An assessment of transmission efficiency on a hard disk's vibration

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Abstract. At present, there is a trend to design a hard disk with a larger capacity, a faster revolution speed, and a precise mechanism. Therefore, the influence of data transmission with respect to vibration is obvious. To reduce interference of the vibrational impact on the data transmission efficiency, vibrational abatement on the hard disk using the damping material becomes crucial. Because of the complicated relationship for the damping coefficient and spring constant to the hardness (D1, D2, and D3) of the damping material installed under the hard disk, it is difficult to theoretically assess an optimal hardness combination of the damping material. Therefore, an alternative way by using an experimental study in conjunction with Taguchi method, an Artificial Neural Network (ANN), and a GA Method is proposed. In this paper, a hard disk is placed on a vibration tester that is an analogue to a dynamic vibrational circumstance induced by a vibrational base. The data transfer rate of the hard disk will be detected by using IOmeter software under various base-excitation accelerations, tilted angles of the hard disk, and targeted frequencies. To reduce the vibrational impact on the data transmission efficiency, an assessment of an optimal three-layer damping material installed under the hard disk using the Taguchi method, the Artificial Neural Network (ANN), and the GA Method is proposed. Before the optimization of the damping material is performed, the required experimental sets (the hardness for three layers of damping material) of the data transmission testing with respect to various design parameters will be determined by using the Taguchi method. The ANN, a simplified objective function (OBJ), will be established by inputting the hardness of three layers of damping material and their related data transmission efficiency at three targeted frequencies. Thereafter, the optimal hardness for three layers of the damping material will be obtained using a genetic algorithm (GA). Consequently, the optimal hardness of the three-layer damping material with respect to various tilted angles and target frequencies will be assessed.

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1 Nomenclature

This paper is constructed on the basis of the following notations:
bit: bit length of chromosome
B_0, B_i, B_{ij}, B_{ijk}: the coefficient of the node function in the ANN
chrm: the length of the chromosome
c_i: the damping coefficient of the i-th layer damping material (N-m s^{-1})
c_{sys}: damping coefficient of vibration system (N-m s^{-1})
CPM: the product of the penalty function
D_1, D_2, D_3: design parameters of hardness for damping material (Shore, HS)
$f_{i1}(D_i)$: the implicit function of the damping coefficient for the i-th layer damping material with hardness of D_1
$f_{i2}(D_i)$: the implicit function of the spring constant for the i-th layer damping material with hardness of D_1
FSE: the deviation of mean square
h: the unit's number in a hidden layer
IOPS: transmission rate (Input/Output per second)
$iter_{max}$: maximum iteration during GA optimization
k_i: the spring constant of the i-th layer damping material
k_{sys}: the spring constant of vibration system
m: mass of the hard disk (kg)
M: the number of the design parameters
N: the number of training data
N_p: the total possible searching number (=2^M)
pc: crossover ratio
pm: mutation ratio
pop: number of population
Q: the number of the network's coefficients
r: the ration of ω / ω_n
x_i, x_j, x_k: the input data in the ANN
y_k: the output value in the ANN
k_p: the penalty function in the ANN
Y : input amplitude for the exciting base (m)
$\hat{y}_i$: the required data in the ANN
y_i: the predicted data for ANNM
σp^2 : the error variation in the ANN
ς : damping ratio of a vibration system
ω : angular velocity of the vibrational base
ω_n : natural angular velocity of the vibrational system

2 Introduction

Because of a larger capacity, a faster revolution speed, and a precise mechanism designed for a hard disk, the vibrational impact on data transmission becomes obvious. In order to reduce the influence of the data transmission on a hard disk, a vibrational control for the hard disk is necessary. Chiou and Hung (1993) simulated a floppy disk using a fixed–free circular plate rotating with a constant speed. Tsai *el al.* (2007) developed an active vibration-isolated system for a notebook's hard disk by modifying the connection between the hard disk and the primary board using both the Piezoelectric actuator and sensor within a space-constrained situation. They also verified the above vibration abatement effect by analyzing the natural frequency and the mode shape via ANASYS and an experimental test. Shiu (2008) investigated the influence of the disk's data transmission with respect to various vibrational frequencies, vibrational amplitudes and tilted angles of the disk. Because of the wide application of neural network techniques used in the parameter design during the manufacturing process (Chen, 2006; Tai, Chi, 2008), Chang (2011) advanced Shiu's study (2008) and assessed the optimization of the hardness on the damping material using the neural network in conjunction with the GA optimizer. However, only one-layer of the damping material was applied in vibration reduction. No effective experimental plan used in reducing the number of experimental tests is proposed. Therefore, in order to enhance vibration control and reduce the number of experimental tests, an assessment of the vibrational impact on the data transmission efficiency, an assessment of an optimal three-layer damping material (shown in Fig. 1) installed under the hard disk using a Taguchi method, an Artificial Neural Network (ANN), and a GA Method is proposed.

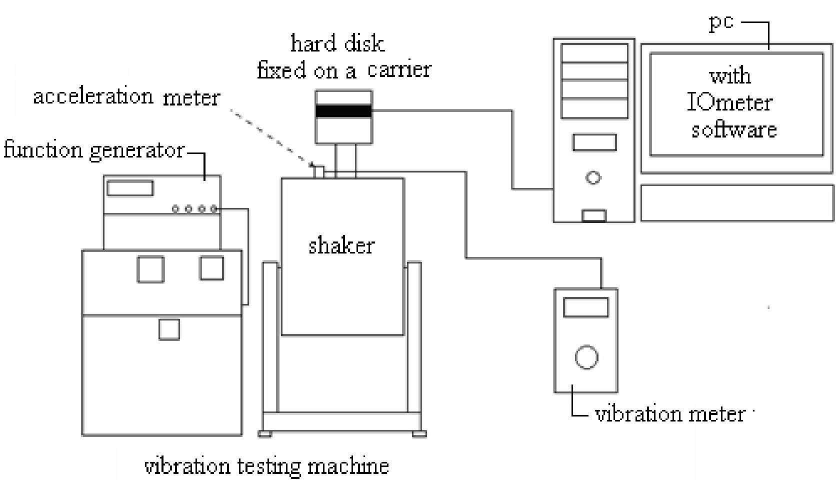

Fig. 1. The measurement of IOPS Base-excitation vibrating system for a hard disk.

3 Mathematical model in vibration

For a three-layer damping material installed under the hard disk with tilted angle of 0^{o}, the equivalent spring/damping system is depicted in Fig.2. The related free-body diagram for a one-mass vibrational system is also shown in Fig. 3. Based on Newton's second law, the equation of motion is

$$m\ddot{z}_1 + c_{sys}(\dot{z}_1 - \dot{z}_o) + k_{sys}(z_1 - z_o) = 0 \tag{1a}$$

$$\frac{1}{c_{sys}} = \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3} \quad ; \quad \frac{1}{k_{sys}} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} \quad ; \quad c_1 = f_{11}(D_1) \quad ; \quad k_1 = f_{12}(D_1) \quad ;$$

$$c_2 = f_{21}(D_2);\, k_2 = f_{22}(D_2);\, c_3 = f_{31}(D_3);\, k_3 = f_{32}(D_3); \tag{1b}$$

where D_1, D_2 , and D_3 are the hardness with respect to three kinds of damping material. Assuming that the base is harmonically excited yields

$$z_o = Y\sin(\omega \cdot t) \tag{2}$$

The relative displacement z is set at

$$z = z_1 - z_o \tag{3}$$

Plugging Eqs.(2) and (3) into Eq. (1) yields

$$m\ddot{z} + c_{sys}\dot{z} + k_{sys}z = m\omega^2 Y \sin(\omega \cdot t) \tag{4}$$

The solution to Eq. (4) is

$$z(t) = Z\sin(\omega t - \phi) \tag{5a}$$

$$Z(\omega) = \frac{mY\omega^2}{\sqrt{\left(k - m\omega^2\right)^2 + c_{sys}^2\omega^2}};$$

$$= Y\frac{r^2}{\sqrt{\left(1-r^2\right)^2 + \left(2r\zeta\right)^2}} \tag{5b}$$

$$r = \frac{\omega}{\omega_n}; \phi = \tan^{-1}\left(\frac{c_{sys}\omega}{k - m\omega^2}\right); \tag{5c}$$

$$\varsigma = \frac{c_{sys}}{2\sqrt{k_{sys}m}} = \frac{\dfrac{c_1 \cdot c_2 \cdot c_3}{c_1 \cdot c_2 + c_1 \cdot c_3 + c_2 \cdot c_3}}{2\sqrt{\left(\dfrac{k_1 \cdot k_2 \cdot k_3}{k_1 \cdot k_2 + k_1 \cdot k_3 + k_2 \cdot k_3}\right)m}} \tag{5d}$$

$$= \frac{\dfrac{f_{11}(D_1)\cdot f_{21}(D_2)\cdot f_{31}(D_3)}{f_{11}(D_1)\cdot f_{21}(D_2) + f_{11}(D_1)\cdot f_{31}(D_3) + f_{21}(D_2)\cdot f_{31}(D_3)}}{2\sqrt{\dfrac{f_{12}(D_1)\cdot f_{22}(D_2)\cdot f_{32}(D_3)}{f_{12}(D_1)\cdot f_{22}(D_2) + f_{12}(D_1)\cdot f_{32}(D_3) + f_{22}(D_2)\cdot f_{32}(D_3)}\cdot m}}$$

Because the damping coefficients and spring constants with respect to three kinds of damping material are related to the implicit functions ($f_{11}, f_{12}, f_{21}, f_{22}, f_{31}, f_{32}$) of the hardness ($D_1$, D_2, and D_3), it is difficult to exactly find a best hardness combination of the three damping material. Therefore, an alternative way by using a Taguchi method, an Artificial Neural Network (ANN), and a GA Method is proposed.

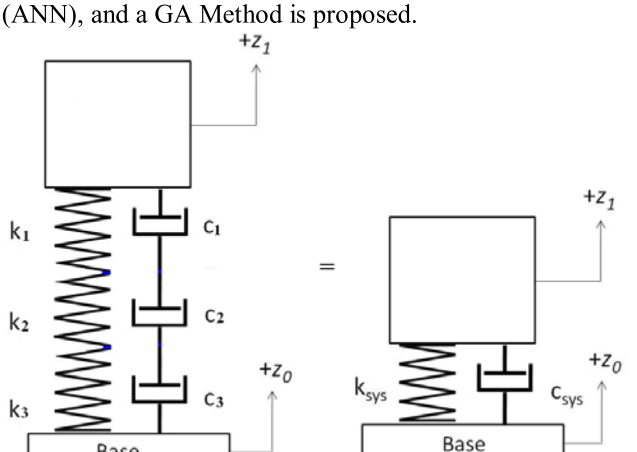

Fig. 2. The equivalent spring/damping system of IOPS base-excitation vibrating system for a hard disk (tilted angle: 0 °).

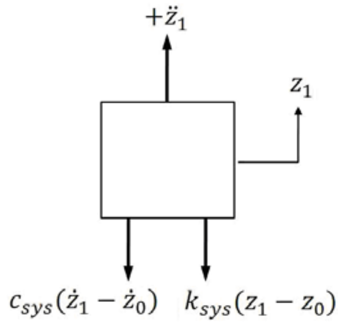

Fig. 3. The free-body diagram for a one-mass vibrational system(tilted angle: 0 ^{o}).

4 Taguchi method

The Taguchi design is an experimental method used to improve quality by using appropriate design parameters determined by practical operations on a site or computer simulation (2000). To efficiently reduce the number of conventional experiments, the orthogonal array (Chang, 2000; Wei, 2002) using design parameters (control factors) in columns and standard (level) quantities in rows is presented. By analyzing the parameters' sensitivity to quality, the optimal parameters can be approached by the Taguchi Method (Lan, Chiu, Yeh, 2008). The steps in establishing the analysis of engineering quality using Taguchi Method include the following:

A. Selection of quality.
B. Judging the ideal functions of quality.
C. Listing all the factors that will influence quality.
D. Deciding the control factors and the related levels.
E. Selecting an appropriate orthogonal table and arranging a complete experimental plan for the control factors and the related levels.
F. Performing experimental work and recording experimental results.
G. Data analysis and comparison.

5 Artificial neural network model (ANNM)

Artificial Neural Networks (ANNs) have an advantage in establishing complex non–linear relationships for complicated problems. They may be viewed as universal approximators; however the main disadvantage of this approach is that detected dependencies are hidden. To overcome this drawback, the Group Method of n Data Handling (GMDH) was developed by Ivakhnenko (1971). The GMDH is a self-organized adaptive model. The interconnections between the layers of neurons are simplified, and an automatic algorithm for structure design and weight adjustment is established. Based on the GMDH's feed-forward networks and short-term polynomial transfer functions, the coefficients of the polynomial transfer functions are obtained using a regression technique. The regression technique is then combined with the emulation of the self-organizing activity for neural network (NN) structural learning. In addition, the input variable set in each layer is created. The assembled number is $p!/[(p-r)!r!]$ where p is the number of input variables and r is normally set to be two. As indicated in Fig. 4, the polynomial neural network is composed of an input layer, a hidden layer — Σ（Summation）, and an output layer（product）where the hidden layer is the weight summation and the output layer is the product of the input and weighted value (Patrikar, Provence, 1996). The jth output —z_{jk} is

$$z_{jk} = \sum_{i=0}^{n} W_{ij} X_{ij} \tag{6}$$

The total output of the neural network is expressed as

$$y_k = \prod_{j=1}^{h} z_{jk} \tag{7}$$

where h is the unit's number in a hidden layer.
Combining Eqs.(4)(5) yields

$$y_k = B_0 + \sum_{i=1}^{n} B_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} B_{ij} x_i x_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} B_{ijk} x_i x_j x_k + ... \tag{8}$$

where y_k is the output value, x_i, x_j, x_k is the input data, and B_0, B_i, B_{ij}, and B_{ijk} are the coefficient of the node function.

To obtain the ANNM, the experimental data of the hardness (D1, D2, and D3) for three layers of damping material installed under the hard disk and the output data (IOPS) is used. The trained ANNM can be achieved using both the training data bank and the polynomial calculation in conjunction with the PSE standard (deviation of mean square).
PSE has the form

$$\text{PSE} = \text{FSE} + k_p \tag{9}$$

$$\text{FSE} = \frac{1}{N}\sum_{i=1}^{N}\left(\hat{y}_i - y_i\right)^2 \tag{10}$$

where FSE is the deviation of the mean square, k_p is the penalty function, N is the number of training data, $\hat{y}_i$ is the required data, and y_i is the predicted data for the ANNM.
The penalty function k_p is

$$k_p = \text{CPM}\frac{2\sigma p^2 Q}{N} \tag{11}$$

where CPM is the product of the penalty function, σp^2 is the error variation, and Q is the number of the network's coefficients. The related steps of the ANNM construction are shown in Fig. 5. The predicted IOPS can be obtained by inputting arbitrary design data. The ANNM, an OBJ function, works in conjunction with the GA optimizer during the optimization process.

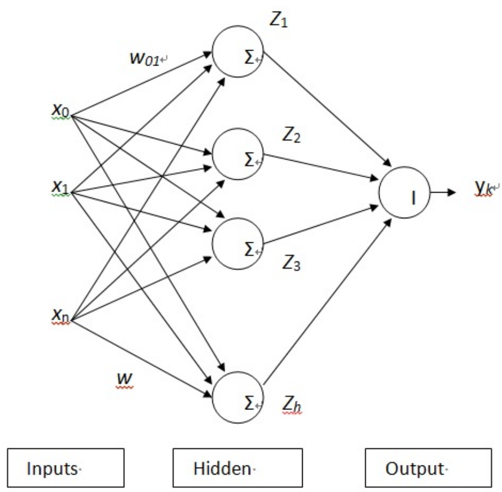

Fig. 4. Structure of the artificial neural network.

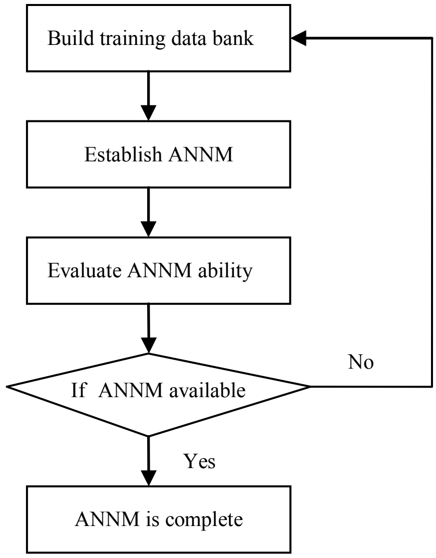

Fig. 5. The steps in the ANNM.

6 Genetic algorithm

The concept of Genetic Algorithms, was first formalized by Holland (1975) and later extended to functional optimization by Jong (1975). It involves the use of optimization search strategies patterned after the Darwinian notion of natural selection. For the optimization of the objective function (*OBJ*), the design parameters of $X1$, $X2$, …, X_m were determined. Initialization is carried out by setting the population size (pop), the length of the chromosome (chrm), the crossover ratio (pm), the mutation ratio (pc), the maximum iteration ($iter_{max}$), the selection method(elitism), the parameter numbers, and the searching ranges of the parameters. Each candidate parent will be selected by the coding/decoding transformation and the fitness (*OBJ*) calculation. The precision (M) of the parameter search is

$$M = \frac{P_{\max} - P_{\min}}{N_p - 1} \tag{12}$$

where N_p ($=2^m$) is the total possible searching number, m is the number of the design parameters, P_{max} is the maximum range of the parameter, and P_{min} is the minimum range of the parameter. The tournament selection will be adopted as the elitism mechanism in the GA optimization. In addition, the uniform crossover shown in Fig. 6 is applied in the optimization process. Moreover, as indicated in Fig. 7, the mutation scheme is also used to widen the range of the chromosome. The operations in the GA method are pictured in Fig. 8. The process was terminated when a number of generations exceeded a pre-selected value of $iter_{max}$.

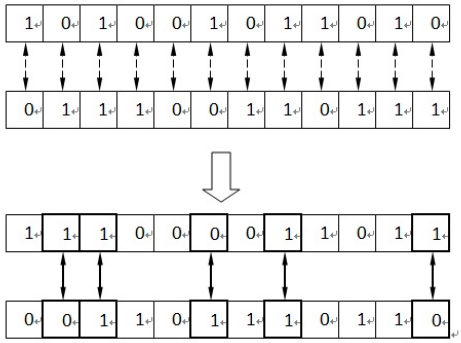

Fig. 6. Mechanism of uniform crossover.

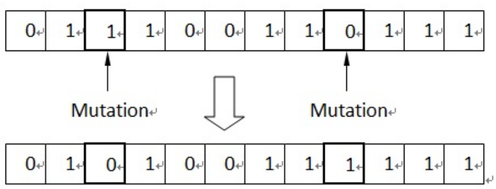

Fig. 7. Mechanism of mutation.

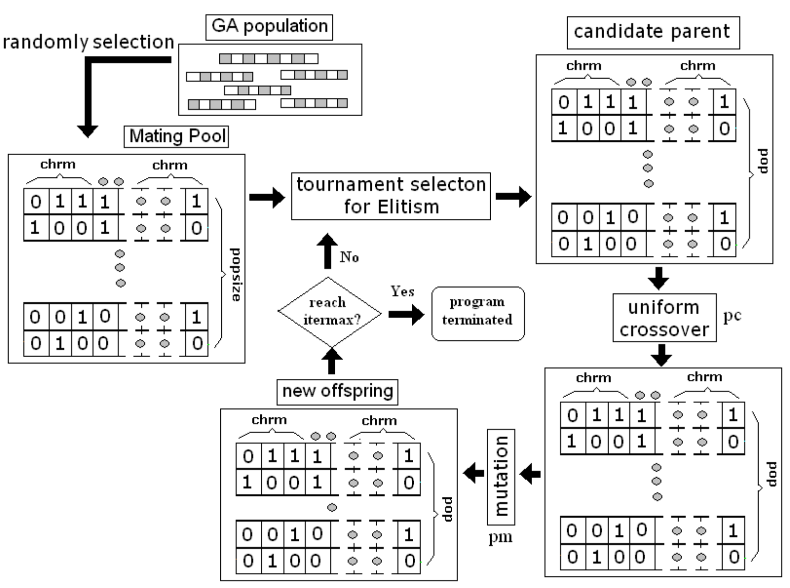

Fig. 8. The block diagram of the GA optimization on plenums.

7 Case study

In this paper, a three-layer damping material installed under the hard disk shown in Fig. 1 is established. An acceleration of 0.2 g is added in the base-excitation vibration. There are three kinds of hard disk with tilted angles (0^o, 5^o, and 10^o) adjusted during the experimental test. To improve the transmission efficiency of a hard disk within a base-excitation environment, a three-layer damping material with various combination of hardness is adopted. In addition, to realize the critical frequencies (target frequencies) that reduce the transmission efficiency of the hard disk, experimental work of an IOPS measurement at three tilted angles without damping material is carried out in advance. Thereafter, for optimal design with the highest transmission efficiency on a hard disk during the base excitation situation, three kinds of hardness (D_1, D_2, and D_3) for three layers of damping material bundled and installed under the hard disk are chosen as the input data. The related experimental transmission rate (IOPS) serves as the output data in the ANNM. In addition, to verify the ANNM correction, training data will be inputted into the ANNM. Using the ANNM as an OBJ and adopting the GA in the optimal process, the best hardness combination of the three-layer damping material with respect to three kinds of tilted angles at the target frequency will be assessed. Moreover, in order to efficiently reduce the number of conventional experiments, the Taguchi design is introduced. The orthogonal array with respect to three tilted angles (0^{o}, 5^{o}, and 10^{o}) and three critical frequencies (140 Hz, 150 Hz, and 160 Hz) will be established by using design parameters (control factors) in columns and standard rows (level) of quantities.

8 Results and discussion

8.1 Results

In order to realize the critical frequency (target frequency) that reduces the transmission efficiency of the hard disk, a hard disk without added damping material is tested using three kinds of tilted angles. The results shown in Fig. 9 indicate that the IOPS at the ranges of 120Hz~180Hz is fairly low. Therefore, three target frequencies of 140 Hz, 150 Hz, and 160 Hz are selected. Before establishing the ANNM and based on the Taguchi method, an orthogonal array with respect to three tilted angles (0^{o}, 5^{o}, and 10^{o}) and three critical frequencies (140 Hz, 150 Hz, and 160 Hz) will be planned in advance. According the orthogonal tables, related experimental work for various combinations of damping material and tilted angles at various critical frequencies is planned.

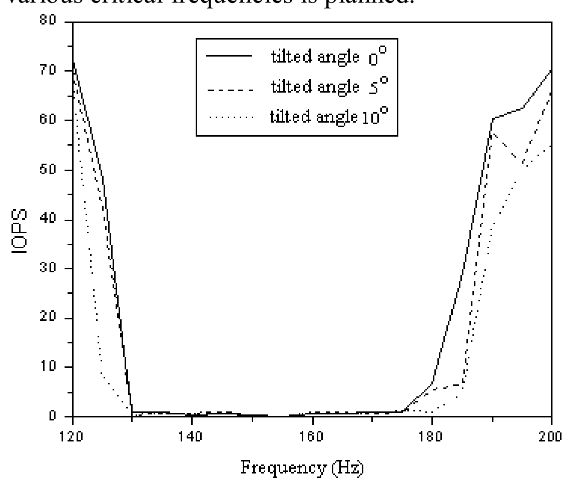

Fig. 9. The hard disk's IOPS with respect to three kinds of tilted angles without adding damping material.

8.1.1 IOPS at a Hard Disk's Tilted Angle of 0°

Using damping material of $D_1=D_2=D_3=50$, the IOPS with respect to acceleration at the target frequency of 140 Hz is shown in Fig. 10. Fig. 10 indicates that the IOPS has the maximum value of acceleration at 0.08 (g). Similarly, adopting damping material of $D_1=D_2=D_3=50$, the IOPS with respect to acceleration at the target frequency of 150 Hz is shown in Fig. 11. Fig. 11 indicates that the IOPS has the maximum value of acceleration at 0.03 (g). Also, using damping material of $D_1=D_2=D_3=50$, the IOPS with respect to acceleration at the target frequency of 160 Hz shown in Fig. 12 indicates that the IOPS has the maximum value of acceleration at 0.06 (g). Therefore, the experimental work on the transmission measurement with respect to three target frequencies 140 Hz, 150 Hz, and 160 Hz under a tilted angle of 0° and accelerations of 0.08, 0.03, and 0.06 (G) is performed and shown in Tables 1~3.

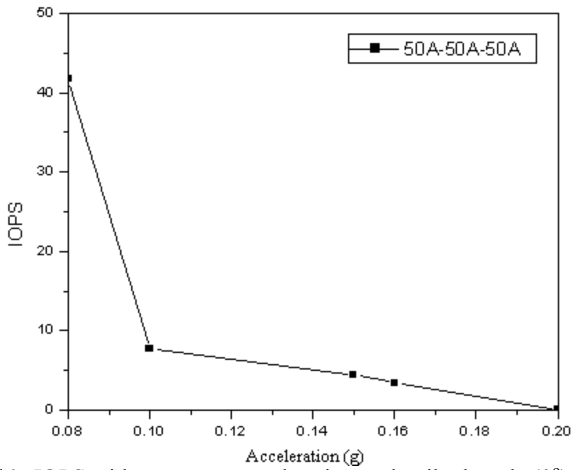

Fig. 10. The hard disk's IOPS with respect to acceleration at the tilted angle (0°) and the target frequency (140 Hz) using damping material (D1=D2=D3=50).

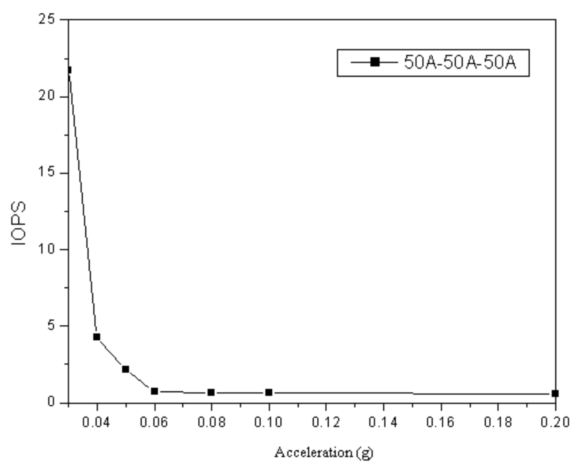

Fig. 11. The hard disk's IOPS with respect to acceleration at the tilted angle (0°) and the target frequency (150 Hz) using damping material (D1=D2=D3=50).

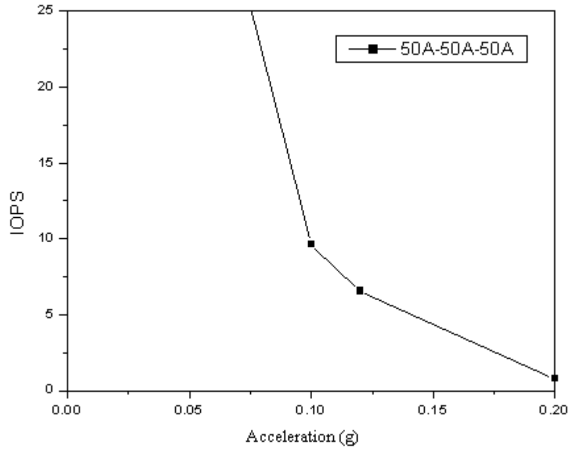

Fig. 12. The hard disk's IOPS with respect to acceleration at the tilted angle (0^o) and the target frequency (160 Hz) using damping material (D1=D2=D3=50).

Table 1. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 0^o and 140 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	21.97232
2	30	60	70	55.29873
3	30	70	40	9.57526
4	30	40	60	7.86317
5	30	50	70	3.30748
6	40	50	60	60.14307
7	40	70	30	57.00203
8	40	40	40	58.85171
9	40	30	50	59.83321
10	40	70	60	14.17967
11	50	60	70	56.15763
12	50	30	60	57.31137
13	50	70	50	54.46577
14	50	40	60	56.48192
15	50	30	70	60.81673
16	60	70	50	57.26186
17	60	40	50	3.23626
18	60	60	60	58.67868
19	60	30	50	34.40444
20	60	40	70	8.46796
21	70	30	40	1.70073
22	70	50	60	60.57304
23	70	70	70	54.00194
24	70	40	60	58.30641
25	70	50	30	61.19392

Table 2. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 0^o and 150 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	4.55979
2	30	60	70	18.63423
3	30	70	40	2.17793

4	30	40	60	6.44938
5	30	50	70	18.16737
6	40	50	60	27.91441
7	40	70	30	1.60061
8	40	40	40	9.94398
9	40	30	50	55.45931
10	40	70	60	53.85391
11	50	60	70	39.70867
12	50	30	60	35.34186
13	50	70	50	23.01421
14	50	40	60	21.13465
15	50	30	70	49.11832
16	60	70	50	40.18326
17	60	40	50	53.69491
18	60	60	60	20.15838
19	60	30	50	52.57962
20	60	40	70	21.34739
21	70	30	40	21.94138
22	70	50	60	35.19878
23	70	70	70	43.44021
24	70	40	60	54.94346
25	70	50	30	26.09167

Table 3. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 0^o and 160 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	32.46401
2	30	60	70	4.35431
3	30	70	40	3.74602
4	30	40	60	47.84439
5	30	50	70	20.38102
6	40	50	60	4.89399
7	40	70	30	5.44983
8	40	40	40	16.99811
9	40	30	50	1.85630
10	40	70	60	20.50971
11	50	60	70	3.38123
12	50	30	60	8.46935
13	50	70	50	1.01219
14	50	40	60	1.56729
15	50	30	70	1.42908
16	60	70	50	45.36873
17	60	40	50	10.61518
18	60	60	60	42.03457
19	60	30	50	47.61785
20	60	40	70	13.42458
21	70	30	40	1.83411
22	70	50	60	2.34113
23	70	70	70	15.12661
24	70	40	60	15.65359
25	70	50	30	44.52777

Using the experimental data from the ANNM and applying the GA optimizer, the optimization of the combined hardness (D_1, D_2, and D_3) is performed. The related GA control parameters are shown in Table 4. The optimal results of the design parameters (D_1=D_2=D_3=50) at the target frequencies is shown in Table 5. To meet the real hardness specifications of the damping material, real design data that is close to the optimal data are adopted. The real design data and related IOPS for three target frequencies at a tilted angle of 0^{o} are depicted in Table 6. Moreover, the original design data (without optimization) and related IOPS are illustrated in Table 7. Comparing the transmission efficiency before and after optimization is performed, results in targeted frequencies of 140 Hz, 150 Hz, and 160 Hz are plotted in Figs. 13~15.

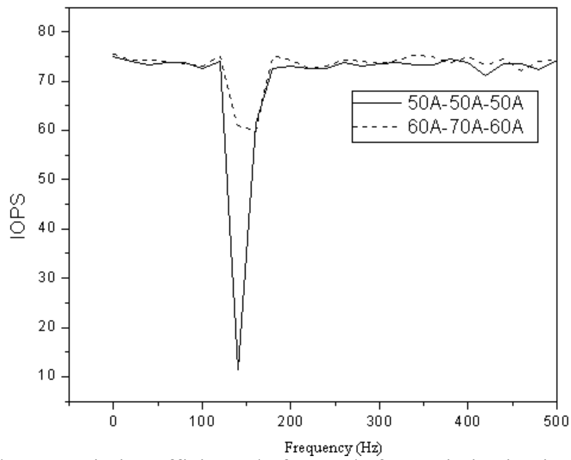

Fig. 13. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 140 Hz (tilted angle of 0^{o}).

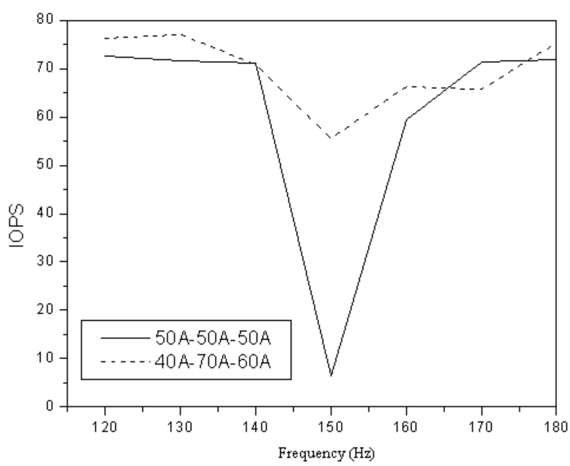

Fig. 14. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 150 Hz (tilted angle of 0^{o}).

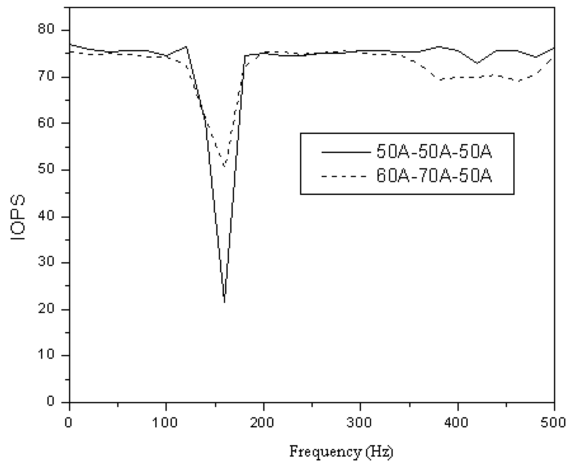

Fig. 15. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 160 Hz (tilted angle of 0°).

Table 4. Selected GA parameters during shape optimization.

GA parameters	Value (or condition)
design variables	3
chrm	40
pop	100
elitism	(tournament)
crossover	(uniform crossover)
pc	0.8
pm	0.05
$iter_{max}$	1000

Table 5. Optimal results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at three target frequencies (tilted angle = 0°).

Target frequency (Hz)	Optimal design parameter			OBJ
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
140	57.5589	73.5525	62.3321	74.48192
150	38.6027	67.3665	59.2364	64.3681
160	57.3395	68.1867	52.0627	56.3769

Table 6. Practical results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at three target frequencies (tilted angle = 0°).

Target frequency (Hz)	Practical design parameter			IOPS
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	
140	60	70	60	61.06
150	40	70	60	55.45
160	60	70	50	50.57

Table 7. Original IOPS (D_1=D_2=D_3=50) at three target frequencies without optimization (tilted angle = 0°).

Target frequency (Hz)	Practical design parameter			IOPS
	Parameter 1(D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	
140	50	50	50	11.36
150	50	50	50	6.36
160	50	50	50	21.43

8.1.2 IOPS at a Hard Disk's Tilted Angle of 5°

Similarly, the optimization of hardness (D_1, D_2, and D_3) for a hard disk at a tilted angle of 5 ° is performed. The experimental work on the transmission measurement with respect to three target frequencies 140 Hz, 150 Hz, and 160 Hz under a tilted angle of 5 ° and accelerations of 0.08, 0.03, and 0.06 (G) is performed and shown in Tables 8~10. Using the experimental data from the ANNM and applying the GA optimizer, the optimal design parameters (D_1=D_2=D_3=50) at the target frequencies is shown in Table 11. To meet the real hardness specification for the damping material, real design data that is close to the optimal data is adopted. The real design data and related IOPS for three target frequencies at a tilted angle of 5 ° are depicted in Table 12. Moreover, the original design data (without optimization) and related IOPS are illustrated in Table 13. Comparing the transmission efficiency before and after optimization is performed, results in targeted frequencies of 140 Hz, 150 Hz, and 160 Hz are plotted in Figs. 16~18.

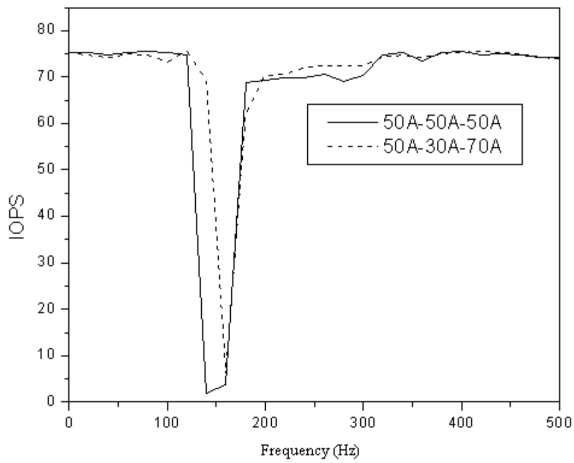

Fig. 16. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 140 Hz (tilted angle of 5°).

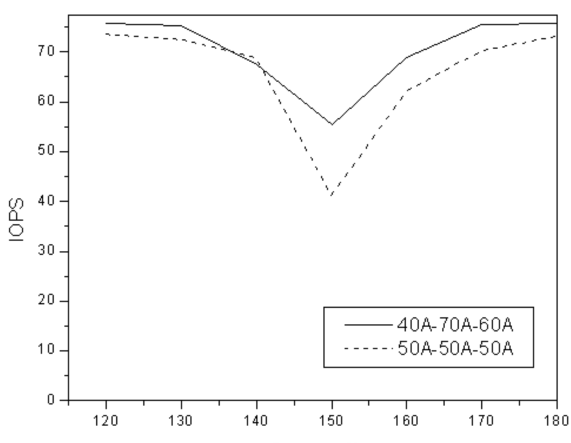

Fig. 17. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 150 Hz (tilted angle of 5°).

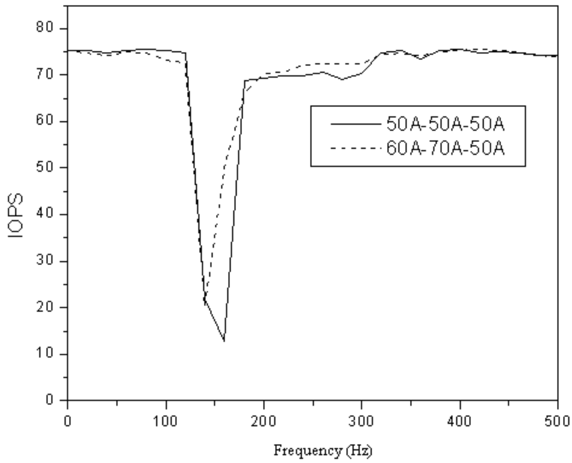

Fig. 18. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 160 Hz (tilted angle of 5°).

Table 8. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 5° and 140 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	3.09138
2	30	60	70	46.66624
3	30	70	40	8.46956
4	30	40	60	17.57293
5	30	50	70	8.92974
6	40	50	60	15.87552
7	40	70	30	58.84662
8	40	40	40	53.74312
9	40	30	50	27.87799
10	40	70	60	11.23359
11	50	60	70	65.64529
12	50	30	60	33.51206
13	50	70	50	59.55521
14	50	40	60	64.06865
15	50	30	70	65.92546
16	60	70	50	63.33052
17	60	40	50	3.85896
18	60	60	60	56.78851
19	60	30	50	33.13341
20	60	40	70	1.08436
21	70	30	40	1.08953
22	70	50	60	11.36135
23	70	70	70	59.00901
24	70	40	60	60.67589
25	70	50	30	52.10223

Table 9. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 5° and 150 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	47.52115
2	30	60	70	32.82668
3	30	70	40	6.44015

4	30	40	60	4.52681
5	30	50	70	26.76372
6	40	50	60	5.16036
7	40	70	30	8.50283
8	40	40	40	22.62648
9	40	30	50	33.25664
10	40	70	60	66.28423
11	50	60	70	20.91662
12	50	30	60	28.80622
13	50	70	50	4.21008
14	50	40	60	22.10794
15	50	30	70	5.63342
16	60	70	50	13.67966
17	60	40	50	51.90243
18	60	60	60	44.63756
19	60	30	50	55.86545
20	60	40	70	48.08131
21	70	30	40	24.77616
22	70	50	60	8.86914
23	70	70	70	13.55824
24	70	40	60	24.37131
25	70	50	30	38.42977

Table 10. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 5° and 160 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	27.22337
2	30	60	70	5.98962
3	30	70	40	2.66482
4	30	40	60	19.90615
5	30	50	70	9.59281
6	40	50	60	6.80697
7	40	70	30	1.56727
8	40	40	40	3.11403
9	40	30	50	2.17442
10	40	70	60	23.17627
11	50	60	70	17.51487
12	50	30	60	7.00062
13	50	70	50	1.10011
14	50	40	60	1.81187
15	50	30	70	2.81924
16	60	70	50	50.95341
17	60	40	50	17.82112
18	60	60	60	40.61928
19	60	30	50	44.27424
20	60	40	70	10.56677
21	70	30	40	1.82861
22	70	50	60	1.70727
23	70	70	70	47.45103
24	70	40	60	23.71135
25	70	50	30	21.09823

Table 11. Optimal result of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at three target frequencies (tilted angle = 5°).

Target frequency (Hz)	Optimal design parameter			OBJ
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
140	47.2256	33.4489	66.3825	72.8632
150	42.8749	70.3235	61.8612	57.3342
160	62.0962	70.9005	45.3971	64.8916

Table 12. Practical results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at three target frequencies (tilted angle = 5°).

Target frequency (Hz)	Practical design parameter			IOPS
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	
140	50	30	70	66.22
150	40	70	60	55.36
160	60	70	50	50.02

Table 13. Original IOPS (D_1=D_2=D_3=50) at three target frequencies without optimization (tilted angle = 5°).

Target frequency (Hz)	Practical design parameter			IOPS
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	
140	50	50	50	6.43
150	50	50	50	41.24
160	50	50	50	12.12

8.1.3 IOPS at a Hard Disk's Tilted Angle of 10°

Equally, the optimization of hardness (D_1, D_2, and D_3) for a hard disk at a tilted angle of 10 ° is performed. The experimental work for the transmission measurement with respect to three target frequencies 140 Hz, 150 Hz, and 160 Hz under a tilted angle of 10 ° and accelerations of 0.08, 0.03, and 0.06 (G) is performed and shown in Tables 14~16. Using the experimental data from the ANNM and applying the GA optimizer, the optimal design parameters (D_1=D_2=D_3=50) at the target frequencies are shown in Table 17. To meet real hardness specifications for the damping material, real design data that is close to the optimal data is adopted. The real design data and related IOPS for the three target frequencies at a tilted angle of 10 ° are depicted in Table 18. Moreover, the original design data (without optimization) and related IOPS are illustrated in Table 19. Comparing the transmission efficiency before and after optimization is performed, results in frequencies of 140 Hz, 150 Hz, and 160 Hz are plotted in Figs. 19~21.

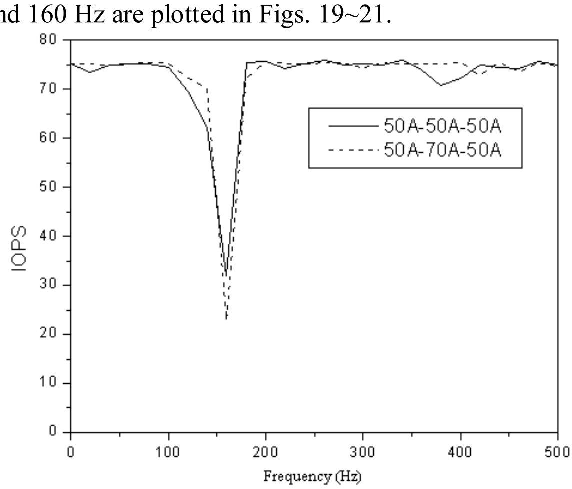

Fig. 19. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 140 Hz (tilted angle of 10°).

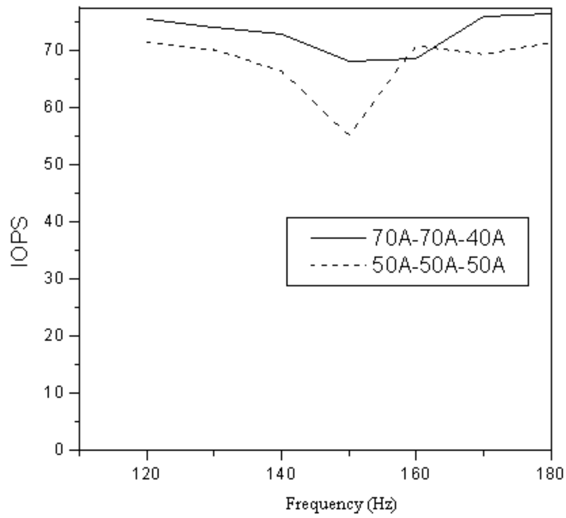

Fig. 20. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 150 Hz (tilted angle of 10°).

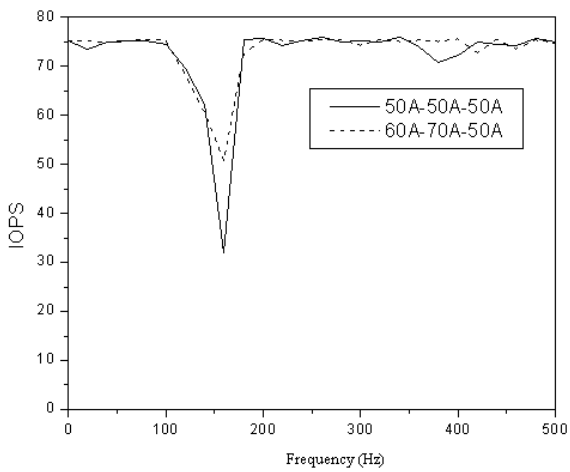

Fig. 21. Comparing the transmission efficiency before and after optimization is performed at the target frequency of 160 Hz (tilted angle of 10°).

Table 14. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 10° and 140 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	1.80081
2	30	60	70	48.68469
3	30	70	40	13.81347
4	30	40	60	3.19666
5	30	50	70	3.00747
6	40	50	60	3.30326
7	40	70	30	65.93559
8	40	40	40	29.20518
9	40	30	50	53.84428
10	40	70	60	10.00949

11	50	60	70	65.52351
12	50	30	60	10.81129
13	50	70	50	66.19763
14	50	40	60	39.31431
15	50	30	70	40.71456
16	60	70	50	55.72275
17	60	40	50	57.18641
18	60	60	60	54.34626
19	60	30	50	44.93873
20	60	40	70	3.17489
21	70	30	40	1.68952
22	70	50	60	59.49621
23	70	70	70	47.39454
24	70	40	60	53.81705
25	70	50	30	46.89436

Table 15. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 10^o and 150 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	45.32489
2	30	60	70	40.98301
3	30	70	40	2.81179
4	30	40	60	8.98616
5	30	50	70	17.39083
6	40	50	60	43.29303
7	40	70	30	8.76413
8	40	40	40	12.17231
9	40	30	50	44.13115
10	40	70	60	56.33476
11	50	60	70	28.36053
12	50	30	60	41.23089
13	50	70	50	4.53785
14	50	40	60	7.09557
15	50	30	70	21.23833
16	60	70	50	56.01829
17	60	40	50	50.85596
18	60	60	60	34.41528
19	60	30	50	52.28129
20	60	40	70	15.39809
21	70	30	40	60.10214
22	70	50	60	26.79049
23	70	70	70	21.32682
24	70	40	60	48.12752
25	70	50	30	29.67769

Table 16. Experimental results of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at a tilted angle of 10^o and 160 Hz.

Item	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
1	30	40	50	25.32489
2	30	60	70	2.57491
3	30	70	40	3.11967
4	30	40	60	27.58612
5	30	50	70	13.67468
6	40	50	60	11.70491
7	40	70	30	1.55053

8	40	40	40	3.84822
9	40	30	50	1.73401
10	40	70	60	3.99291
11	50	60	70	5.18783
12	50	30	60	7.23593
13	50	70	50	1.86749
14	50	40	60	1.71731
15	50	30	70	1.83482
16	60	70	50	47.65246
17	60	40	50	22.72884
18	60	60	60	49.75337
19	60	30	50	40.21922
20	60	40	70	12.46766
21	70	30	40	1.41149
22	70	50	60	1.38483
23	70	70	70	49.78942
24	70	40	60	4.23209
25	70	50	30	37.41532

Table 17. Optimal result of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at three target frequencies (tilted angle = 10°).

Target frequency (Hz)	Optimal design parameter			OBJ
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	IOPS
140	46.3258	71.0052	54.6587	70.3894
150	72.2311	67.5274	41.5288	67.2318
160	56.1108	73.5341	54.2323	59.5564

Table 18. Practical result of a hard disk with a three-layer damping material (hardness of D_1, D_2, and D_3) at three target frequencies (tilted angle = 10°).

Target frequency (Hz)	Practical design parameter			IOPS
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	
140	50	70	50	70.14
150	70	70	40	68.11
160	60	70	50	50.85

Table 19. Original IOPS (D_1=D_2=D_3=50) at three target frequencies without optimization (tilted angle = 10°).

Target frequency (Hz)	Practical design parameter			IOPS
	Parameter 1 (D_1)	Parameter 2 (D_2)	Parameter 3 (D_3)	
140	50	50	50	62.14
150	50	50	50	55.16
160	50	50	50	32.03

8.2 Discussion

As deduced in Eq.(5), in case of $\omega^2 << \omega_n^2$, $Z(\omega)$, the displacement of the disk, is simplified as

$$Z(\omega) = Yr^2 \tag{13}$$

If the frequency is $\omega^2 >> \omega_n^2$, $Z(\omega)$ will become

$$Z(\omega) = Y \tag{14}$$

Whereas, in case of $\omega^2 = \omega_n^2$ (resonance), $Z(\omega)$ yields

$$Z(\omega)=\frac{Y}{2\varsigma_{sys}}$$

$$=\frac{\sqrt{\left(\frac{k_1\cdot k_2\cdot k_3}{k_1\cdot k_2+k_1\cdot k_3+k_2\cdot k_3}\right)m\cdot Y}}{\frac{c_1\cdot c_2\cdot c_3}{c_1\cdot c_2+c_1\cdot c_3+c_2\cdot c_3}}$$

$$=\frac{\sqrt{\left(\frac{f_{12}(D_1)\cdot f_{22}(D_2)\cdot f_{32}(D_3)}{f_{11}(D_1)\cdot f_{21}(D_2)+f_{11}(D_1)\cdot f_{31}(D_3)+f_{21}(D_2)\cdot f_{31}(D_3)}\right)m\cdot Y}}{\frac{f_{11}(D_1)\cdot f_{21}(D_2)\cdot f_{31}(D_3)}{f_{11}(D_1)\cdot f_{21}(D_2)+f_{11}(D_1)\cdot f_{31}(D_3)+f_{21}(D_2)\cdot f_{31}(D_3)}} \quad (15)$$

As mentioned in Eqs.(13)~(15), for a tilted angle of 0 ^{o}, the displacement of the hard disk induced by the external based-excitation vibration is tightly related to the forcing based-excitation frequency, the system's natural frequency, the amplitude of the base-excitation (Y), and the hardness combination of three damping material. Here, the amplitude of the base-excitation (Y) is related to the base acceleration. If it is in the case of the resonant condition (for a specified bas-excitation motion), the displacement of the hard disk will decrease when the system's damping ratio increases. Also, the transmission efficiency will be improved if the induced displacement of the hard disk is small. Therefore, the finding of a best combination for three damping material is essential. Moreover, for a tilted angle with non-zero degree, because of the unbalance force installed on the spring/damping system, the induced displacement of the hard disk will be expected to increase.

As indicated in Fig. 4, the transmission efficiency at the ranges of 120Hz~180Hz is very low. Therefore, the three target frequencies of 140 Hz, 150 Hz, and 160 Hz are selected and used in the hardness optimization for the three-layer damping material. As indicated in Tables 6~7, for a hard disk vibrating at a tilted angle of 0 ^{o} and accelerating at 0.08(G), the transmission efficiency (IOPS) will be improved from 11.36 to 61.06 at 140 Hz using the hardness combination of (60, 70, 60). In addition, the transmission efficiency (IOPS) will be enhanced from 6.36 to 55.45 at 150 Hz using the hardness combination of 40, 70, and 60. Also, the transmission efficiency (IOPS) will increase from 21.43 to 50.57 at 160 Hz using the hardness combination of 60, 70, and 50. Additionally, as indicated in Tables 12~13, for a hard disk vibrating at a tilted angle of 5 ^{o} and accelerating at 0.03(G), the transmission efficiency (IOPS) will be improved from 6.43 to 66.22 at 140 Hz when using the hardness combination of 50, 30, and 70. Also, the transmission efficiency (IOPS) will be enhanced from 41.24 to 55.36 at 150 Hz when using the hardness combination of 40, 70, and 60. In addition, the transmission efficiency (IOPS) will increase from 12.12 to 50.02 at 160 Hz using the hardness combination of 60, 70, and 50. Moreover, as indicated in Tables 18~19, for a hard disk vibrating at a tilted angle of 10 ^{o} and accelerating at 0.06(G), the transmission efficiency (IOPS) will be improved from 62.14 to 70.14 at 140 Hz when the hardness combination is 50, 70, and 50. Also, the transmission efficiency (IOPS) will be enhanced from 55.16 to 68.11 at 150 Hz when the hardness combination is 70, 70, and 40. Consequently, the transmission efficiency (IOPS) will increase from 32.03 to 50.85 at 160 Hz when the hardness combination is 60, 70, and 50.

9 Conclusions

As can be seen in Eqs.(13)~(15), the induced displacement of the hard disk is closely related to the forcing based-excitation frequency, the system's natural frequency, the acceleration (Y), and the hardness combination of three damping material. Also, the tilted angle with unbalanced force will largely influence the hard disk's motion. In order to depress the vibration effect to the hard disk's data transmission, a best combination for three damping material, an appropriate base acceleration, and a fitful tilted angle are necessary.

Experimental work shown in Fig. 4 indicates that the transmission efficiency at the ranges of 120Hz~180Hz is very low when using the acceleration of base-excitation at 0.2 (G). To reduce the vibrational impact on data transmission efficiency, a three-layer damping material installed under the hard disk is adopted. An assessment of the damping material's hardness (D_1, D_2, and D_3) is performed by using the Artificial Neural Network Model (ANNM) and the GA Method. Before the optimization of the damping material is performed, the required experimental sets for data transmission testing will be determined by using the Taguchi method. Here, the ANNM, a simplified objective function (OBJ), is established by inputting the hardness (D_1, D_2, and D_3) of three layers of damping material and their related data transmission efficiency (IOPS) at a targeted transmission frequency. Results reveal that the transmission efficiency of a hard disk at three tilted angles can be efficiently improved at targeted frequencies within a base-excitation vibrating environment using the GA optimization. For a hard disk with a tilted angle of 0^{o}, the increments of IOPS at the target frequencies (140Hz, 150 Hz, 160 Hz) are 49.7, 49.09, and 29.14. In addition, for a hard disk tilted at 5^{o}, the increments of IOPS with respect to the target frequencies (140Hz, 150 Hz, 160 Hz) are 50.79, 14.12, and 37.9. Also, for a hard disk tilted at 10^{o}, the increments of IOPS with respect to the target frequencies (140Hz, 150 Hz, 160 Hz) are 8.0, 12.95, and 18.82.

Consequently, the assessment of the three-layer damping material's hardness using the Taguchi method, the GA optimization, as well as the ANN's model is quite efficient.

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