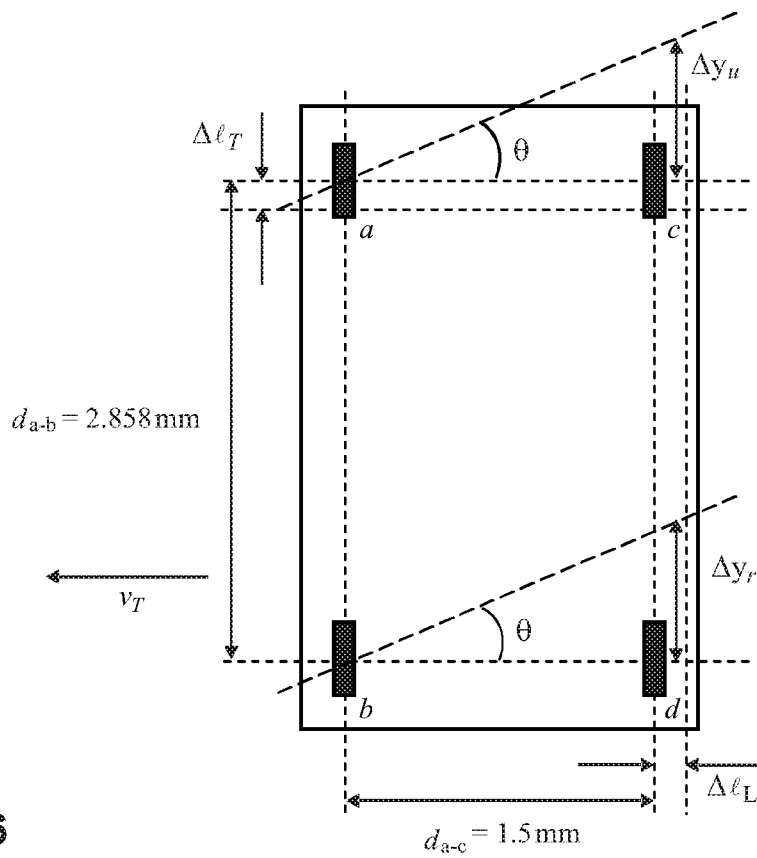


Fig. 6

Top servo pattern signals

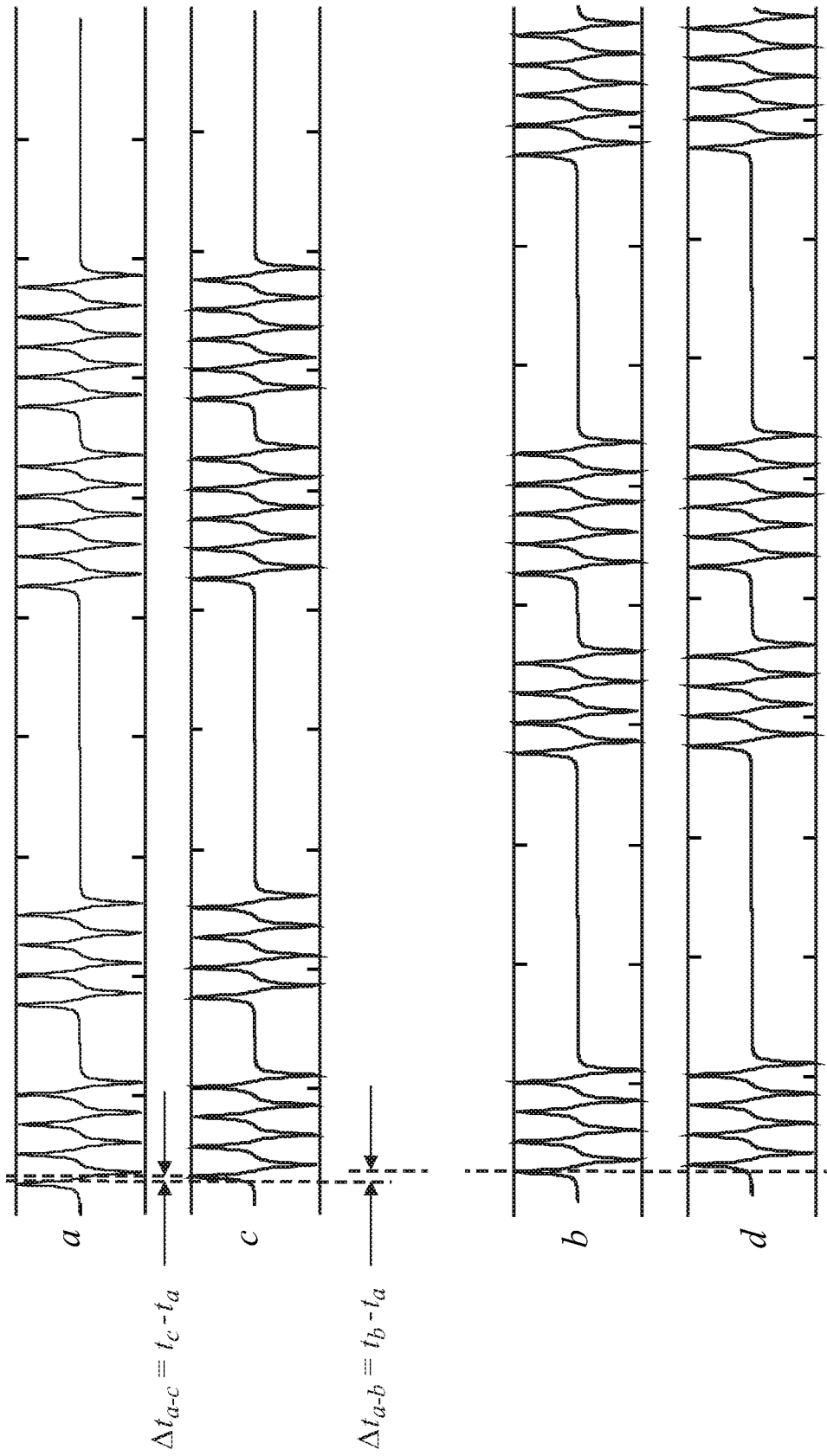


Fig. 5