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HIGH-PERFORMANCE ADAPTIVE-SPEED/CAV CD-ROM DRIVE

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Abstract— This paper describes a novel type of CD-ROM drive which can automatically distinguish between two basic operating modes: continuous playback and continuous access. The drive, based on the adaptive-speed technology, is optimized for a very high data throughput during sustained read-out using a new cubic overspeed profile. In addition, by detecting the state of continuous access and switching the spindle motor into a CAV (constant angular velocity) loop, the drive features very low power consumption. Two dedicated firmware algorithms which can detect one of the two operating modes either at the bit-engine level or at the data-path level are also presented. While implementing the algorithm at the data-path level, the paper will also approach a novel technique for the optimization of the data flow via controlling the speed of the spindle motor. A better buffer management can therefore be achieved. Last but not least, the cubic overspeed profile is shown to be optimal not only for sustained playback but also while the drive is performing either a unique seek action or a short sequence of seeks.

Keywords— access time, adaptive-speed, bit rate, CAV control, CD-ROM, CLV control, data throughput, quasi-CLV control, seek time.

I. INTRODUCTION

NOWADAYS, the performance of a CD-ROM drive is being evaluated mainly in terms of data throughput, average access time and CPU (central processing unit) utilization. One of these performance indicators, namely the latter one, is primarily determined by the data-path firmware (particularly by the buffer management) and the CD-ROM driver installed on the host computer.

However, the first two specification points mentioned above are intrinsically related to the bit engine of the drive. Although the entire data channel between the bit engine and the host computer will still have a contribution to the overall access performance, it is basically the bit engine which determines the speed of searching between two locations on the disc. As for the sustained data throughput, it is again and only the bit engine which can improve this figure.

In order for a CD-ROM drive to boost its general performance, a trade-off has always been made between achieving a high data throughput during continuous playback and still keeping a low average seek/access time (which is

measured during continuous access). It will be shown in this paper that, by using an adequate software algorithm to distinguish between continuous playback and continuous access, it is possible to lighten the trade-off requirements. As a consequence, the drive can separately be optimized for data throughput as well as for average access time. An additional feature of such a drive is the reduced power dissipation which takes place in the spindle motor loop while continuously accessing in CAV mode.

II. CAV AND CLV MOTOR CONTROL

Before proceeding further, it will be worth to briefly describe two basic methods for driving a rotary DC motor. These two control techniques, generally known as constant angular velocity (CAV) and constant linear velocity (CLV), are particularly found in data storage devices.

The most simple way to achieve a steady state of rotation is to feed the motor coils with a constant voltage. The angular frequency the motor shaft rotates with will hence be given by the well-known Laplace equation [1], [2]

$$\Omega(s) = \frac{UK_m}{(sL_a + R_a)(sJ_{rot} + D) + K_m^2} \quad (1)$$

where U is the supplied voltage, K_m is the torque constant, L_a and R_a are the inductance and respectively the resistance of the motor armature, J_{rot} is the moment of inertia at the motor shaft and D is the damping (or viscous friction). The numerical value of K_m is equal to the back e.m.f. constant K_e when both are expressed in the SI system of units. By using Eq. (1) and eventually employing a feedback loop, the resulted angular frequency can be kept constant in time.

A second method to drive a DC motor is mostly related to an information carrier (such is a compact disc) which is recorded with linearly distributed information. In this case, the linear velocity v measured at a distance R from the motor shaft (at which the information is located during the read-out) should be kept constant. This control technique will always need a feedback loop to adjust the supplied voltage such that

$$v(t) = \omega(t)R(t) = \text{const} \quad (2)$$

where all variables depend on time at each read-out moment. It follows from the above equation that a change ΔR of the read-out position will always imply an opposite change $\Delta\omega$ of the angular frequency. This very particular situation has been approached in detail in [3] in case of

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a CD-ROM drive. However, the CLV control can also be found in tape-based systems, such as the audio compact cassette or the video recorders.

III. DATA THROUGHPUT VERSUS ACCESS TIME

During the last couple of years, the market of the CD-ROM drives has witnessed two important trends:

First of all, by increasing the disc rotational frequency, the so-called "X-factor" [4] has been boosted in order to increase the transfer rate of the drive. This approach has forced the designers to carefully deal with a larger spectrum of vibrations distorting the system, but also to solve in one way or another the problem of power dissipation in the motor control loop.

Secondly, the access time of the drive has been substantially reduced from about 270-300 ms featured by the 2X drives in 1992 to about 110 ms (or even below 100 ms for some models) at the present time. And there is no reason to believe this race will not go on, even for the mere fact that everyone wants to search faster through a data base, for example.

At the engine level, there are still some remarks to be made with respect to the trade-off between very high data-throughput values and very low seek times. On one hand, as it has already been shown in [3], the CLV control becomes of no use when the optical head moves very fast from one location to another along the disc radius. Hence, the pure CLV mode should be avoided in those systems where very short seek times are desired. On the other hand, because the compact disc is prerecorded with a constant linear velocity, the CLV mode remains the only way to control the spindle motor such that an absolute maximum in terms of bit rate will be achieved. There are two alternative solutions to this trade-off: either implementing a full CAV control (which worsens the average bit rate of the engine) or implementing an adaptive-speed profile based on quasi-CLV control, as described in [3]. In turn, a well-implemented adaptive-speed technique requires a suitable optimization.

Our last remark herein concerns the terms of seek and access time. Without introducing a significant error, it can be considered that only a constant time difference separates these two drive parameters [5]. It will be therefore of less importance for the purpose of this paper if we are talking about seek or access time.

IV. THE COMBINED ADAPTIVE-SPEED/CAV SYSTEM

A. Quasi-CLV revisited

The use of the quasi-CLV mode, which practically dominates the control of the spindle motor in high-end drives (under names such pseudo-CLV, variable playback system, etc.) offers the cheapest way to implement an adaptive-speed algorithm when compared to a tacho control. Other advantages of the quasi-CLV technique are summarized below:

- reduces the seek time of the bit engine by allowing the system to deliver data as soon as the right track has been found after a seek action;

- no need for very powerful spindle motors when compared with CLV control at the same overspeed, because the acceleration or brake possibilities of the motor hardly affect the average seek performance;
- during sustained read-out, features the same bit rate as a classical CLV system of the same overspeed.

Fig. 1. Simulated variations of the disc radius, disc rotational frequency, data overspeed N (X-factor) and data validity flag during an outward-oriented third-stroke seek starting from the inner radius of the disc, in a quasi-CLV system.

A typical example of an outward-oriented seek action in a quasi-CLV system is illustrated in Fig. 1. The reader should notice that, because the spindle motor is being driven by the real-time linear velocity of the disc, it will be always braked while seeking outwards (or accelerated for inward-oriented seeks).

This situation is depicted in Fig. 2 as recorded during a benchmark test. The motor does not arrive at a steady-state speed nor reaches its final quasi-CLV velocity. However, because the motor driver (motor IC) is driven in saturation, additional power dissipation will take place.

One very important remark should be made at this point: **due to the quasi-CLV control, the average seek performance of the engine (access performance when talking about the whole drive) does not differ from the performance of the same drive as it were driven in full CAV.** This feature represents, in fact, the most important strength of the quasi-CLV control.

Fig. 2. Measured signals during a full-stroke access in a quasi-CLV drive. The overspeed in the system (plotted above) reaches a maximum value only during the first seek and oscillates afterwards within the decoder limits without distorting the seek performance. The price to be paid is due to the power dissipation in the motor loop where the motor driver is controlled in saturation (voltage plotted below).

B. The need for CAV control

As shown in the previous subsection, the spindle motor keeps braking and accelerating if a long sequence of seek actions is carried out. As a matter of fact, we are not interested at all in boosting the sustained bit rate of the engine during continuous seeking. On the other hand, we have also mentioned before that a CAV system would not necessarily perform better than its quasi-CLV counterpart with respect to the average seek time.

However, at higher rotational speeds, the power dissipated in the motor control loop during a long sequence of seeks becomes very important. This disadvantage has been only recently emphasized, since the very high-speed drives have become a reality. Moreover, with the 18X and even 24X or 30X drives at the horizon, the power dissipation in the motor control loop turns into a problem to be solved. At these speeds the temperature of some loop components can reach disastrous values. A typical situation is shown in Fig. 3 where the temperature of a motor IC is plotted versus time from the beginning of a repeated sequence of full-stroke seeks.

As a conclusion of this subsection, it is quite obvious that we cannot tolerate anymore a motor loop which accelerates and brakes the motor during continuous seeking. This means that **CAV control should be used but, again, not because of a better seek performance compared to quasi-CLV.**

Fig. 3. The temperature of the motor IC (passively cooled via a heat sink) during continuous full-stroke seeking. The evaluated system used quasi-CLV control between 12X at the inside and 18X at the outside of the disc.

C. The adaptive-speed/CAV combination as optimal choice for a CD-ROM drive

We are now in a position to define a novel CD-ROM system which is able to optimally function under all circumstances and which can guarantee high-end performance for the following situations:

Continuous read-out of data. A quasi-CLV motor control governed by a carefully optimized adaptive-speed algorithm such that a very high bit rate is obtained, on average, for the whole disc.

Solely performed seek. A quasi-CLV control which, in combination with the chosen adaptive-speed algorithm, does not lengthen at all or only with acceptable quantities the servo-mechanical seek time. Besides, from the moment the right data has been found after a performed seek, the motor speed will be regulated back to a value corresponding to a high bit rate.

Short sequence of seeks. Quasi-CLV control, which performs equally well when compared to a CAV system, but yet has the advantage of bringing back the motor speed to a value corresponding to a high bit rate. Power dissipation in the motor control loop does not represent an issue when only a few consecutive seeks are performed.

Long sequence of seeks. CAV control, which has the advantage of less power dissipation in the motor loop. A high bit rate during continuous seek is not only impossible to achieve but is also hardly needed.

In addition to the above system description, a software algorithm will be needed to detect the state of the system and choose the right motor control mode.

V. A NEW AND HIGHLY-OPTIMIZED SPEED PROFILE

It is a fact that, at this very moment, almost every drive on the market uses an adaptive-speed algorithm [3] though not always optimized for maximum bit rate. For example, some CD-ROM drives use a combination between CAV at the inside of the disc and (quasi-)CLV at the outside, which is mostly chosen because of the rotational frequency limitations imposed by the tracking servo. Other drives let the overspeed (X-factor) smoothly vary from the inner to the outer diameter of the disc, but again, without paying attention to the right optimum.

We shall present within this paper, however, a novel adaptive-speed profile which is optimized for maximum bit rate during sustained read-out as well as for seeks of an average length equal to one-third stroke.

A. After-seek over- and underspeeds

Due to the fact that the information is recorded onto the disc with a constant velocity along the spiral, the data processing unit (compact-disc decoder) will always detect an overspeed at the end of an outward-oriented seek, respectively an underspeed while seeking towards the inner diameter. This phenomenon does not depend on the choice of the motor control.

In order to calculate the overspeed values occurring after seeks, we recall the fact that most motor drivers steer the spindle motor in current-limited mode. This is necessary in order to avoid the power dissipation due to the relatively large currents flowing through the coils while the motor accelerates or brakes.

It can be shown that, if an outward-oriented seek of length ΔS seconds has to be carried out starting from the subcode timing S_i , the overspeed N_{out} which occurs is given by

$$N_{out}(T_{seek}, S_i, \Delta S) = \frac{2\pi R_{target}}{v_a} \times \left[f_i - (f_{max} + f_i) \left(1 - \exp \left(-\frac{T_{seek}}{\tau_{mech}} \right) \right) \right] \quad (3)$$

where T_{seek} represents the time necessary to move the optical pick-up unit to the new location,

$$R_{target} = \sqrt{R_{in}^2 + \frac{v_a q (S_i + \Delta S)}{\pi}} \quad (4)$$

is the disc radius where the new target subcode is located,

$$f_i = \frac{v_a N_i}{2\pi} \left(R_{in}^2 + \frac{v_a q S_i}{\pi} \right)^{-1/2} \quad (5)$$

determines the rotational frequency of the motor before carrying out the seek action and

$$f_{max} = \frac{K_{sw} I_{max} K_m}{2\pi D} \quad (6)$$

is the maximum rotational frequency the motor can achieve when driven with a maximum current I_{max} . The other parameters involved in the above equations are either defined by the disc standard [6] such as

- $v_a = 1.3 \text{ m/s}$ – linear velocity of the audio disc
- $R_i = 25 \text{ mm}$ – inner radius of the program area
- $q = 1.6 \text{ } \mu\text{m}$ – track pitch

or belong to the motor control loop:

- K_{sw} – coefficient less than one, determined by the current losses in the motor IC during commutation
- τ_{mech} – mechanical constant of the motor, being equal to J_{rot}/D when the motor works with current saturation
- K_m – torque constant of the motor
- D – viscous damping
- J_{rot} – moment of the inertia at the motor shaft

Note that, if the motor is driven with voltage instead of current saturation, the coefficient K_{sw} will depend on the voltage losses during commutation, the mechanical time constant in Eq. (3) will be replaced by the time constant of the whole motor

$$\tau_{mot} = J_{rot} \left(D + \frac{K_m^2}{R_a} \right)^{-1} \quad (7)$$

and the maximum rotational frequency the motor can reach will be determined by

$$f_{max} = \frac{1}{2\pi} \cdot \frac{K_{sw} K_m U_{max}}{R_a} \left(D + \frac{K_m^2}{R_a} \right)^{-1} \quad (8)$$

where U_{max} is the maximum voltage applied to the motor coils and R_a is the armature resistance.

In a similar manner we can calculate the underspeed which occurs after an inward-oriented seek

$$N_{in}(T_{seek}, S_i, \Delta S) = \frac{2\pi R_{target}}{v_a} \times \left[f_i + (f_{max} - f_i) \left(1 - \exp \left(-\frac{T_{seek}}{\tau_{mech}} \right) \right) \right] \quad (9)$$

and again, the remarks made for the case of a voltage-limited driven motor hold for the relation (9) as well.

The over- and underspeed given by Eqs (3) and (9) can be further used to better trigger the optimization of the adaptive-speed profile we are interested in.

Fig. 4. Overspeed profile and related rotational frequency for a linear variation of the X-factor with respect to the disc radius (i.e. quadratic variation of the X-factor with respect to the subcode timing).

B. Adaptive-speed cubic profile

A speed profile varying linearly with the disc radius between two fixed overspeeds N_{in} and N_{out} has already been described in [3] and is given by

$$N(R_x) = \frac{N_{out} - N_{in}}{R_{out} - R_{in}} (R_x - R_{in}) + N_{in} \quad (10)$$

with R_{in} and R_{out} being respectively the inner and outer disc radii. A formula for the average bit rate has also been given in the mentioned paper.

We shall rewrite herein the formula for the average bit rate in order to make use of the subcode timing recorded onto the disc. The relation we get is

$$B_{av} = \frac{B_a}{S_{tot}} \int_0^{S_{tot}} N(S_x) dS_x \quad (11)$$

where $B_a = 150 \text{ kB/s}$ is the constant bit rate of a disc spinning at $N = 1$ and $N(S_x)$ is the real-time overspeed which depends on a particular subcode timing S_x .

It is quite obvious from (11) that a higher bit rate can be achieved if the curve $N = N(S_x)$ displays more convexity with respect to its variable. By using Eq. (10) we obtain a quadratic function of S_x which is plotted in Fig. 4 for a system with $N_{in} = 12$ and $N_{out} = 18$.

By shaping this profile further away from its abscissa we can increase the average bit rate of the system. However, we do not want to exceed a maximum given overspeed when seeking outwards. For this reason the upper limit of the desired convexity will be set by Eq. (3) while the requirement imposed by Eq. (9) will become more relaxed as the profile is shaped away from its x-axis.

As a numerical example, we shall reshape the system from Fig. 4. The starting conditions for our calculations are the following:

- the overspeed N_M which occurs at the end of a full-stroke outward-oriented seek will be considered as an absolute maximum in the system;
- a chosen maximum overspeed $N_{max} \leq N_M$ should never be exceeded at the end of an outward-oriented third-stroke seek performed from an initial subcode timing randomly chosen onto the disc;
- we will allow a small portion of the new profile, at higher subcode timings, to remain flat and constant, equal to the final quasi-CLV overspeed N_{out} ; this can be done under the assumption that third-stroke seeks within this region are not possible whilst smaller seeks will not lead to overspeeds greater than N_{max} ;
- because we intend to shape more the convexity of the overspeed profile, there will be, obviously, no problems when seeking inwards from any location on the disc; the lowest underspeed in the system (obtained at the end of a full-stroke inward-oriented seek) will also correspond to a CAV profile and is approximately equal to $N_{out} R_{in}/R_{out}$.

Under the conditions stated above, the overspeed (X-factor) allowed during sustained read-out of the subcode timing S_i will be given by the relation

$$N_i(T_{seek}, S_i, \Delta S) \leq \frac{A}{v_a} \cdot \frac{K_{sw} I_{max} K_m}{D} \sqrt{R_{in}^2 + \frac{v_a q S_i}{\pi}} + \frac{N_{max}}{1-A} \sqrt{\left(R_{in}^2 + \frac{v_a q S_i}{\pi}\right) \left(R_{in}^2 + \frac{v_a q (S_i + \Delta S)}{\pi}\right)^{-1}} \quad (12)$$

where, for a current-limited motor driving,

$$A = 1 - \exp\left(-\frac{T_{seek}}{\tau_{mech}}\right) \quad (13)$$

and N_{max} is given by Eq. (3) for $S_i = 0'2''.$ 00 and $\Delta S = 60'$. For a typical motor loop we have $K_{sw} = 0.9$, $I_{max} = 0.75 \text{ A}$, $K_m = 11.3 \cdot 10^{-3} \text{ Nm/A}$, $D = 3.9 \cdot 10^{-6} \text{ Nm/s}$ and $J_{rot} = 32 \cdot 10^{-6} \text{ kg} \cdot \text{m}^2$ while typical values for the sledge

displacement are $T_{seek} = 200 \text{ ms}$ for a full stroke, respectively $T_{seek} = 90 \text{ ms}$ for a third stroke. These values lead to $N_{max} = 23.7$ for $N_{in} = 12$.

Further, we have to find an overspeed profile which fulfills the inequality (12) for all values of S_i and the corresponding seek lengths ΔS . The solution to this problem is the curve determined by

$$N_i(S_i) = \min\{N_i(T_{seek}, S_i, \Delta S)\} \Big|_{S_i \leq \Delta S \leq S_{max}} \quad (14)$$

where T_{seek} depends on the sledge mechanics and electronics via the number of tracks

$$\Delta N_{track}(S_i, \Delta S) = \sqrt{\left(\frac{R_{in}}{q}\right)^2 + \frac{v_a (S_i + \Delta S)}{q\pi}} - \sqrt{\left(\frac{R_{in}}{q}\right)^2 + \frac{v_a S_i}{q\pi}} \quad (15)$$

to be crossed over during a seek action.

Without minimization, the relation (14) leads to a three-dimensional plot of overspeeds but after minimization an overspeed profile can be extracted. In practice, there is a simpler approach to this problem. We can take into account an average seek length $\Delta S_{av} = 20 \text{ min}$ for a 60-min data disc (see [5] for the related calculations) and use further Eq. (12) to determine the maximum N_i overspeeds for a couple of points between the start and the end of the subcode timing. Accordingly, a polynomial of a certain degree will be fitted through these points. Due to statistical reasons, we are entitled to use only an average seek length ΔS_{av} instead of minimizing (14) for $S_i \leq \Delta S \leq S_{max}$. The error introduced by this statistical (and practical) approach is insignificant with respect to (14).

For our numerical example from Fig. 4 we start from a given maximum rotational frequency in the system which cannot be exceeded due to servo-mechanical limitations. Accordingly, an overspeed $N_{in} = 12$ at the inner radius can be defined. On the other hand, the overspeed N_{out} during playback at the outer radius of the disc will be determined by the maximum speed the decoder can still cope with and the tolerances introduced by the quasi-CLV loop. For a decoder able to work up to $N_{dec} = 18.5$ we carefully choose $N_{out} = 18$.

Further, as we do not want to exceed $N_{dec} = 18.5$ while seeking outwards with $\Delta S_{av} = 20 \text{ min}$, it will be necessary to solve the inequality (12) for $N_{max} = N_{dec}$ and $\Delta S = \Delta S_{av}$. We shall use nine initial points defining the initial subcode timing S_i and their corresponding seek times as moving the sledge ΔS_{av} away from each S_i point. These seek times should be calculated from the servo equations of the sledge but they do not make the purpose of this paper. The overspeed values determined with (12) are summarized in Table 1. A third-order polynomial connecting the points from this table becomes

$$N(S_i) = 2.904 \cdot 10^{-10} S_i^3 - 1.923 \cdot 10^{-6} S_i^2 + 4.766 \cdot 10^{-3} S_i + 12 \quad (16)$$

where the initial and final points N_{in} , respectively N_{out} have also been taken into account. The overspeed $N_{out} = 18$ will be reached at $S_i = 60'00''.00$ because a 60-min data disc has been considered.

S_i [min,sec,frames]	T_{seek} [ms]	N_i
05'00''.00	100	13.884
10'00''.00	95	14.593
15'00''.00	92	15.147
20'00''.00	89	15.586
25'00''.00	86	15.941
30'00''.00	84	16.243
35'00''.00	82	16.497
40'00''.00	80	16.713
45'00''.00	78	16.898

Table 1. Subcode values and corresponding initial overspeeds necessary for determining a high-order polynomial.

The optimized cubic profile for the considered CD-ROM system will be defined by

$$N_{cub}(S_i) = \begin{cases} N(S_i) & \text{if } N(S_i) \leq N_{out} \\ N_{out} & \text{otherwise} \end{cases} \quad (17)$$

and is plotted in Fig. 5 for the overspeed as well as for the rotational frequency of the disc.

Fig. 5. Cubic overspeed profile and related disc rotational frequency.

When compared to the quadratic profile given by Eq. (10) and shown on Fig. 4, the new shape from Fig. 5 will increase the average bit rate of the system during continuous playback. Moreover, while performing a unique seek smaller than 20 minutes, the maximum speed tolerated by the decoder will not be exceeded. This latter remark is being based on the statistical distribution of the seek length when seeking on a 60-minute disc.

The increase in data throughput of the calculated cubic profile with respect to the quadratic one is plotted in Fig. 6, where the total integration time from Eq. (11) is used as variable.

Fig. 6. The increase in average data throughput of the cubic overspeed profile with respect to the quadratic profile, as function of the total subcode timing.

C. Pushing further the average bit rate

It will be also possible to give up some margin when using Eq. (12) to calculate a desired overspeed profile. Practically, there are two constraints which can still be relaxed: first, not all discs are fully recorded which means that ΔS_{av} becomes statistically smaller than 20 minutes; second, the decoding speed N_{dec} can be slightly exceeded.

By choosing the second option there will be no decrease in the average seek performance of the drive. The reason behind is that the average seek time is measured during continuous seek and we do switch during this particular mode to another overspeed (i.e. CAV) profile. Nevertheless, the seek time measured during a unique third-stroke seek will be slightly lengthened.

A practical case derived again from Fig. 4 and calculated with Eq. (12) for $N_{max} = 19.5$ leads to an average increase in data throughput as shown in Fig. 7. It can be seen that a boost of more than 200 kB/s can be achieved, on average, for half-recorded discs while a disc completely recorded will be read out about 150 kB/s faster than during the typical situation from Fig. 4.

The polynomial used for this second cubic profile is

$$N'(S_i) = 2.923 \cdot 10^{-10} S_i^3 - 2.182 \cdot 10^{-6} S_i^2 + 5.629 \cdot 10^{-3} S_i + 12 \quad (18)$$

and the initial pairs of subcode values and seek times used to derive this polynomial are again the ones from Table 1.

Fig. 7. The increase in average data throughput of a second cubic profile with respect to the quadratic profile, as function of the total subcode timing.

VI. THE CONTINUOUS-SEEK CAV CONTROL

It has been shown in Section IV-B that a CAV motor control is basically desired whilst continuously performing seek actions. As far as the quasi-CLV control is concerned,

there will be no problem to implement an adaptive-speed profile identical to the needed CAV one.

However, because the motor is still being accelerated or braked during seeks, the quasi-CLV control will not be the right choice in order to follow a CAV curve. Instead, the spindle motor should either be driven by a tachometer circuitry or merely by an open-loop current (voltage). Because of its simplicity, the latter choice is always preferred if there is enough margin for overspeed tolerances in the system.

A. The adaptive-speed/CAV control electronics

A block diagram of the combined adaptive-speed/CAV motor control is presented in Fig. 8.

The CAV profile (i.e. given by a constant rotational frequency of the disc) will be determined by the voltage difference between the filtered pulse-density modulated (PDM) output (normally at $V_{cc}/2$ during open loop) and the new reference of the motor IC (normally at $V_{cc}/2$ during adaptive-speed mode). The desired commands are issued by the drive microprocessor(s) according to a dedicated algorithm which will be described in Section VII.

The paramount advantage of using only CAV control while performing a long sequence of seeks is the decrease of the power dissipation in the motor loop. For example, while using the proposed switching technique, the maximum temperature attained by the motor IC as shown on Fig. 3 will not exceed 55°C anymore. This will also mean that a heat sink will not be required as passive cooling for the IC, which makes the application a bit cheaper.

Fig. 8. Block diagram and functionality of a combined adaptive-speed (quasi-CLV)/CAV controller.

B. The combined cubic/CAV overspeed profiles

The cubic profile needed for continuous playback has already been calculated in Section V-B. The requirements for the CAV profile are much more relaxed and there is

no after-jump under- or overspeed to be taken into account. However, because of the combination cubic/CAV profile, the maximum linear velocity in CAV mode, which is reached at the outer diameter of the disc, will have to be equal to the linear velocity of the cubic profile at the same outer diameter. And then, of course, the decoder phase-locked loop (PLL) should be able to remain in lock through the whole range of CAV X-factors.

For the chosen system with $N_{in} = 12$ and $N_{out} = 18$, the CAV overspeeds depending on the varying disc radius R will satisfy the inequality

$$N_{out} \frac{R_{in}}{R_{out}} \leq N_{cav}(R) \leq N_{out} \quad (19)$$

which for $R_{in} = 25\text{ mm}$ and respectively $R_{out} = 58\text{ mm}$ leads to

$$7.8 \leq N_{cav}(R) \leq 18.0 \quad (20)$$

$$f_{cav} = \frac{v_a N_{out}}{2\pi R_{out}} = 64.2\text{ Hz}$$

with f_{rot} being the CAV disc rotational frequency. The combined cubic/CAV profiles are plotted in Fig. 9.

Fig. 9. Combined cubic/CAV overspeed profiles. A dedicated firmware algorithm switches between the two profiles each time the conditions for continuous playback (or short sequence of seeks), respectively for continuous seek are satisfied.

VII. FIRMWARE ALGORITHMS FOR SWITCHING BETWEEN ADAPTIVE-SPEED AND CAV CONTROL

We have shown already in Section IV-C that a better performance can be expected from a CD-ROM system if a distinction between continuous read-out, solely performed seek, short sequence of seeks and continuous seek modes can be made.

We have also calculated both an optimal overspeed profile of third order which boosts the sustained bit rate of the drive and the CAV characteristic needed during continuously performed seeks.

Nevertheless, a detection mechanism should be provided in order to distinguish between the four operating states defined in Section IV-C. While implemented at the bit-engine

level, this firmware algorithm might look different than its counterpart implemented at the data-path level. However the case would be, the detection mechanism should monitor some variables related to the seek length and number of seeks performed within a certain time. The information being present at the data-path level may not look the same as the information monitored at the bit-engine level. For example, the data path does not know if a requested seek will be performed only by the actuator or combined within a sledge-actuator displacement. But yet the data path has knowledge about the length of the seek from one address to another one.

A. Switching algorithm at bit-engine firmware level

At this level it is possible to precisely determine if a requested seek action begins or not with a sledge displacement. In case of a sledge jump, a counter will be incremented each time the sledge has to be moved. The CAV mode will therefore be switched on if the counter reaches a maximum predefined value (see Fig. 10), namely 7 sledge jumps following quite shortly after each other.

Fig. 10. Flowchart of the switching algorithm at the bit-engine level.

At the end of the sledge-based seek action a timer has to be started in order to detect an eventual next seek. This timer should be correlated with the maximum latency in the drive such that the target sector can be read immediately after seek in all circumstances. If there is no seek request within the allowed timing, it can be concluded that the host system has found the right data and keeps reading it. This is the right moment to switch back to the adaptive-speed profile in order to increase the data throughput of the system.

Finally, the algorithm measures the number of seeks performed within a given time. This will be done by decrementing the counter as soon as no seek has been requested within a second predefined timer value.

The flowchart of the bit-engine algorithm is drawn in Fig. 10. It is already supposed that, before executing the very first requested seek after power-up, the drive is switched by default into adaptive-speed mode. A practical measurement of the voltage driving the motor IC is shown in Fig. 11. An additional signal on this plot indicates the off-track state of the servo circuitry (which actually corresponds either to a sledge or to an actuator seek). One can see that, once the first 7 consecutive sledge-based seeks have been completed, the spindle motor will neither be accelerated nor braked anymore from this moment onwards. Nevertheless, at the end of the access sequence, the spindle motor is brought back to quasi-CLV control and the right adaptive-speed set-point will be further followed.

Fig. 11. Driving voltage of the motor IC during randomly-performed continuous access, in an adaptive-speed/CAV CD-ROM drive. After 7 consecutive seeks (indicated by the off-track detection - OTD - signal) the motor will not be accelerated or braked anymore but it will be driven in CAV mode by a fixed voltage. The playback quasi-CLV control is resumed at the end of the access sequence.

B. Switching algorithm at data-path firmware level

The distinction between a sledge and an actuator seek cannot be made at the data-path level. However, the algorithm can monitor the seeks longer than a predefined length. On the other hand, the data-path firmware is oriented towards the communication with the host system. For this reason, the algorithm should monitor the read requests coming through the host interface. The flowcharts describing the switching algorithm at the data-path level are shown in Figs 12 and 13. The default state of the drive after power-up is again the adaptive-speed mode. The number of long-range seeks are recorded by a counter and, if enough seeks have been performed within a given time interval, the counter will be reset and the CAV mode will be switched on.

In addition, depending on whether or not a read command has been issued by the host system, the algorithm keeps either the CAV or the adaptive-speed mode turned on. This decision depends on the size of the empty buffer which can still be used by the data path at that particular moment but also on the amount of data to be transferred

towards the host system. This approach ensures an optimized flow of data through the host interface by monitoring the data flow coming from the bit engine. The disc speed can therefore be regulated and better correlated with a given strategy for the buffer management.

VIII. GENERAL CONCLUSIONS

Apart from emphasizing again the advantage of the quasi-CLV control and the optimization possibilities of the adaptive-speed CD-ROM systems, this paper leads to a couple of new conclusions.

A. It is possible to lighten the trade-off required to be made between high bit rate and fast access by monitoring the operating mode of the drive at a given moment in time. A firmware algorithm can detect one of the following operating modes: continuous playback, solely performed seek, short sequence of seeks or continuous seek. Depending on the detected operating mode, the spindle motor will be switched into the most suitable control loop.

B. An additional detection algorithm can be implemented at the data path level in order to better perform the buffer management and to optimally control the data flow towards the host system. This algorithm will also switch the spindle motor into the proper control loop such that the data flow between the bit engine and the data-path buffer will be better correlated with the data flow through the host interface.

C. By separating the state of continuous playback of the drive from the other three operating modes it will be possible to further optimize the read-out overspeed profile. A third-order overspeed function can be analytically determined while taking into account the maximum overspeed occurring after an average third-stroke seek.

D. By separating the state of continuous seek of the drive from the other three operating modes named above, a CAV control of the spindle motor can be enabled. The bit rate of the system during continuous seek is, however, of less importance but the substantial decrease in power dissipation within the motor loop represents an important achievement.

E. By keeping the spindle motor in a quasi-CLV loop following an adaptive-speed profile during uniquely performed seeks or during a short sequence of seeks, the maximum available acceleration (or braking) of the motor will be achieved. The quasi-CLV control loop will begin to drive the motor with full voltage (or current) as soon as the sledge has left the initial track. The drive will deliver data as soon as the target track (and right sector) has been found. In the mean time, the motor continues adjusting its velocity according to the set-point prescribed by the optimized overspeed profile (i.e. the cubic profile).

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Fig. 12. Flowchart (1/2) of the switching algorithm at the data-path level (continued on the next page).

Fig. 13. Flowchart (2/2) of the switching algorithm at the data-path level.

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