Dynamic Compensation of Hard-Disk R/W Head and Head-Stack

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Abstract: - *R/*W heads of HDDs are inherently unstable or highly underdamped. Compensations are always necessary for the heads and actuators to function properly under motion control. This article provides the control models of the single-head and the head-stack. Comparison studies of various compensation structures are presented. Resonance issue has been addressed with the corresponding mitigation technique. The design optimization to improve the R/W head performance and stability has been achieved via adaptive tabu search.

Key-Words: - hard disk R/W head, head-stack, dynamic compensation, resonance, adaptive tabu search.

1 Introduction

Present day HDDs employ R/W head-stack as depicted in Fig. 1, even though single head types still exist in commercial drives. Without proper compensations, both types of the R/W heads exhibit highly underdamped responses, even unstable. There have been many attempts in recent years to compensate for undesirable and unstable responses of these heads. Robust control approach has been proposed [1] to handle this dynamic compensation problem. Nonlinearity, friction, and resonance have been compensated for by the composite nonlinear feedback control [3]-[4], linear compensation and fuzzy control [5]. Nonlinear PID, and adaptive robust control approaches for the problems can be found in [6], and [7], respectively. The review presented is not exhaustive, but serves to show some good examples in the field.

This article intends to show that using linear control technique is possible to solve the dynamic compensation problems of the HDD-heads. Since the dynamic of the head is quite complicated, manual design is usually not possible. Computational efforts under some optimization algorithms are particularly useful to achieve the design criteria. The works presented herein are different from the previous works in [5] in that the following materials are presented: comparison studies of various control system structures, head-stack dynamic compensations, and resonance countermeasure via notch filtering.

This article consists of 5 sections including the introduction. Section 2 presents the models of the single-head, and the head-stack. Section 3 discusses the resonance problems, and the corresponding

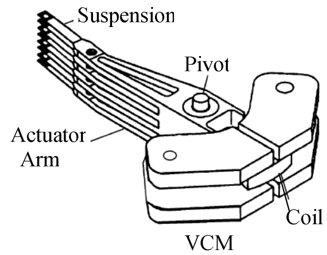


Fig. 1 R/W head-stack [2].

mitigation via notch filters. Section 4 describes the structure of the compensation problems as well as the adaptive tabu search algorithms as the tool to reach the optimal design goal. Sections 5 and 6 provide results, discussions, and conclusions, respectively.

2 Transfer Function Models of The R/W Heads

2.1 The Single-Head

The main components of the single-head of a hard drive are a voice-coil-motor (VCM), a pivot, an actuator arm, and suspension. The small tip of the suspension holds the actual R/W head. The structure looks very similar to Fig. 1 except that there are only one arm and one suspension.

Fig. 2 illustrates the unstable open-loop responses of the single-head. It is reported that the dynamic of the single-head contains 5 resonance modes [3] which can be described by the following transfer function

$$G_{sh}(s) = \frac{2.35\times10^{8}}{s^{2}} G_{sh1}(s)G_{sh2}(s)G_{sh3}(s) \times G_{sh4}(s)G_{sh5}(s) \quad (1)$$

, in which

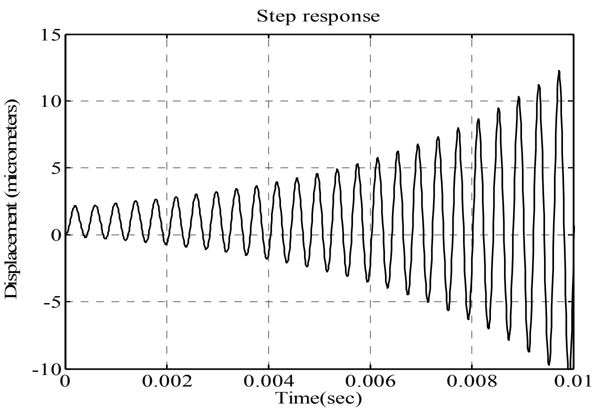
$$G_{sh1}(s) = \frac{0.8709s^{2} + 1726s + 1.369\times10^{9}}{s^{2} + 1480s + 1.369\times10^{9}}$$

$$G_{sh2}(s) = \frac{0.9332s^{2} - 805.8s + 1.739\times10^{9}}{s^{2} + 125.1s + 1.739\times10^{9}}$$

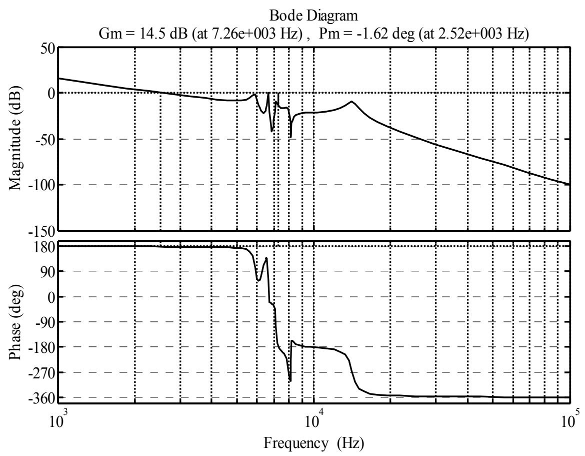
$$G_{sh3}(s) = \frac{1.072s^{2} + 925.1s + 1.997\times10^{9}}{s^{2} + 536.2s + 1.997\times10^{9}}$$

$$G_{sh4}(s) = \frac{0.9594s^{2} + 98.22s + 2.514\times10^{9}}{s^{2} + 1805s + 2.514\times10^{9}}$$

$$G_{sh5}(s) = \frac{7.877\times10^{9}}{s^{2} + 6212s + 7.877\times10^{9}} .$$



(a)

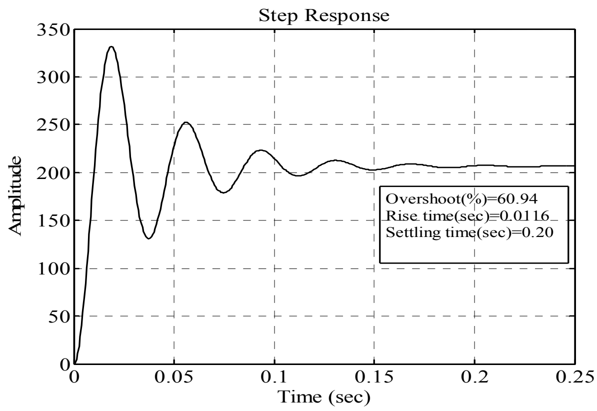


(b)

Fig. 2 Open-loop responses of the single-head: (a) time-domain, and (b) frequency-domain.

2.2 The Head-Stack

The structure of the head-stack is shown in Fig.1. Several arms and suspensions offer more masses which dampen out the inherently unstable dynamic of the single-head, its predecessor. The open-loop response of the head-stack is highly underdamped and contains more than 50% overshoot as shown in Fig. 3.



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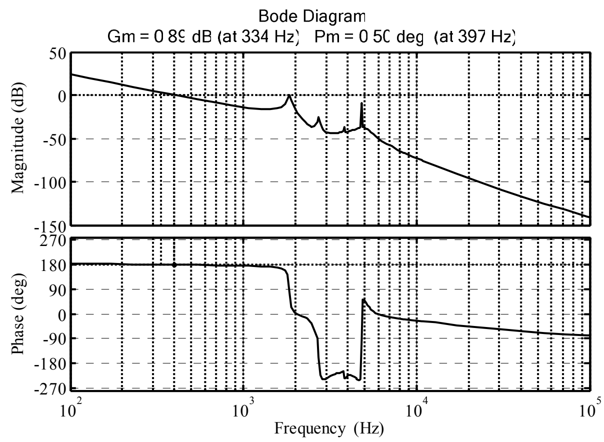


(b)

Fig. 3 Open-loop responses of the head-stack: (a) time-domain, and (b) frequency-domain.

An accurate transfer function model is 12th order with 10 zeros [2] expressed by the $G_{h.st}(s)$ as follows

$$G_{h.st}(s) = G_{h.st1}(s)G_{h.st2}(s)G_{h.st3}(s) \times G_{h.st4}(s)G_{h.st5}(s)G_{h.st6}(s) \quad (2)$$

, where

$$G_{h.st1}(s) = \frac{1}{s^{2} + 4656s + 9.65\times10^{8}}$$

$$G_{h.st2}(s) = \frac{s^{2} - 2410s + 2.676\times10^{8}}{s^{2} + 53.76s + 2.903\times10^{4}}$$

$$G_{h.st3}(s)=\frac{s^2+4645s+3.368\times10^8}{s^2+342.3s+1.352\times10^8}$$

$$G_{h.st4}(s)=\frac{s^2+375.6s+5.82\times10^8}{s^2+400.4s+2.913\times10^8}$$

$$G_{h.st5}(s)=\frac{s^2+413.7s+9.176\times10^8}{s^2+213.6s+5.854\times10^8}$$

$$G_{h.st6}(s)=\frac{s^2-2.162\times10^{10}s+2.522\times10^{15}}{s^2+342.4s+9.1\times10^8}.$$

3 Mitigation of Resonance Problems

The frequency responses of the heads contain several resonance modes as illustrated by the Figs. 2(b) and 3(b). If they were not properly treated beforehand, some of them would still remain after compensations, and would seriously destabilize the R/W heads due to high frequency noise and disturbance. In particular, the suspension structural vibration occurs during the track-following mode since the resonance is excited during the track-seeking operation [8]-[9]. One approach to solve this resonance problem is to use a notch or an anti-resonance filter of the form

$$G_n(s)=\frac{s^2+2\zeta_n\omega_0 s+\omega_0^2}{s^2+2\zeta_0\omega_0 s+\omega_0^2} \quad (3)$$

, where ω_0 = estimated resonant frequency, and ζ_0, ζ_n = dominator and numerator damping factors, respectively.

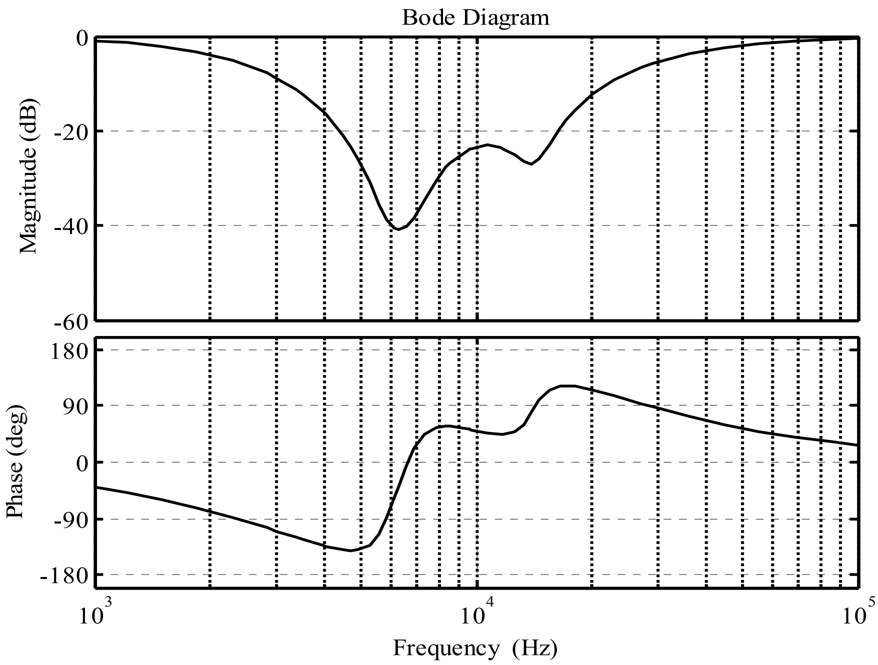
Referring to the responses in Fig. 2(b), the dominant resonant frequencies are at 5.89, 6.64 and 14.10 kHz, respectively. Using $\zeta_0=1$ and $\zeta_n=0.1$, the obtained notch filter can be expressed as

$$\begin{aligned}G_{nsh}(s)=&\left(\frac{s^2+7402s+1.37\times10^9}{s^2+74020s+1.37\times10^9}\right)\\&\times\left(\frac{s^2+8344s+1.741\times10^9}{s^2+83440s+1.741\times10^9}\right)\\&\times\left(\frac{s^2+1.772\times10^4s+7.849\times10^9}{s^2+1.772\times10^5s+7.849\times10^9}\right)\end{aligned} \quad (4).$$

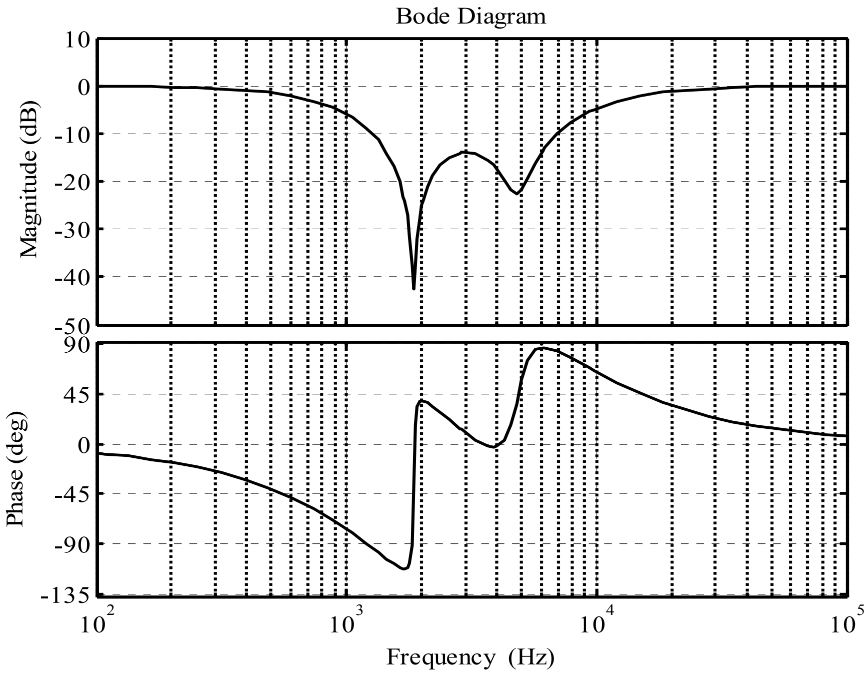
The frequency-domain characteristics are shown in Fig. 4(a).

Referring to Fig. 3(b) for the head-stack, only 2 resonant frequencies are considered, which are 1.85, and 4.82 kHz, respectively. The damping factors $\zeta_0=1$ and $\zeta_n=0.01$ are also used. The filter transfer function is shown in Eq. (5), and its characteristics are depicted in Fig. 4(b).

$$\begin{aligned}G_{nhs}=&\left(\frac{s^2+232.5s+1.351\times10^8}{s^2+23250s+1.351\times10^8}\right)\\&\times\left(\frac{s^2+6057s+9.172\times10^8}{s^2+60570s+9.172\times10^8}\right)\end{aligned} \quad (5)$$



(a)



(b)

Fig. 4 Notch filter characteristics: (a) for single-head, and (b) for head-stack.

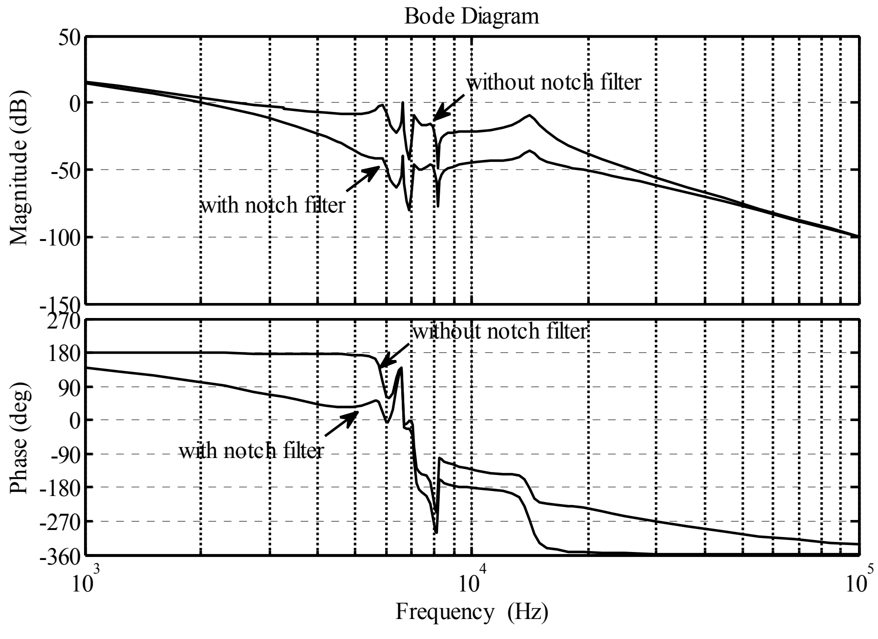


Fig. 5 Frequency responses of the single-head without and with notch filters.

Figs. 5 and 6 illustrate the frequency responses of the single head, and the head-stack, respectively. For both types of the R/W heads, it can be clearly seen that the designed notch filters properly suppress the severe resonant frequencies. In the resonant frequency ranges after compensation, the magnitudes of the frequency responses are well below 0 dB. As a result, more robusted stability is achieved.

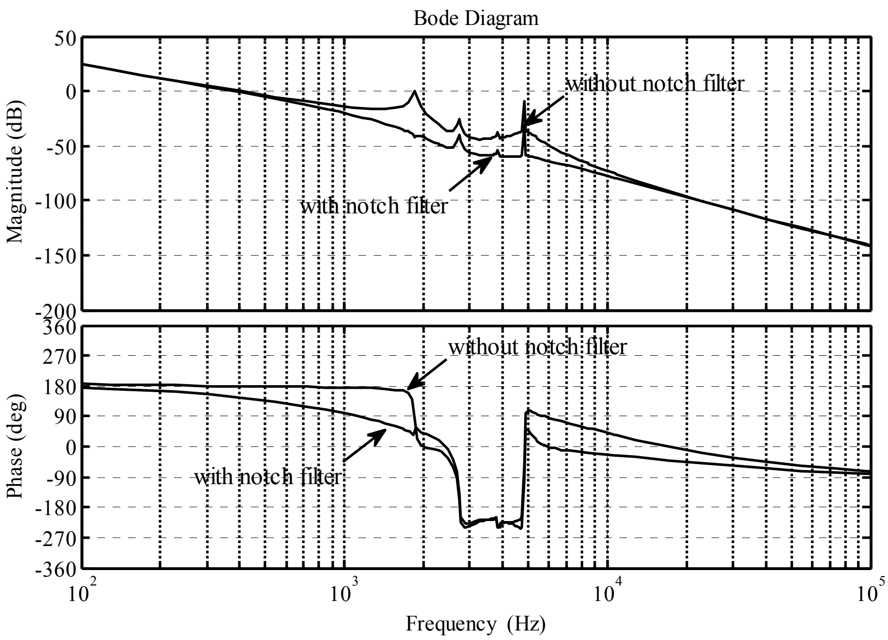
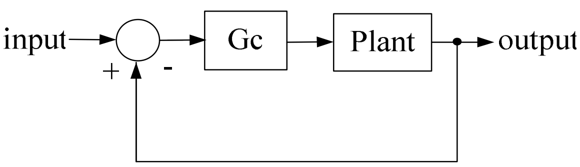


Fig. 6 Frequency responses of the head-stack without and with notch filters.

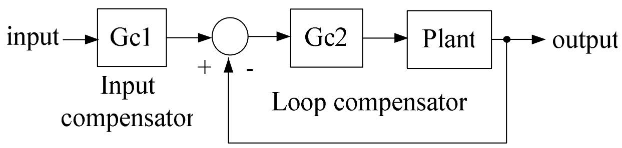
4 Optimalizing The Compensation

4.1 Problem Formulation

As shown in Fig. 7, three control-system structures are considered, which are (i) the simple feedback control regarded as 1-DOF in Fig. 7(a), (ii) the 2-DOF of type-I in Fig. 7(b), and (iii) the 2-DOF of type-II in Fig. 7(c). In practice of the hard-disk industry, the design criteria are given by GM $\geq$ 5dB and PM $\geq$ 25deg. The response overshoot can be allowed up to 25%. However, engineers tend to design toward the time response having as small overshoot and settling time as possible. The compensators used by this work are 3rd order with real poles and zeros. It will be later shown in the results, and discussion section that the 2-DoF of type-II structure renders very good performances for the single-head. Consequently, it will be only this structure considered for use with the head-stack.



(a)



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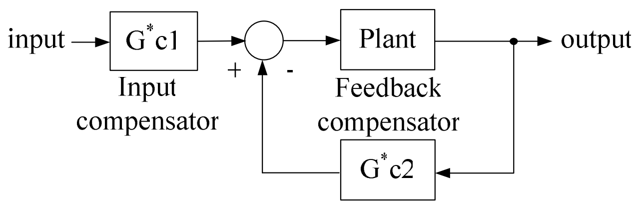

(c)

Fig. 7 System structures: (a) 1-DOF, (b) 2-DOF of type-I, and (c) 2-DOF of type-II.

4.2 Optimization Tool

The compensation for the hard-disk heads is a kind of transfer-function synthesis problem consisting of many unknown parameters, and usually being over/under-determined cases. Design such systems manually to meet stringent specifications is very tedious or even impossible. Since the design process is iterative, CAD with optimization procedures are employed. This work utilizes the adaptive tabu search (ATS) as a tool to reach the optimal design goal under the principle of inequalities [10].

Tabu search was introduced by Glover [11]-[12] to solve combinatorial optimization problems. Various modified forms exist [14] with a diversity of applications. Among those, the ATS has been proposed and applied to various fields [13]-[16].

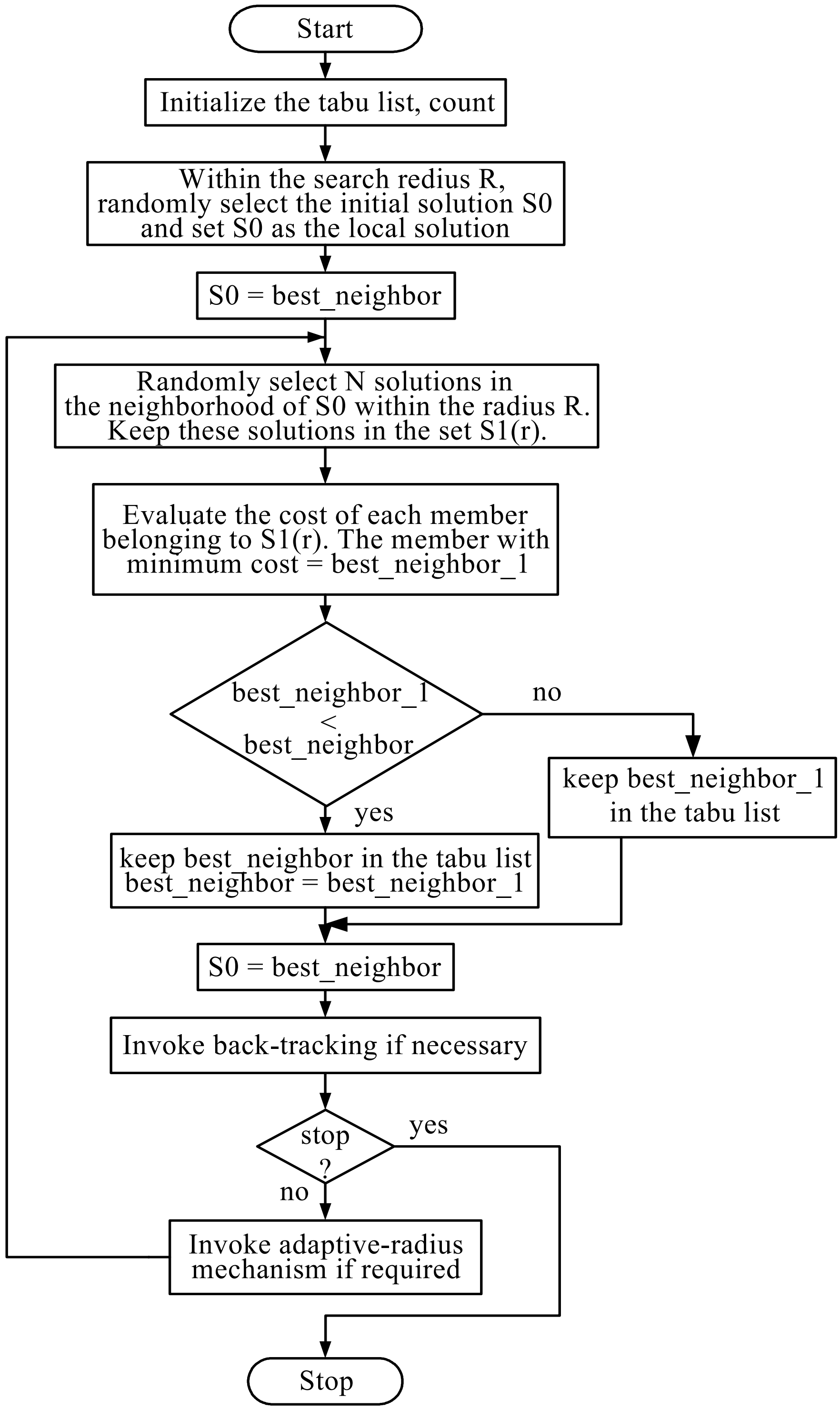

Fig. 8 ATS algorithms.

The ATS consists of three main parts namely (i) the tabu search skeleton, (ii) the adaptive search radius (AR) mechanism for search acceleration, and (iii) the backtracking (BT) mechanism for deadlock release. Parallel TS and pseudo-parallel ATS can be found in [17]-[19]. The ATS can be summarized by the flow diagram in Fig. 8.

The present problem becomes an optimal synthesis of compensators of the form shown in Eq. (6). The objective is to minimize the sum of absolute errors between the input shape and the actual response in time-domain. Simultaneously, the closed-loop control must meet the requirements of stability margins. Due to the high order of the plant

$$G_C(s) = K_1 \frac{(s+z_1)(s+z_2)(s+z_3)}{(s+p_1)(s+p_2)(s+p_3)} \quad (6).$$

models and the filters, design the compensators manually is not possible. Although with an aid of a computer, some trials-and-errors are necessary, and the design process would be very tedious and time-consuming. Thus, the design process is formulated as a search and optimization problem of multi-parameter control synthesis. The requirements for control performances are overshoot ≤ 5%, GM > 5dB, PM > 25deg., and sum of absolute errors < 60. Referring to Table 1 summarizing the search parameters, the second to the rightmost column states the AR. The initial search radius is R=20. The AR rules can be read as follows: if (Σ|e|<100) then (R=10), if (Σ|e|<80) then (R=7), and if (Σ|e|<65) then (R=4), respectively. The ATS invokes the BT when a deadlock occurs, and it retrieves a 5-step backward solution stored in the tabu list (TL) for use as an initial solution. With this initial solution, the ATS forms a new search move. Further more, Table 1 declares the search-parameter boundaries of 7 and 14 parameters to be searched according to the types of the control-system structures.

Table 1 Boundaries and search parameters.

Compensators	Search parameters	BT	R	AR	N
1-DOF	$z_1, z_2\ z_3,\ p_1,\ p_2,\ p_3,\ K_1$; [100-$10^{11}$]	5	20	$\sum\|e\|<100$; R = 10 $\sum\|e\|<80$; R = 7 $\sum\|e\|<65$; R = 4	50
2-DOF type I, 2-DOF type II	$z_1, z_2\ z_3,\ z_4, z_5,\ z_6,\ p_1, p_2,$ $p_3, p_4,\ p_5, p_6,\ K_1, K_2$; [100-$10^{11}$]				

Table 2 Summary of the compensators for the single-head.

Compensators	Mp (%)	t_r (ms)	t_s (ms)	GM (dB)	PM (deg.)
1-DOF: $Gc(s)=7.168\times10^4 \frac{(s+1.639\times10^4)(s+7.305\times10^7)(s+685.7)}{(s+2.461\times10^8)(s+2.925\times10^4)(s+9.270\times10^8)}$	15.9	0.371	3.62	19.8	62.1
2-DOF Type I: $Gc1(s)=7.515\times10^3 \frac{(s+5.946\times10^4)(s+3.991\times10^9)(s+8676)}{(s+1.193\times10^9)(s+2174)(s+5.967\times10^9)}$ $Gc2(s)=6.547\times10^3 \frac{(s+2.625\times10^4)(s+9.822\times10^9)(s+3291)}{(s+6.556\times10^8)(s+9.9\times10^4)(s+5.333\times10^9)}$	41.7	0.671	8.40	28.2	22.3
2-DOF Type II: $G^*c1(s)=8.541\times10^3 \frac{(s+3.838\times10^4)(s+5.025\times10^9)(s+3295)}{(s+5.233\times10^9)(s+3.125\times10^4)(s+2.08\times10^9)}$ $G^*c2(s)=9.133\times10^3 \frac{(s+9.245\times10^4)(s+7.62\times10^9)(s+1232)}{(s+3.627\times10^9)(s+2.596\times10^4)(s+5.279\times10^9)}$	1.93	0.696	1.10	14.0	43.2

Remarks: BT=backtracking, R=search radius, AR=adaptive radius, N=number of members in the neighbourhood.

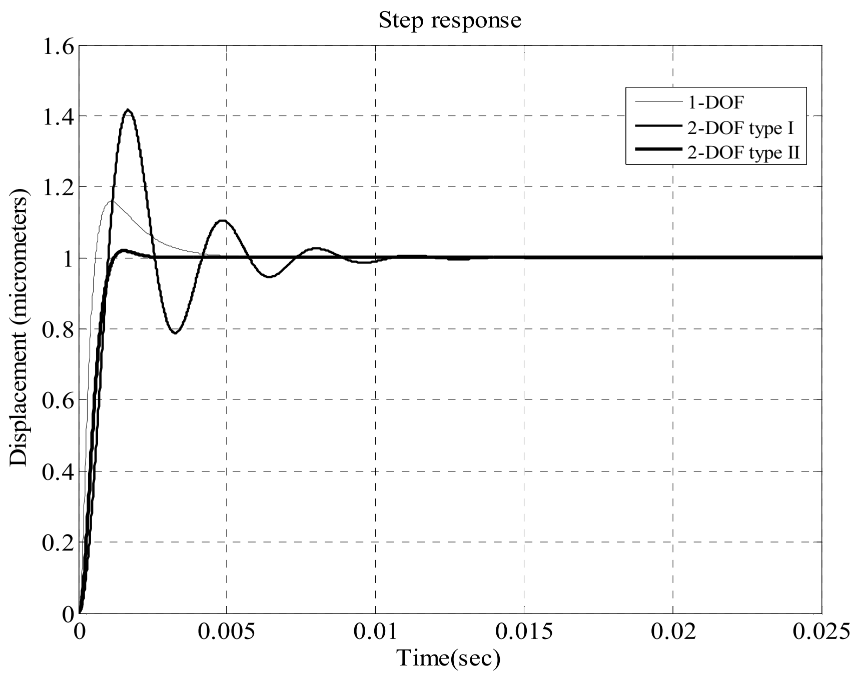

Fig. 9 Compensated responses (single-head).

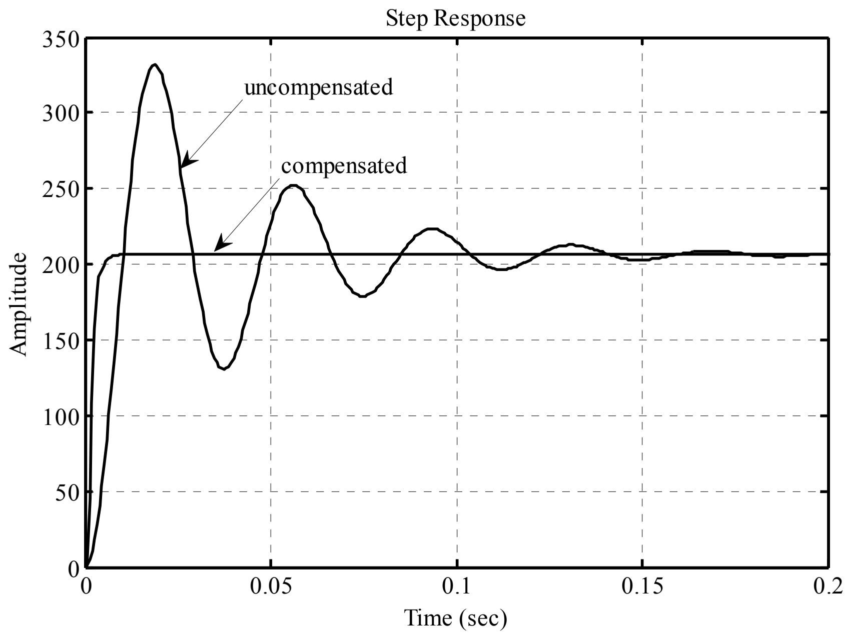

Fig. 10 Step responses of the head-stack.

5 Results and Discussion

5.1 The Single-Head

Table 2 summarizes the compensators found by the ATS, and their corresponding performance indices. Fig. 9 shows the step responses of the compensated head. It is noticed that all compensation structures render very satisfactory stability margins. In the case of strictly demanded low overshoot, the 2-DOF (type II) is the optimum choice. If the overshoot is lenient, the 1-DOF can be an alternative.

5.2 The Head-Stack

Since the 2-DOF (type II) structure renders very good results for the single-head compensation, the same structure is applied to the head-stack. The search by the ATS, which employs the same search parameters declared in Table 2, provides the following compensators:

$$G_{cs1}(s) = 5.153\times10^{3}\frac{(s+\ 2.086\times10^{6})}{(s+3.399\times10^{10})} \times\frac{(s+\ 3.671\times10^{7})(s+2.459\times10^{7})}{(s+3.216\times10^{3})(s+3.113\times10^{9})} \quad (7)$$

$$G_{cs2}(s) = 1.192\times10^{3}\frac{(s+5.959\times10^{6})}{(s+4.398\times10^{9})} \times\frac{(s+6.09\times10^{9})(s+514.6)}{(s+5318)(s+7.141\times10^{9})} \quad (8).$$

The compensated system has GM = 10.1dB, and PM = 36.1deg. Fig. 10 depicts the uncompensated and the compensated responses. The ATS offers an excellent set of the compensators rendering the step response with 0.92% overshoot, and 5 ms settling time, which is much better than the uncompensated one.

6 Conclusion

Dynamic compensations based on linear system approach for R/W HDD heads have been presented. The transfer function models of the single head, and the head-stack have been reviewed. Discussions on resonance problems inherently exist with HDD heads are presented as well as the corresponding mitigation using anti-resonance filters. With the proposed filters, the R/W head stability becomes more robusted. Performance and stability improvements have been achieved by using the linear control design with an aid of the adaptive tabu search (ATS) algorithms to seek for optimal solutions. The simulation results indicate that the compensators obtained from search provide very good compensated performances, and stability margins for the single-head and the head-stack. The control structure determined superior to the others is the 2-DOF of type-II having one input, and one feedback compensators, respectively.

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