Japanese Journal of Applied Physics
Vol. 43, No. 8A, 2004, pp. 5623–5629

Surface Response Methodology for Write Strategy Optimisation in Optical Drives

Geert LANGEREIS*

Philips Research Laboratories, Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands

(Received February 9, 2004; accepted March 22, 2004; published August 10, 2004)

A method for optimising write strategies in optical drives is proposed which is rigid and gives additional information on the reliability of the calculated results. In addition, the mathematical tool is used to examine the typical differences in write strategies with respect to parameter variations. As a test platform, digital versatile discs of the recordable type (DVD+R) are used at a speed of 8×. A comparison is made between the "castle" strategy and the blocked "thermally balanced" strategy. The differences are verified on three different discs. It appears that the write strategy determines the interdependence between write strategy parameters, while the disc brands differ in the optimum settings of the parameter. The presented method and experiments once more show the power of mathematical tools for understanding and applying physical processes.
[DOI: 10.1143/JJAP.43.5623]

KEYWORDS: Digital Versatile Disc Recordable (DVD+R), design of experiments (DOE), optical disc storage, jitter, response surface methodology, write-once storage, write strategy optimisation, regression

1. Introduction: Write Strategies in Optical Drives

In optical storage drives (CD, DVD and Blu-ray Disc) information is stored on a polycarbonate disc which can be read-out using a focused laser beam. The user data is encoded in the positions of high to low reflection transitions and low to high reflection transitions. In the read-only formats, the reflection differences are realised by the geometry of the marks on the disc. A mark has a phase depth and width which are optimised for maximum resulting signal modulation when imaged onto a photo detector. Recordable discs (CD-R, DVD+R) are commonly made of organic dye materials on a mirror. The recording process is based on irreversible deformation and decomposition of a thin recording layer by heating a dye material. By proper design of the stack of materials on the disc, the resulting read-out signal has similar modulation as the read-only system. On the other hand, rewriteable (or erasable) systems like CD-RW and DVD+RW, are made of phase-change materials. A blank disc contains a layer of crystalline inorganic materials. Amorphous marks are written utilising a short high-power laser pulse that melts the recording material, followed by quenching to temperatures below the crystallisation temperature. This enables the possibility of directly overwriting previously recorded data. Since variation of the mark and space lengths enables the storage of binary data, the quality of bit-detection during readout of data is mainly determined by the uncertainty in the position of the mark edges. This uncertainty in mark position is reflected in timing uncertainty, better known as timing jitter.

Jitter can be defined in two ways. First, the deviation of mark to space and space to mark transitions can be defined with respect to the retrieved clock signal. In that case, we speak of trailing, respectively leading, data to clock jitter. The second option is to refer to the variations in mark and space lengths. These are the data to data jitters from which the most statistically relevant are the jitters on the shortest marks and spaces. The shortest length defined for the CD and DVD system is the length of three clock cycles, referred to as 3T-mark and 3T-space.

For optimum writing on the disc, which means writing in such a way that a minimum number of errors is encountered during read-out, the jitter should be minimised. The maximum allowed jitter is 15% data to data 3T-jitter for the CD system and 9% data to clock jitter for the DVD system. The sources of jitter are numerous. In-track intersymbol interference is observed during writing (thermally) and during reading (optically). Cross-track interference can have several causes, originating from optical cross-talk or thermal cross-write. Tracking problems may result into non-optimum write performance. All these phenomena result into variations in the detected transitions and are therefore observed as jitter. Also noise sources, especially laser noise, result into jitter components.

The write strategy is the envelope of the electrical signal which is supplied to the laser in order to write the marks on the disc. By means of the write strategy, the recorder positions the mark to space and space to mark positions in such a way that minimum jitter is observed during read-out. Note that only in-track intersymbol interference can be compensated by write pre-compensation.[1–4] Up to a certain level, the optimum write strategy is disc dependent and also drive dependent. The standard books for optical storage system description define reference write strategies in order to make the discs and drives compatible. Nevertheless, fine tuning is always done by the drive manufacturers.

Write strategy optimisation is guided by understanding the physical write process. However, the scanning of parameters in order to find optima and margins is needed to define the best compromised optimum.

2. Mission

We would like to design a general method for optimising write strategies. Experiments are done on DVD+R discs at a recording speed of 8×. Two write strategies are compared: the "thermally balanced" strategy[1–5] and the "castle" strategy.[6,7]

The thermally balanced write strategy was developed for CD-R, but is also applicable for low speed DVD+R. This write strategy is shown in Fig. 1. A write strategy consists of a series of write pulse definitions for the mark lengths 3T up to 14T. Thermal balancing is implemented on the rising edge of the marks after 3T spaces (by means of the τ-parameter) and on the 3T marks (as the ΔP parameter). The nominal

*E-mail address: geert.langereis@philips.com

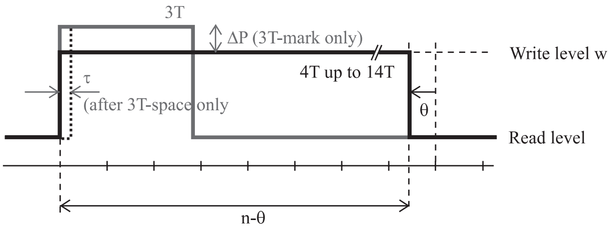

Fig. 1. Write pulse for the thermally balanced write strategy.

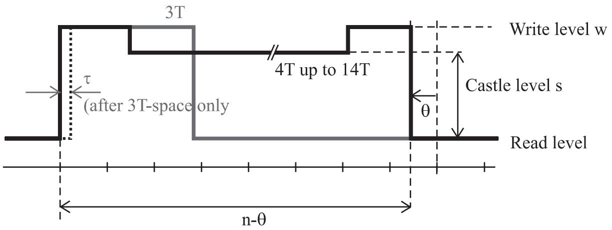

Fig. 2. Write pulse for the castle write strategy.

pulselength is equal to the mark length to be written with a pulse shortening parameter θ. This parameter is commonly chosen based on the dye type.

The "castle strategy" was developed for high speed DVD+R. It comprises thermal balancing for marks after a 3T space and improved in-mark temperature compensation by means of a notch in the larger marks (hence the name "castle strategy"). The definition of the power levels is shown in Fig. 2.

To find the optimum parameter settings, the write strategy parameters are scanned and the settings resulting in the lowest read jitter are determined. However, the write strategy parameters are not independent. Therefore, all possible combinations must be tested. This results into a huge number of experiments. To solve this problem, the method of surface response fitting is proposed.

3. Response Surface Methodology

With surface response methodology, system parameters are explored in order to fit an assumed response surface.[8,9] Based on statistical evaluations, the quality of the fitted response is determined. When the fit is reasonable, the optimum parameter settings can be calculated from the model.

3.1 Choice of the model

The first problem is to find the correct model describing the jitter response on the chosen write strategy parameters. The solution comes from the definition of jitter. Jitter is defined as the variance of timing errors. This can be either a data to clock or a data to data timing error. From that point of view it is easily understood that data to data jitter is $\sqrt{2}$-times larger than data to clock jitter since data to data jitter is the result of two uncorrelated jittering data to clock edges. In spite of this difference, all types of jitters can be treated similar in the following deduction.

The variance of a vector $\boldsymbol{u}$ with N elements is defined as

$$\mathrm{Var}(\boldsymbol{u}) \equiv \frac{1}{N}\sum_{n=0}^{N-1} |u_n - \hat{u}|^2 \tag{1}$$

with $\hat{\boldsymbol{u}}$ the mean of vector $\boldsymbol{u}$. In case of measuring jitter, vector $\boldsymbol{u}$ can be seen as the true position of an edge in time while $\hat{\boldsymbol{u}}$ represents the desired position (available as the retrieved channel clock). So, for jitter a measurement is not compared to its own average, but to the desired optimum.

Now, imagine a parameter x in a certain write strategy which can be either an amplitude during a clock subdivision or a location of an edge in time. Consider the range $x \pm \delta x$ in which this parameter results linearly into a shift in a specific edge in the hf-signal. In that case, an edge in the read out hf-signal shifts in time according to

$$u_n = u_n|_x + s_x \delta x \tag{2}$$

with s_x the sensitivity of hf-edge $\boldsymbol{u}_n$ on the strategy parameter x. In general, thermally balanced write strategies are defined in such a way that parameter x affects a specific edge between the runlengths pT and qT. So, for data to clock jitter measured on random EFM sequences, the sum in eq. (1) can be separated into two sums: one is affected by parameter x and the other is not. The variance, now expressed as jitter as a function of the parameter x, can be written as

$$\begin{aligned} J(x) = {} & \frac{1}{N_{\mathrm{Not\_}x}} \sum_{n=0}^{N_{\mathrm{Not\_}x}-1} |u_n - \hat{u}|^2 \\ & + \frac{1}{N_x} \sum_{n=0}^{N_x - 1} \left| u_n|_x + s_x \delta x - \hat{u} \right|^2. \end{aligned} \tag{3}$$

The first term is not dependent on parameter x, therefore the jitter $J(x)$ will never be smaller than this term. The second term is a parabolic function which has a minimum for a certain x value referred to as $\hat{x}$ from now on. This jitter minimum can be added to the constant first term to form the bottom jitter J_{Bottom}. Equation (3) can now be simplified to

$$J(x) = J_{\mathrm{Bottom}} + a_x (x - \hat{x})^2 \tag{4}$$

with a_x the sensitivity of the jitter on variations in x^2.

In Fig. 3 the "τ" and "ΔP" parameter in the thermally balanced write strategy of Fig. 1 are scanned on a CD-R disc at 16× and the space and mark jitters are plotted separately. One can see that if the τ parameter is adjusted, the space jitter is not affected, on the other hand, when the ΔP parameter is adjusted, the mark jitter remains constant. The parabolic dependency of the jitter on the parameter variation is visualised by the plotted second order fits, fitted by using the three diamond-shaped measurement points.

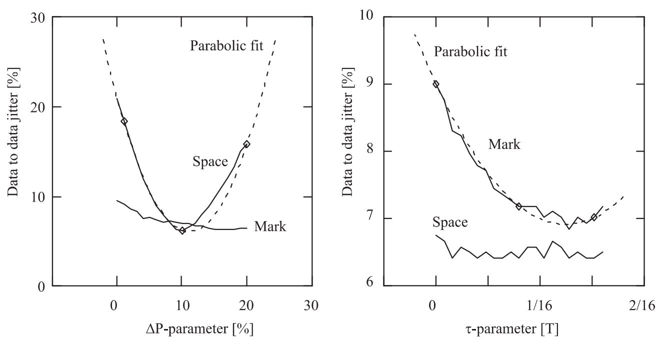

Fig. 3. Measurements on a CD-R disc using the thermally balanced write strategy at 16×.

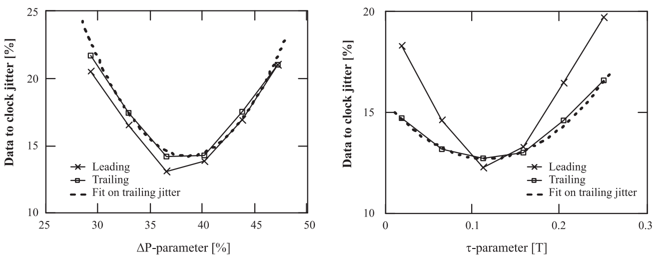

Fig. 4. Measurements on a DVD+R disc using the thermally balanced write strategy at 4×.

The second order dependency is not only experimentally confirmed on CD-R discs with data to data jitter, also on DVD+R discs the same parabolic dependency is easily verified using data to clock jitter as shown in Fig. 4. Since both the leading and trailing jitter have a parabolic dependency on the write strategy parameters, the RMS value (being the total jitter) has a second order shape as well.

3.2 *The response surface*

Assume P write strategy parameters[10] x_1, x_2, to x_p. The full quadratic model for relating the write strategy parameters to the estimated jitter is given by

$$\text{Jitter} = c + \sum_{i=1}^{P} b_i x_i + \sum_{i=1}^{P}\sum_{j=1}^{P} A_{i,j} x_i x_j \tag{5}$$

where the double sum includes both square terms (for $i = j$) and interaction terms (for $i \neq j$). Note that the cross term model coefficients are not unique. We are free to choose the ratio between $A_{i,j}$ and $A_{j,i}$ in each partial sum $A_{i,j}x_i x_j + A_{j,i}x_j x_i$. There are two conventions. First we can make any $A_{i,j}$ zero when $i > j$. The other convention is to make $A_{i,j}$ equal to $A_{j,i}$. This has some minor consequences in the following matrix notation. Equation (5) can be written as

$$\text{Jitter} = c + \langle \boldsymbol{b}, \boldsymbol{x} \rangle + \boldsymbol{x}^T \boldsymbol{A} \boldsymbol{x} \tag{6}$$

with $\langle \boldsymbol{b}, \boldsymbol{x} \rangle$ the vector product $\boldsymbol{b}^T\boldsymbol{x}$ (inner product of $\boldsymbol{b}$ and $\boldsymbol{x}$). Matrix $\boldsymbol{A}$ has the square terms on the diagonal and the cross-interferences on the off-diagonal entries. In the first convention, with $A_{i,j} = 0$ for $i > j$, the matrix $\boldsymbol{A}$ becomes a triangular matrix $\boldsymbol{A}_\nabla$. In the second convention, matrix $\boldsymbol{A}$ is a symmetrical matrix $\boldsymbol{A}_\text{S}$. The relation between these two is

$$\boldsymbol{A}_\text{S} = \frac{A_\nabla + {A_\nabla}^T}{2}. \tag{7}$$

Once the model coefficients c, $\boldsymbol{b}$ and $\boldsymbol{A}$ are known or estimated, the optimum write strategy parameters can be found as the stationary point by

$$\boldsymbol{x}_0 = -\frac{1}{2}{\boldsymbol{A}_\text{S}}^{-1}\boldsymbol{b} \tag{8}$$

which is actually the solution for the vector x where the first derivative of (5) or (6) equals zero. Strictly spoken, we do not know yet if we have found a maximum, a minimum or even a saddle point for the parameters x_p. Even if we are convinced of the true shape of the response, due to noise in the measurements the estimated model might not represent the expected shape. Only an evaluation of the eigenvalues wil give us the correct explanation.[8,9]

The predicted response in the stationary point is given by

$$\hat{y}_0 = c + \frac{1}{2}{\boldsymbol{x}_0}^T\boldsymbol{b} \tag{9}$$

which can be found by substituting (8) into eq. (6).

The method of determining the minimum (or maximum) in a multi-dimensional response by means of fitting an assumed surface is referred to as surface response methodology. Now we have selected the correct shape of the surface in §3.1, we have to find a method to fit the model to a set of measurements.

3.3 *Regression analysis*

Fitting the model is a matter of estimating the model coefficients c, b_i and $A_{i,j}$. This is done by the minimum mean square method. The separate model coefficients are placed in a vector β. The response becomes a vector $\boldsymbol{y}$, with "Jitter" numbers from eq. (5) for each separate experiment ("treatment"). In that case the problem of solving c, $\boldsymbol{b}$ and $\boldsymbol{A}$ can be reduced to solving the equation

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \tag{10}$$

where the matrix $\boldsymbol{X}$ contains the write-strategy parameter settings (treatments), $\boldsymbol{\beta}$ the model coefficients and ε the residual error (mismatch between observation and fit). Matrix $\boldsymbol{X}$ consists of rows

$$\boldsymbol{X}_{n.} = \begin{bmatrix} 1 & x_1 & \dots & x_P & {x_1}^2 & \dots & {x_P}^2 & x_1x_2 & \dots & x_{P-1}x_p \end{bmatrix} \tag{11}$$

where the dot in $\boldsymbol{X}_{n.}$ means the complete row of matrix $\boldsymbol{X}$ and the n represents the row with the n-th measurement. The vector $\boldsymbol{\beta}$ looks like

$$\boldsymbol{\beta} = \begin{bmatrix} c & b_1 & \dots & b_P & A_{1,1} & \dots & A_{P,P} & A_{1,2} & \dots & A_{P-1,P} \end{bmatrix}^T \tag{12}$$

The unbiased least square estimator $\hat{\boldsymbol{\beta}}$ of $\boldsymbol{\beta}$, given the jitter measurements $\boldsymbol{y}$ and the parameter settings $\boldsymbol{X}$ is

$$\hat{\boldsymbol{\beta}} = (\boldsymbol{X}^T\boldsymbol{X})^{-1}\boldsymbol{X}^T\boldsymbol{y} \tag{13}$$

The entries in vector $\hat{\boldsymbol{\beta}}$ have to be remapped into the estimated model representation with coefficients $\hat{c}$, $\hat{\boldsymbol{b}}$, and $\hat{\boldsymbol{A}}$ to describe the model in terms of eq. (6) and the optimum write strategy parameter settings $\boldsymbol{x}_0$ using eq. (8). Besides the solution $\boldsymbol{x}_0$ itself, we are also interested in the validity of the estimate. The complete toolbox of regression analysis[8,9] can be used to qualify the result. Important qualifiers are the regression coefficient, the residual standard error, the standardised residuals of the jitters and the covariances of the fitted model coefficients.

3.4 *Design of experiments*

How to explore the parameter space as efficient as possible? Option one is to use a table with random points. However, such a table will include extreme corners having very high jitters and can probably even not be measured. A better method is to use a central composite design.[8,9] Central composite designs consist of 2^k corner points for k

Table I. Elimination of coefficients when optimising the castle strategy.

	3-factor composite design				2-factor composite design			
Subset:	Full		Remove $\tau \cdot s$		Fix $w = 28\,\text{mW}$		No interferences	
	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)
Offs	583.05	2.5	593.53	2.0	465.23	0.0	463.72	0.0
w^2	1.90	0.0	1.90	0.0				
τ^2	348.63	1.3	348.62	1.2	343.63	0.7	345.92	0.5
s^2	1.09	0.0	1.09	0.0	0.96	0.0	0.97	0.0
w	−55.79	0.2	−56.27	0.2				
τ	489.38	**6.7**	552.76	2.8	−46.85	**40.0**	−9.87	**33.0**
s	19.25	0.7	18.75	0.6	−42.01	0.0	−41.95	0.0
$w \cdot \tau$	−20.10	3.2	−20.10	2.9				
$w \cdot s$	−2.36	0.0	−2.34	0.0				
$\tau \cdot s$	3.02	**48.1**			1.77	**49.4**		
Res. StdErr	0.8608		0.8479		0.5185		0.5028	
R^2	0.9713		0.9703		0.9916		0.9910	

parameters, $2k$ axial points and a number (at least one) of central points. The central points are repeated to obtain reliable statistics on the variance of the error.

The corner points are normalised to 1 and −1, the axial points are determined by the factor α to make it rotatable. For 2 parameters $\alpha = \sqrt{2}$, for 3 parameters $\alpha = 1.682$ and for four parameters $\alpha = 2$.

4. Measurements

4.1 *Castle strategy (2-parameters, with and without write power)*

The castle strategy as described in Fig. 2 has two parameters: τ and s. These two parameters are the thermal balancing parameters and will satisfy the model of §3.1. In the first experiment we will see what happens when the write power is taken as a third parameter. The write power is known to have an asymmetrical jitter curve due to the post-heat effect at high powers. This will be an interesting test for a situation where the chosen second-order model is not adequate.

The pulse shortening θ is fixed to 0.5T and the lengths of the power boosts at the beginning and end of the write pulses are also fixed. It is possible to optimise these parameters as well, but this is beyond the scope of this paper.

In Table I there are two measurements: one using a three factor composite design (on w, τ and s) and one using a two factor design (on τ and s with w fixed to 28 mW), both are based on five central points. The first evaluation is indicated by the column header "Full". It shows the coefficients to be used in eq. (5) with w and s in mW and τ expressed as a fraction of the clock period T. The coefficient for $\tau \cdot s$ has a high uncertainty of 48.1%, which means that the cross-correlation between τ and s is that low that it can be removed from the model. This is done in the next column under the header "Remove $\tau \cdot s$". The removal of the $\tau \cdot s$ coefficient does not increase the regression coefficient R^2 or reduce the residual standard error. Apparently, these two quality indicators are limited by the lack of fit of the model due to the influence of the write power. The third evaluation in Table I is based on the second measurement with a two-factor composite design. The residual error drops from 0.9 to 0.5 while the regression coefficient improves from 0.97 to 0.99. These two numbers indicate a highly accurate fit which confirms that it is the write power w which does not obey a perfect second order jitter response. The uncertainty in the coefficient for τ is high, however, because the coefficient for τ^2 is very reliable, we should not eliminate τ. What can be omitted is the cross-correlation between τ and s which has an uncertainty of almost 50%. In the fourth evaluation of Table I we can see that no large error is introduced by removing the coefficient for $\tau \cdot s$.

The removal of this interference is very interesting. It means that the two write strategy parameters in the castle-strategy are already orthogonal: the two factor experiment is in the canonical form. This can be seen in the contour plot of Fig. 6 where the elliptically shaped contours are oriented parallel to the τ-axis. If τ is changed, the factor s does not have to be modified and vice versa. If this holds for all discs, the castle strategy has a big advantage because the number of measurements needed to fit the optimum τ and s values can be reduced.

Such an observed independence is not trivial. For other write strategies there is a relation between almost any two parameters. This is also the case with the two other interferences $w \cdot \tau$ and $w \cdot s$ in the three factor composite design as shown in Fig. 7. The first contour plot shows the relation between τ and s, similar to the τ–s relation as observed with the two-factor design of Fig. 6. The contour plots for the relations w–τ and w–s show a dependent behaviour.

4.2 *Disc to disc variations*

An important question is whether the regression behaviour depends on the disc or on the design of the write strategy. In this section, experiments with the castle strategy are done on several disc brands, all of the DVD+R type and commercially available. These discs are optimised for the speed of 4× but tested on 8×. Therefore the achieved bottom jitters are sometimes poor, but still, it is the optimum write strategy setting within the chosen parameter space.

A full central composite design with five central points is chosen. The used discs are in Table II together with the nominal write power, tested radius and parameter ranges. The write power is optimised on asymmetry which is roughly independent on the write strategy parameters τ and s.

Regression experiments are in Table III. To avoid large differences in numbers (as encountered in Table I), τ and s are normalised to the structure of Fig. 5. All fits are satisfying, resulting into R^2 values above 0.98. The lower rows of Table III contain the jitters as measured with the optimised parameter settings. The RMS jitter ($\sqrt{(\text{Leading}^2 + \text{Trailing}^2)}/\sqrt{2}$) is close to the estimated best jitter from eq. (9) which confirms the accuracy of the model.

The second order coefficients τ^2 and s^2 appear to be disc-independent. This means that the tested parameter ranges result into similar jitter deviations on the three discs.

Just like observed in the previous section, the interaction coefficient for $\tau \cdot s$ is uncertain because there is a low level of interaction. When this interaction term is removed from the model, as shown in Table IV, the R^2 value and the

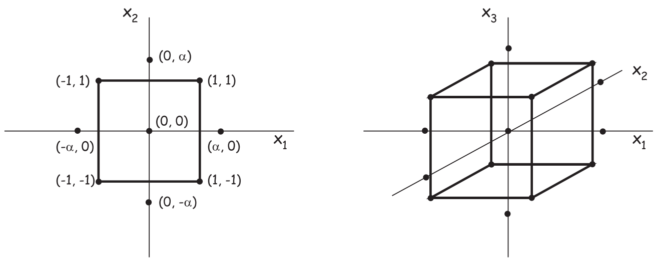

Fig. 5. Central composite designs for $k = 2$ and $k = 3$.

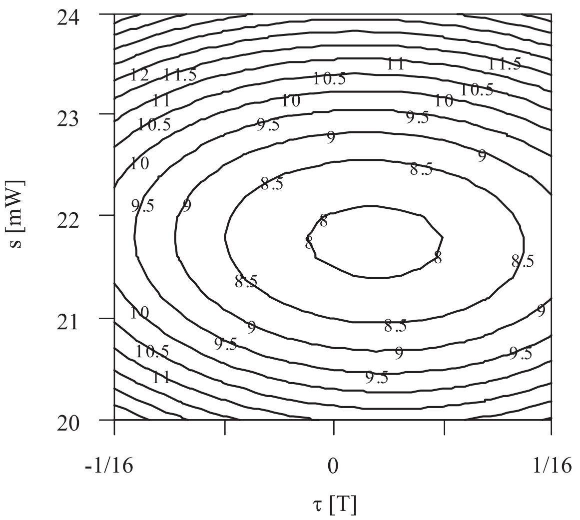

Fig. 6. Contour jitter plots for 2-factor castle strategy with a write power of 28 mW.

Table II. Test discs to compare castle strategy.

Disc brand	Power (mW)	Radius (mm)	τ	s
A	29	40.0	−T/80 .. T/8	0.65 .. 0.85
B	29	40.6	−T/80 .. T/8	0.65 .. 0.85
C	27	40.9	−T/80 .. T/8	0.65 .. 0.85

Table III. 2-Parameter castle strategy on three different discs.

Disc:	A		B		C	
	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)
Offs	9.082	0.0	11.28	0.0	8.987	0.0
τ^2	0.896	0.0	0.857	0.2	0.879	0.0
s^2	2.995	0.0	3.17	0.0	2.788	0.0
τ	0.503	0.6	−0.584	1.8	−1.189	0.0
s	1.656	0.0	3.124	0.0	1.755	0.0
$\tau \cdot s$	0.382	**7.0**	−0.116	**67.6**	−0.275	**22.4**
Res. StdErr	0.5335		0.7657		0.5994	
R^2	0.9851		0.9816		0.9830	
τ	0.0652T		0.0390T		0.0307T	
s	0.7436		0.7304		0.7481	
Ld (%)	8.78		9.44		7.96	
Tr (%)	7.59		8.23		7.93	
RMS (%)	8.21		8.86		7.95	
Est. RMS (%)	8.51		9.08		8.03	

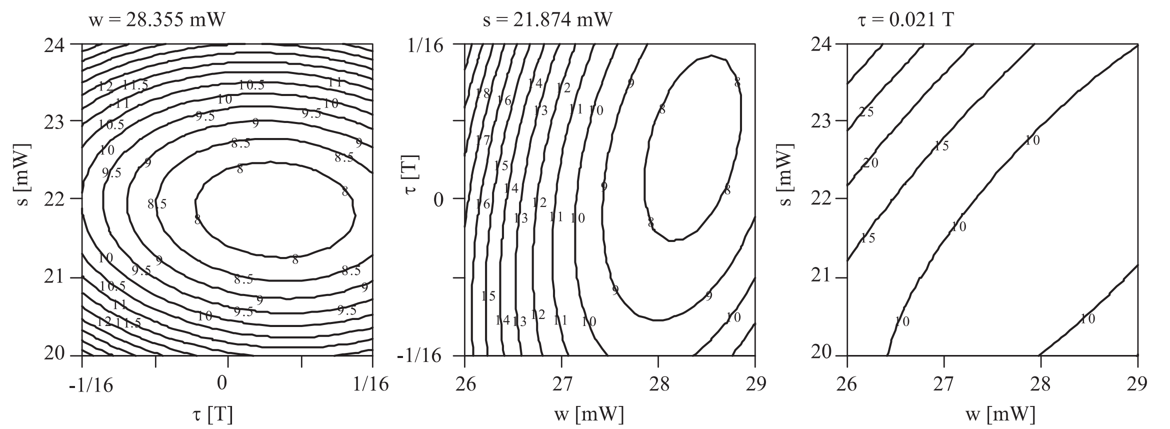

Fig. 7. Contour plots for three-factor design.

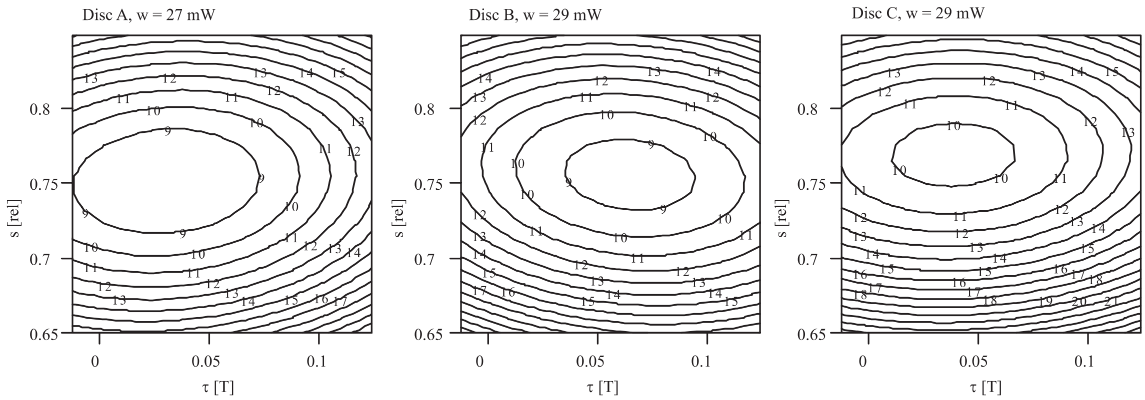

Fig. 8. Contour plots for write strategy parameters τ and s of the castle strategy on three different discs.

Table IV. 2-Parameter castle strategy after elimination of model coefficients.

Disc:	A		B		C	
	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)
Offs	9.082	0.0	11.280	0.0	8.987	0.0
τ^2	0.896	0.0	0.857	0.1	0.879	0.0
s^2	2.995	0.0	3.170	0.0	2.788	0.0
τ	0.503	0.8	−0.584	1.0	−1.189	0.0
s	1.656	0.0	3.124	0.0	1.755	0.0
Res. StdErr	0.5803		0.7110		0.5946	
R^2	0.9789		0.9810		0.9799	
τ	0.0677T		0.0423T		0.0286T	
s	0.7429		0.7295		0.7465	

standard error are not affected. In addition, the optimised write strategy parameters remain the same. The degrees of freedom released by omitting two terms are automatically used for increasing the accuracy of the fit.

Contours of parameter interaction are plotted in Fig. 8. As was concluded in the previous section, the τ and s parameter are highly orthogonal (they are already in the canonical form). This is the reason that these two coefficients are badly determined in the regression table and can be omitted in the fit.

4.3 *Thermally balanced strategy*

So the parameter dependency does not change from disc to disc. To check if the parameter dependency is write strategy dependent the thermally balanced write strategy is applied to three discs. Table V lists the three discs used for this test. This strategy has two parameters, tested in the ranges as given in the table.

Table V. Test discs to compare thermally balanced strategy.

Disc brand	Power (mW)	Radius (mm)	τ	ΔP
A	25	40.0	−T/80 .. T/8	10% .. 25%
B	25	40.6	−T/80 .. T/8	10% .. 25%
C	24	40.4	−T/80 .. T/8	10% .. 30%

Table VI. Thermally balanced strategy on three different discs.

Disc:	A		B		C	
	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)	Value	$Pr(>\|t\|)$ (%)
Offs	1806.00	3.7	1184.0000	**19.4**	606.30	0.4
τ^2	577.69	**13.7**	679.8000	**11.3**	243.82	1.1
ΔP^2	0.13	0.1	0.1750	0.0	0.16	0.0
τ	−19.47	**97.9**	281.1460	**72.9**	159.11	**35.4**
ΔP	−3.56	**60.1**	−4.2810	**56.8**	0.32	**78.3**
$\tau \cdot \Delta P$	−3.19	**49.1**	−5.3360	**29.9**	−2.73	0.3
Res. StdErr	2.33		2.50		0.54	
R^2	0.9250		0.9083		0.9913	
τ (T)	0.0578		0.0662		0.0571	
ΔP (%)	23.9		22.2		19.0	
Ld (%)	11.1		10.3		8.3	
Tr (%)	9.5		8.4		7.9	
RMS (%)	10.3		8.9		8.1	
Est. RMS (%)	7.6		8.7		7.6	

Pulse shortening parameter θ is fixed to 0.5T. The write power is determined based on the read-out duty cycle of an I11–I11 carrier which is mainly independent of the parameters τ and ΔP.

The regression results are in Table VI. No elimination of regression coefficients is done. The quality of the fit is very poor: most of the coefficients have a high error and the residual standard error is 2.5 instead of the 0.5 as observed with the castle strategy. The reason is that post-heat is the interfering factor for high speed DVD+R which can not be tuned by this write strategy.

Nevertheless, the result is clear: in the contour plots of Fig. 9 the orientations of the ellipses are roughly disc independent. The cross term $\tau \cdot \Delta P$ is not equal to zero: the ellipses have the same angle.

5. Conclusion

Measurements are done on three disc brands using two different write strategies. For each disc/strategy combination the parameter space is explored and the best second order response curve is fitted. The regression technique

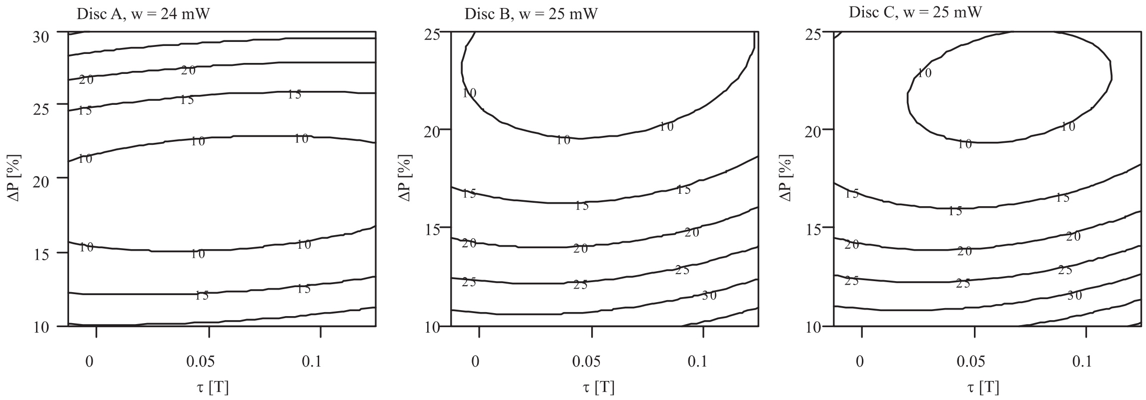

Fig. 9. Contour plots for the thermally balanced strategy on three disc brands.

returns both the optimum and information on the quality of the fit. Note that the conclusions from this paper are about the method and the intrinsic properties of the write strategy, not about the tested disc brands.

The best choice for the write strategy parameter settings is the central composite design. Such a design is preferred above random settings because it does not explore the critical corners of the system while still information on all the cross interferences is retrieved reliably.

The shape of the model is determined by the write strategy, in other words, the orientation of the axes of parameter interference are disc independent. Mathematically this implies that the same transform to the canonical form can be used for all discs.

For 8× DVD+R, write power has an influence on the jitter which does not obey the assumed second order response. The physical origin on the asymmetrical relation between jitter and write power is post heat.

1) B. Tieke, G. R. Langereis, E. R. Meinders, J. G. F. Kablau, R. Woudenberg and R. A. J. Kollenburg: Thermally Balanced Writing for High Speed CD-R Recording, ISOM 2001 Conference, Taipei.
2) B. Tieke, G. R. Langereis, E. R. Meinders, J. G. F. Kablau, R. Woudenberg and R. A. J. Kollenburg: Jpn. J. Appl. Phys. **41** (2002) 1735.
3) G. R. Langereis and B. Tieke: Proc. IEEE ICCE 2002, Int. Conf. on Consumer Electronics, 2002, Los Angeles, CA, p. 252.
4) F. F. L. Tang, G. J. Y. Zhong, D. D. Y. Chen, B. Tieke and G. Langereis: Proc. SPIE **5060** (2003) 24.
5) Recordable Compact Disc Systems (Orange Book), Part II: CD-R, Volume 2 Multi Speed, Version 1.2, April, 2002.
6) J. Hellmig, J. C. Rijpers and H. Spruit: Highspeed 16× DVD Dye Recording, Technical Digest of ISOM 2003, Nara, Japan, 2002, p. 292.
7) DVD+Recordable 4.7 Gbytes, Basic Format Specifications, System Description, Version 1.0, January, 2002.
8) D. C. Montgomery: *Design and analysis of experiments* (John Wiley & Sons, New York, 1976).
9) C. F. Jeff Wu and M. Hamada: Experiments: *Planning, Analysis and Parameter Design Optimisation* (John Wiley and Sons, 2000).
10) In literature concerning statistical methods for experiments, these parameters are called "factors". A certain combination of factors is referred to as "treatment". The term "parameters" is reserved for the model coefficients which have to be estimated. In this paper, I prefer the word "parameters" for the write strategy settings and "model coefficients" for the parameters in the fitted model.