A Simple Skew Angle Detection and Alleviation based on Readback Signal in Bit-Patterned Magnetic Recording

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MOTIVATION

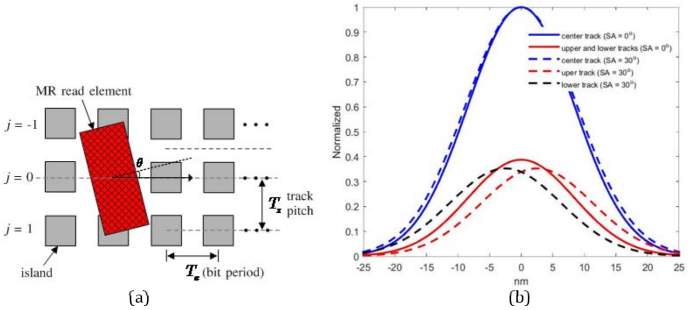
※ **Bit-patterned magnetic recording (BPMR)** can increase an areal density (AD) up to 4 Tb/in^2.

※ **Skew angle (SA)** can change the relative placement of read/write elements on the slider, leading to a design issue in servo and write synchronization.

※ In conventional systems, the SA can increase up to 35º (degrees) for inner and outer diameters [1].

※ Without a SA detection and alleviation method, the system performance will dramatically degrade, particularly at high ADs.

※ **Fig. 1(a)** displays a BPMR magnetic medium and an MR read head with SA effect, whereas **Fig. 1(b)** shows the impulse responses of upper, center, and lower tracks at 0º (degree) and 30º SA at AD of 3 Tb/in^2. Clearly, the impulse responses rely on the SA.



(a) (b)

Fig. 1. (a) A BPMR medium and an MR head with SA effect and (b) the impulse responses of different tracks at AD = 3 Tb/in^2.

CHANNEL MODEL

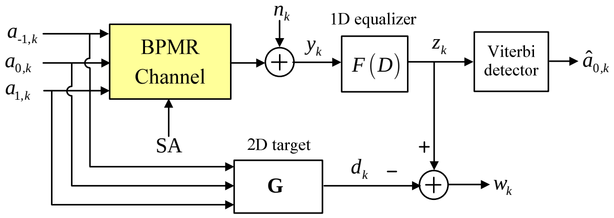


Fig. 2. A BPMR channel model with the SA effect.

※ BPMR channel model with the SA effect

- Readback Signal

$$y_k = \sum_u \sum_v \overset{\text{Coefficients of 2D channel response}}{\boxed{h_{u,v}}}\overset{\text{Recorded bits}}{\boxed{a_{j-u,k-v}}} + \overset{\text{Additive white Gaussian noise}}{\boxed{n_k}}$$

- 2D Gaussian pulse response

$$H(z,x) = \overset{\text{Peak amplitude}}{\boxed{A}}\exp\left\{-\frac{1}{\underset{c=1/2.3548}{\boxed{2c^2}}}\left[\left(\frac{\overset{\text{Along-track direction}}{\boxed{x_r}}}{\underset{\text{PW}_{50}\text{ of the across-track pulse}}{\boxed{\text{PW}_x}}}\right)^2 + \left(\frac{\overset{\text{Cross-track direction}}{\boxed{z_r}}}{\underset{\text{PW}_{50}\text{ of the along-track pulse}}{\boxed{\text{PW}_z}}}\right)^2\right]\right\}$$

where $x_r = x\cos(\theta) - z\sin(\theta)$, $z_r = x\sin(\theta) + z\cos(\theta)$, and θ is the skew angle in degree.

[1] Z. He, et al., MATEC Web of Conferences, 42 (2016).
[2] S. Koonkarnkhai, et al., ECTI Trans. on Comp. and Info. Tech., 6 (2012) 175 – 182.

Acknowledgments

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PROPOSED METHOD

※ The SA detection

- **Fig. 3** shows the SA profiles of the channel coefficient $h_{-1,0}$ and the target coefficient $g_{-1,0}$ at 3, 3.5, and 4 Tb/in^2 for different SAs.

- We found that there is **a relationship** between $h_{-1,0}$ and $g_{-1,0}$.

- A simple SA detection method will utilize $g_{-1,0}$ to approximate the SA experienced in the system (i.e., $g_{-1,0} \approx h_{-1,0}$) by using the target and equalizer design based on an MMSE approach.

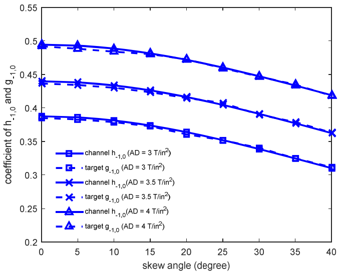

Fig. 3. The SA profile with respect to different channel and target coefficients.

※ The 2D BPMR channel matrix

$$\mathbf{H} = \begin{bmatrix} h_{-1,-1} & h_{-1,0} & h_{-1,1} \\ h_{0,-1} & h_{0,0} & h_{0,1} \\ h_{1,-1} & h_{1,0} & h_{1,1} \end{bmatrix}$$

※ The 2D target (G)

$$\mathbf{G} = \begin{bmatrix} g_{-1,-1} & g_{-1,0} & g_{-1,1} \\ g_{0,-1} & g_{0,0} & g_{0,1} \\ g_{1,-1} & g_{1,0} & g_{1,1} \end{bmatrix}$$

※ The SA alleviation

After the SA is detected, a pair of *flipped-cross-track symmetric* 2D target and 1D equalizer associated with the estimated SA is employed to alleviate the SA in data detection process.

※ Target and Equalizer Design:

The target and its corresponding equalizer are designed by minimizing the mean-squared error between the equalizer output z_k and the target output d_k according to

$$E\left[e_k^2\right] = E\left[\left(z_k - d_k\right)^2\right] = E\left[\left(\mathbf{f}^{\mathrm{T}}\mathbf{y}_k - \mathbf{g}^{\mathrm{T}}\mathbf{a}_k\right)\left(\mathbf{f}^{\mathrm{T}}\mathbf{y}_k - \mathbf{g}^{\mathrm{T}}\mathbf{a}_k\right)^{\mathrm{T}}\right]$$

※ Design of a *flipped-cross-track symmetric* 2D target

Define: $g_{-1,-1} = g_{1,1}$, $g_{-1,0} = g_{1,0}$, $g_{1,-1} = g_{-1,1}$, $\mathbf{g} = [g_{-1-1}\ g_{0,-1}\ g_{1,-1}\ g_{-1,0}\ g_{0,0}\ g_{1,-1}]^{\mathrm{T}}$ is the column vector of the target, $\mathbf{f} = [f_{-K} \ldots f_0 \ldots f_K]^{\mathrm{T}}$ is the column vector of $g_{-1,0}$the equalizer, $M = 2K + 1$ is the number of equalizer coefficients, L is the number of target coefficients, $\mathrm{R} = \mathrm{E}[\mathbf{y}_{\mathrm{k}}\mathbf{y}_{\mathrm{k}}^{\mathrm{T}}]$ is an M-by-M auto-correlation matrix of $\mathbf{y}_{\mathrm{k}}$, $\mathbf{A} = E[\mathbf{a}_{\mathrm{k}}\mathbf{a}_{\mathrm{k}}^{\mathrm{T}}]$ is an L-by-L auto-correlation matrix of $\mathbf{a}_{\mathrm{k}}$, and $\mathbf{T} = E[\mathbf{y}_{\mathrm{k}}\mathbf{a}_{\mathrm{k}}^{\mathrm{T}}]$ is an M-by-L cross-correlation matrix of $\mathbf{y}_{\mathrm{k}}$ and $\mathbf{a}_{\mathrm{k}}$, where $\mathbf{a}_{\mathrm{k}} = [a_{-1,k}\ a_{0,k}\ a_{1,k}\ a_{-1,k-1}\ a_{0,k-1}\ a_{0,k-2}]^{\mathrm{T}}$ and $\mathbf{y}_{\mathrm{k}} = [y_{k+K} \ldots y_k \ \ldots y_{k-K}]^{\mathrm{T}}$

MMSE: $E[\{e_k\}^2] = \mathbf{f}^{\mathrm{T}}\mathbf{R}\mathbf{f} + \mathbf{g}^{\mathrm{T}}\mathbf{A}\mathbf{g} - 2\mathbf{f}^{\mathrm{T}}\mathbf{T}\mathbf{g} - 2(\lambda\mathbf{I}^{\mathrm{T}}\mathbf{g}\text{-}1)$, where $\mathbf{I} = [0\ 0\ 0\ 0\ 1\ 0]^{\mathrm{T}}$. Minimization process give:

$$\lambda = \frac{1}{\mathbf{I}^{\mathrm{T}}\left(\mathbf{A} - \mathbf{T}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{T}\right)\mathbf{I}} \qquad \mathbf{g} = \lambda\left(\mathbf{A} - \mathbf{T}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{T}\right)^{-1}\mathbf{I} \qquad \mathbf{f} = \mathbf{R}^{-1}\mathbf{T}\mathbf{g}$$

SIMULATION RESULTS

※ Parameter Setting

SNR = $10\log_{10}(1/\sigma^2)$ in dB, **Equalizer** : 7-tap 1D equalizer, and **AD**: at 3.0 Tb/in^2, $T_x = T_z =$ 14.5 nm. and 3.5 Tb/in^2, $T_x = T_z =$ 13.5 nm.

※ Define

- "Conv." is the system without SA detection and correction.
- "Prop." is the proposed system with flipped-cross-track symmetric 2D target.
- "Asym. 2D" is the proposed system with asymmetric 2D target [2].

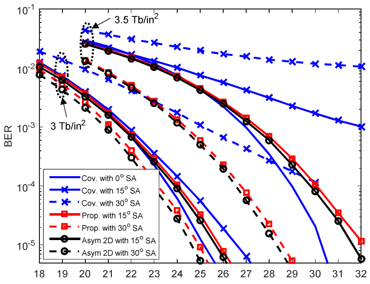

Fig. 4. Performance comparison at 3 and 3.5 Tb/in^2.

※ Conclusion

- The proposed method outperforms the conventional system as shown in **Fig.4**.
- The Viterbi detector used for the flipped-cross-track symmetric 2D target has lower complexity than an asymmetric 2D target.
- Although high SA provides better performance than low SA due to less ITI effect (not shown here), a large SA definitely causes mechanical problems during read/write processes.