Tomasz TRAWIŃSKI

Silesian University of Technology, Faculty of Electrical Engineering, Department of Mechatronics

Kinematic chains of branched head positioning system of hard disk drives

***Abstract**. In the article the branched kinematic chains of head positioning system of hard disk drive are presented. Basic information about data areal density growth over last ten years is given as well exemplary modern head positioning systems of modern hard disk drives. The mathematical expressions for inverted dynamic matrix of branched head positioning system are given.*

***Streszczenie.** W niniejszym artykule zaprezentowano rozgałęzione łańcuchy kinematyczne systemu pozycjonowania głowic dysków twardych. Podano podstawowe informacje dotyczące wzrostu powierzchniowej gęstości danych na przełomie ostatnich kilku lat, jak również zaprezentowano nowoczesny system pozycjonowania głowic dysków twardych. Wyprowadzono również elementy odwrotnej macierzy bezwładnościowej omawianego systemu. (**Łańcuchy kinematyczne systemu pozycjonowania głowic dysków twardych**)*

Keywords: hard disk drives, kinematic chain, data areal density, VCM motor.
Słowa kluczowe: dyski twarde, łańcuch kinematyczny, gęstość powierzchniowa, silnik VCM.

Introduction

In the recent years we may observe incredible increase of hard disk drive (HDD) capacity. The capacity of HDD is defined by one fundamental factor – so-called data areal density. This factor to determine the amount of data possible to store on unit disk surface, and it is expressed in Gb/in^2 (giga bits per square inch). The data areal densities growth over the ten last years is in Fig.1 presented. Today's highest data areal density applied in commercial products is used in WD 2TB hard disk drive (manufactured by Western Digital company).

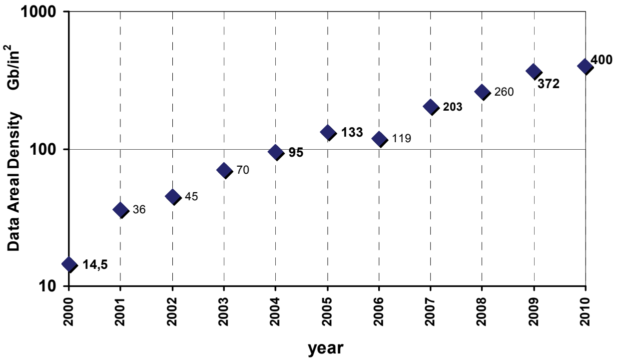


Fig.1. Data areal density growth in commercial products over the last 10 years

In Fig. 2 the data areal density which was reached in laboratory environment is presented and three regions are assigned on it.

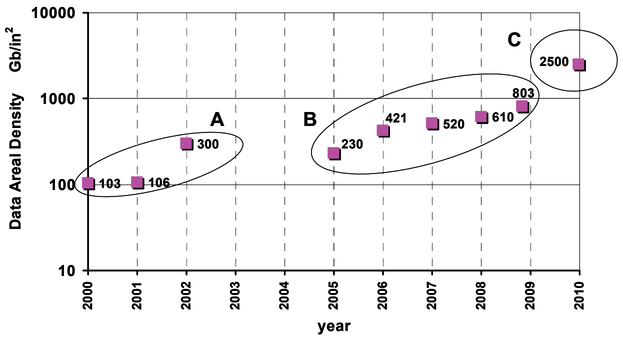


Fig.2. Data areal density reached in laboratory environments

Region denoted by capital letter A collect the data areal densities written by the means of longitudinal recording methods. Most promising method for data writing was perpendicular method of magnetic recording and in Fig. 2 corresponding data are marked by region B. This method is commonly used in modern hard disk drives. Basing on perpendicular methods of magnetic writing the border of 1 Tb/in^2 should be overcome soon. At the beginning of this year the Hitachi engineers reached in laboratory 2.5 Tb/in^2 areal density using thermally assisted magnetic recording method. And they got the physical dimension of bit cell equals 9 nm in length and 28 nm in width. Reaching such incredible values in commercial product is difficult, and limited by many factors related with: super paramagnetic barrier, presence of internal and external vibration [1, 2], limitation of servo bandwidth of head positioning system [3], flying high control of the sliders, etc.

Data density versus kinematic chain

The data areal density affects construction of kinematic chain of head positioning system. For relatively low density only one driving motor (so-called voice coil motor, VCM) was sufficient to satisfactory tracing the data tracks. For very high densities (e.g. 400 Gb/in^2) the magnetic track pitch is really small (about 50 nm) and for proper tracing auxiliary micro motor (actuator) should by applied into kinematic chain. In the case of not large data areal densities reaches value of 20 Gb/in^2 the head positioning systems were equipped only with one motor – VCM motor. In Fig. 3 the head positioning system taken from hard disk drive with areal density in range of 11 – 15 Gb/in^2 is presented.

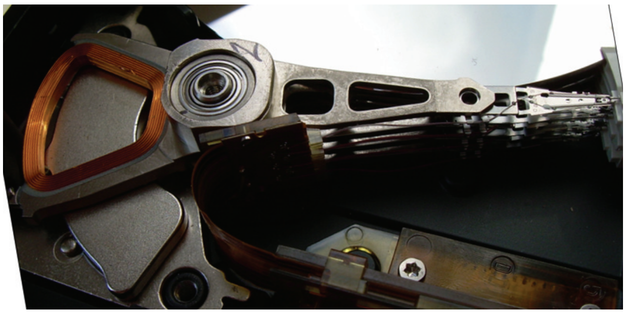


Fig.3. The head positioning system working with areal densities up to 15 Gb/in^2

In Fig. 4 the head positioning system taken from hard disk drive with areal density in range of 60 Gb/in2 is presented. The fundamental differences between head positioning system presented in Fig. 3 and Fig. 4 is disclosed in construction of E-block, high of armature winding of VCM motor, shape of permanent magnets. The E-block presented in Fig. 4 is flat and very wide what assures high stiffness in the plain of motion and it is very important and helpful in following very thin data tracks.

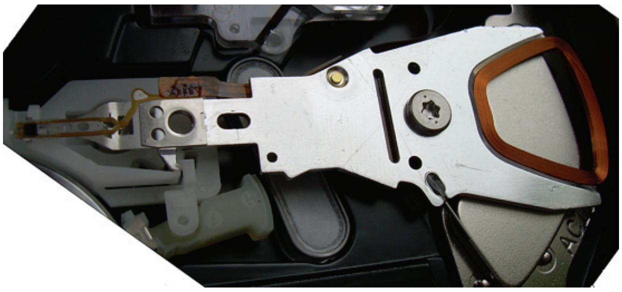


Fig.4. The head positioning system working with areal densities up to 60 Gb/in^2

In Fig. 5 the head positioning system taken from Western Digital WD 2TB drive is presented. In this head positioning system additional piezoelectric PZT motors (actuators) are used for suspension vibration suppressing, increasing servo bandwidth and increase of track tracing ability. In the right bottom corner is shown magnified top view of one PZT motor (actuator).

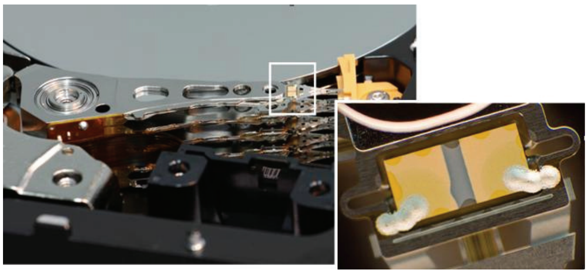


Fig.5. Head positioning system with additional PZT motors able to work with areal data densities equals 400 Gb/in^2 (fot. Maciej Miszczuk)

Bringing additional actuators is necessary for vibration attenuation which results, among other things, from spindle motor unbalanced magnetic pull, ripple torque and bearings problems [1], [2]. In conceptual way the real structure of head positioning system may be decomposed into joints (rotary or/ and prismatic) and stiff links, in such way it may be regarded as a special case of small robots manipulator [4]. Equated parts of head positioning system to joints and links are in Fig. 6 presented. The kinematic chain consists of bough and branch. The bough in opposite to branch has always only one degree of freedom.

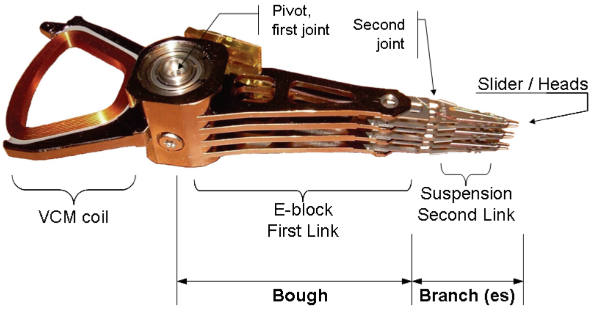


Fig.6. Real structure of head positioning system decomposed into links and joints [4]

Branched kinematic chain of head positioning system

Usually the HDD are equipped with more then one data disk and more then one side of data disk are used for data storage. The kinematic chain of head positioning system which allows for data processing on multiple disks should have highest number of branches. For effective vibration suppression the number of degrees of freedom of branches may vary from one to the highest numbers. The branches which were analysed are collected in Table I. Explanation of symbolic graphical representation of joints are in Fig. 7 presented. The first rotating joint of branch may have his rotating axes parallel (R) or perpendicular (r) to rotating axes of bough joint. The last joints are prismatic and they have the motion axes parallel (P) or perpendicular (p) to bough axes. The forward kinematics for branched kinematic chains of head positioning system may be decomposed into forward kinematics of bough and branches itself; it results with simpler way for kinematic analysis.

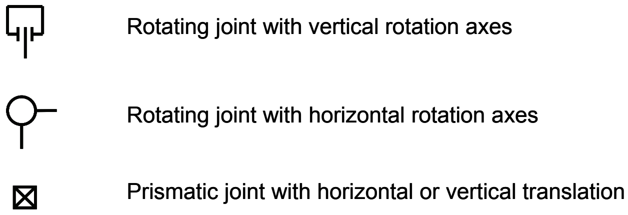
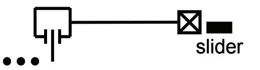
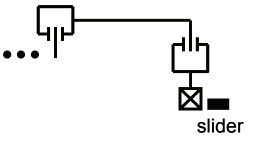
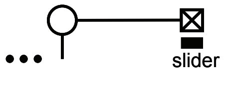
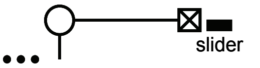
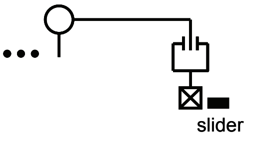


Fig.7. Symbolic graphical representation of joints

Table I. Analyzed kinematic chains of branches

No.	Kinematic chains of branches	Symbol of branch
1		Rp
2		RP
3		RRP
4		rp
5		rP
6		rRP

The general form of forward kinematics is given by expression:

$$\boldsymbol{T}_0^{gi} = \boldsymbol{A}_{g1}\prod_{i=2}^{n}\boldsymbol{A}_{gi} \qquad (1)$$

where A_{g1}, A_{gi} – elementary homogenous transformation matrix for bough and for i-th link of "g" branch respectively, n – number of degree of freedom of elementary branch.

Eqn. (1) expressing the position and orientation adequate head in base coordinate system. Exemplary form of forward kinematic matrix for "Rp" "a" branch is given by form:

$$(2)\quad \boldsymbol{T}_{a1}^{a4}=\prod_{i=2}^{4}\boldsymbol{A}_{ai}=\left[\begin{array}{ccc:c} c_{a2} & 0 & s_{a2} & (a_{a2}+a_{a4})c_{a2}+d_{a3}s_{a2} \\ s_{a2} & 0 & -c_{a2} & (a_{a2}+a_{a4})s_{a2}-d_{a3}c_{a2} \\ 0 & 1 & 0 & -a_{a3} \\ \hdashline 0 & 0 & 0 & 1 \end{array}\right]$$

where c_{a2}, s_{a2} – shortened notation of cosine and sinus function; a_{a2}, a_{a3}, a_{a4}– lengths of the links, d_{a3} – translation of prismatic joint.

The position of all coordinate system fixed with kinematic chain of "Rp" branch is in Fig. 8 presented.

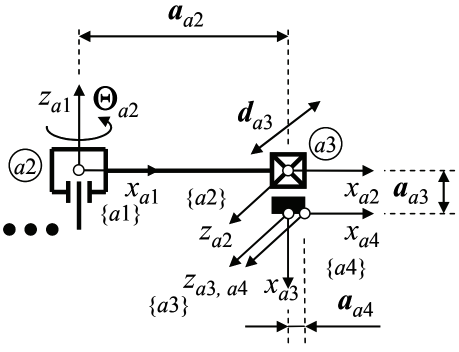


Fig. 8. Described kinematic chain of "a" branch

The formulated dynamics equations may be given in Lagrange form with most important component – dynamic matrix. Method of dynamic matrix for branched head positioning system formulation is discussed in [4, 5, 9]. The resultant dynamic matrix has block structure which corresponding to structure of kinematics chain – consist of submatrices connected with bough dynamics, branches dynamics and mutual dynamics couplings between bough and branches. The dynamics matrix elements filling changes very much depending on branch kinematic chain shape. Exemplary structure of dynamic matrix is in Fig. 9 presented.

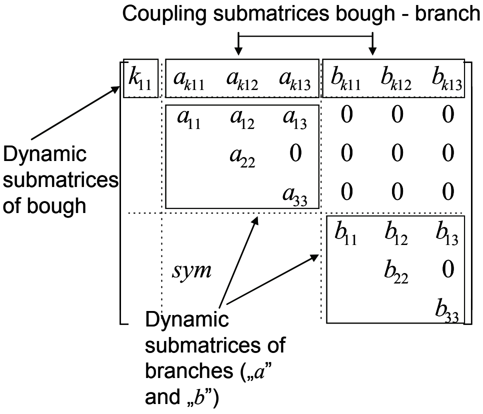


Fig. 9. Exemplary block structure of dynamic matrix or branched kinematic chain consisted with two "rRP" branches

The general expressions for every elements of inverted dynamic matrix are as follows:

- main leading element:

$$(3)\qquad (1,1)=\left(k_{11}-\sum_{g\in\{z_n\cup z_p\}}\frac{g_{\mathrm{k}11}^{2}}{g_{11}}\right)^{-1}=d^{-1}$$

for $g\in\{z_\mathrm{n}\ \cup\ z_\mathrm{p}\}$. z_n denotes the set of all branches cooperating with top part of data disk (starting with branch "a"), z_p otherwise.

- diagonal elements:

$$(4)\qquad (i,i)=g_{ii}^{-1}\left(1+\frac{g_{k11}^{2}}{g_{11}}d^{-1}\right),$$

for $g\in\{z_n\cup z_p\}$.

- elements in first row:

$$(5)\qquad (1,i)=-\frac{g_{k1i}^{2}}{g_{ii}}d^{-1}$$

for $g\in\{z_n\cup z_p\}\ \wedge\ i=1,2\ldots n.$

- elements beside diagonal and first row:

$$(6)\qquad a_{ij}^{-1}=\frac{a_{k11}}{a_{11}}\frac{g_{k11}}{g_{11}}d^{-1}$$

for $g\in\{z_n\cup z_p\}\cap\{a\}\ \wedge\ i\neq j,\ \ i=1,\ \ j=1{,}2\ldots n.$

$$(7)\qquad b_{ij}^{-1}=\frac{b_{k11}}{b_{11}}\frac{g_{k11}}{g_{11}}d^{-1}$$

for $g\in\{z_n\cup z_p\}\cap\{a,b\}\ \wedge\ i\neq j,\ \ i=1,\ \ j=1{,}2\ldots n.$

$$(8)\qquad c_{ij}^{-1}=0$$

for $g\in\{z_n\cup z_p\}\cap\{a,b,c\}\ \wedge\ i\neq j,\ \ i=1,\ \ j=1{,}2\ldots n.$

Summary

According to the usefulness estimate of proposed kinematic chains of branches they were compared under different criterions: attenuation of structural vibrations of positioning system acting in the plain and out of plain of rotating disk, possibility of head skew compensation [6], increases the following ability of data track, possibility of head flying high control [7] and simple mathematical description of kinematics and dynamics. The branches in first and fourth row of Table I reach only 2 points, because they only assure vibration attenuation and increase the data tracing ability. The most points reaches the kinematic chain from third row of Table I (5 points), denoted by "rRP", it assure vibration control, head skew compensation, head flying high control and it is described by relatively simple mathematical model of forward kinematics and dynamics. The second joint of "rRP" should be driven by electrostatic MEMS micromotor [6], the prismatic joint (third joint) may be driven by thermal actuator proposed in [7] and [8]. The first joint may be not actuated it creates passive joint [9]. The "rRP" branch seems to be very promising for construction the head positioning systems for cooperation with very high data areal densities.

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***Authors**: PhD eng. Tomasz Trawiński, Silesian University of Technology, Faculty of Electrical Engineering, Department of Mechatronics, ul. Akademicka 10a, 44-100 Gliwice, Poland, E-mail: tomasz.trawinski@polsl.pl;*

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