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Topological Design of a Hard Disk Drive suspension Using Multi-objective Population Based Incremental Learning

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Abstract

The work in this paper presents topological design of a hard disk drive (HDD) suspension. A multiobjective design problem is set to explore Pareto optimum topologies that maximise the first sway mode natural frequency and simultaneously minimizing bending stiffness of the suspension. Design constraints include the first bending and torsion modes natural frequencies. Population based incremental learning (PBIL), as an optimiser for multi-objective optimization, is used to explore a Pareto optimal front of the design problem. Some selected suspension topologies thereafter are modified so as to meet all HDD suspension requirements. It is illustrated that the proposed design approach is a powerful numerical tool for design/optimization of HDD suspension systems.

Key words: population based incremental learning (PBIL); topology optimization; Pareto optimal front; bending stiffness, hard disk drive suspension

Introduction

A suspension system is a component that connects an E-block to a sliding head in a HDD. Suspensions can be categorized as being 3-piece or 4-piece. The former has three main components i.e. baseplate, load beam and gimbal (flexure) whereas the later has four main parts with a hinge being added to the system. The baseplate is used as an attachment to the E-block part. The hinge is introduced to the system so as to enable pitching and rolling movement of the load beam. The load beam is often stiffened by adding to its edges a couple of stiffeners, usually called rails [1]. The sliding head is attached at the tip of the beam by a spherical joint called a dimmer. The dimmer enables the head to move without a severe contact between itself and the platter's flexible shape.

Suspension design is said to be complicated and difficult due to some conflicting design conditions and manufacturing tolerances. It can be thought of as a cantilever beam extended from an E-block. On the other hand, it is said to be a compliance mechanism which attain its motion by means of structural flexibility. The suspension needs to have sufficiently low vertical (bending) stiffness so that the air bearing to suspension stiffness ratio is maintained at the proper range [2]. However, the in-plane dynamic stiffness has to be as high as possible in order to alleviate the off-track phenomenon and enable the servo bandwidth being increased [1-2]. This means that we need to minimise the suspension vertical stiffness and, at the same time, maximise the natural frequencies associated with the sway and torsion modes [2].

In the past, engineers designed their suspension by using a trial-and-error approach. However, it has been found recently that the use of optimisation technology to suspension design is the more efficient and effective approach [3]. Some research work on the use of topology optimisation for the design of a HDD suspension has been made [1-6]. The design problems are mostly the maximisation of sway or torsion mode natural frequencies whereas the mass and vertical stiffness are constrained [2].

This paper proposes a multiobjective evolutionary approach to deal with HDD suspension design. The design problem is posed to find a set of optimum suspension topologies so as to maximize the first sway mode frequency and the suspension bending stiffness. Design constrains include the first torsion, and bending modes frequencies of a structure. The multiobjective version of PBIL is employed to tackle the design problem. Some of the non-dominated results obtained are refined to meet the practical bending stiffness requirement. It is shown that the present design approach is effective and practical for HDD suspension design.

Topology Optimization of a Suspension

The more advanced design technique to achieve a HDD suspension is using topological optimization incorporating with finite element analysis [1-6]. A structure achieved by means of topology optimization is the best structural layout that optimizes a predefined objective function while fulfilling design constraints. For a general pre-process of structural topology design as shown in Fig. 1, the structure consists of the predefined design domain, boundary conditions and applied loads. Voids and unchangeable areas can also be added to the system.

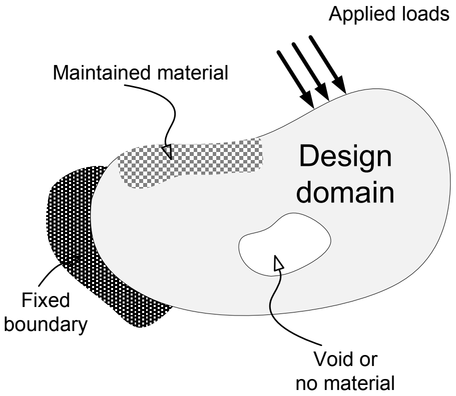

Fig. 1 The generalized shape for exploring the structural topology optimization

In practice, a topological design process can be carried out by using finite element analysis in combination with a numerical optimization method. For a plate structure, the design domain is discretised into a number of finite elements as many as possible. Topological design variables are the thicknesses of the elements. It can be said that the distribution of elements' thicknesses determines a structural topology. Having obtained the optimum solution, the elements with nearly zero thicknesses represent holes or voids on the structure whereas other elements indicate the existence of the structural material as shown in Figure 2.

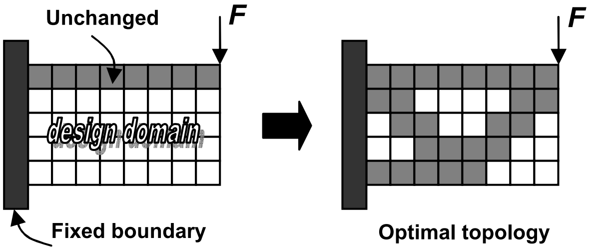

Fig. 2 Topology design process

Several well-established design approaches for this type of design problem have been introduced and the most popular method is the solid isotropic material with penalization (SIMP) [7]. The use of gradient-based optimisers for topological design is said to be efficient and practical. The application of evolutionary algorithms (EAs) such as genetic algorithm for this large-scale problem is questionable due to their low convergence rate and complete lack of consistency.

Nevertheless, several attempts have been made so as to enhance the searching performance of EAs for structural topological design [8-11]. Recently, it has been found that, by introducing a numerical scheme to reduce the total number of topological design variable while preserving the topological diversity as much as possible, the searching performance enhancement of EAs can be accomplished [8, 12]. The results obtained from using those ideas can be compared with topologies obtained from using their gradient-based counterparts although they are still inferior to the later in terms of convergence rate. Using EAs for topological design with acceptable searching performance is still attractive to engineering designers since one simulation run of multiobjective evolutionary algorithms (MOEAs) results in many optimum design solutions. Also, as MOEAs require no function derivative, the methods can deal with almost all kinds of optimum design problem.

Multiobjective Population-Based Incremental Learning

PBIL is a simple version of the estimation of distribution algorithm (EDA). The method was first proposed by Beluja [12] for single objective optimization. It has been developed as one of MOEAs as presented in [13] and [14]. It has been found that the multiobjective version of PBIL is among the most powerful MOEAs using binary string as design variables. For multiobjective PBIL, the search procedure starts with an initial probability matrix and an empty external Pareto archive. A binary population is then generated according to the current probability matrix. The non-dominated solutions of the population are then sorted and put into an external Pareto archive. The probability matrix is updated based upon the non-dominated binary solutions in the Pareto archive and a new population according to the updated probability matrix is then created. The external Pareto archive is updated by replacing the members in the archive with the non-dominated solutions sorted from the combination of the new population and the members in the previous archive. In cases that the number of non-dominate solutions in the archive exceeds the predefined archive size, the normal line technique is activated to remove some of the members from the archive while maintaining population diversity. The computational steps are repeated until the termination criterion is met. For more details of MOPBIL, see [13-14].

HDD Suspension Topology Design

The HDD suspension design problem is based upon the work in [2], which is adapted to become a multiobjective problem. The problem can be expressed as:

$$\text{min: } K_{BS} \;\; \& \;\; \text{max: } \omega_{1SW} \qquad (1)$$

subject to

$$\omega_{1B} \geq 3.5 \text{ kHz}$$

$$\omega_{1T} \geq 8.0 \text{ kHz}$$

where K_{BS} is a bending stiffness

ω_{1SW} is the first frequency of sway mode

ω_{1B} is the first frequency of bending mode

ω_{1T} is the first frequency of torsion mode.

In this work, the suspension system is assigned to have the baseplate, hinge, and load beam as a 1-piece suspension. The initial suspension model as shown in Fig. 3 is a rectangular plate (14×4 mm) with a hole. Figure 3 illustrates the design domain of the rectangular plate (10×4×0.08 mm) and the base plate (4×4×0.12 mm) with the hole (*radius* = 1.333 mm) which is fixed along the edge of the hole. A femto slider is attached at the right-hand of the plate. The unchangeable areas during the optimisation process are the baseplate and the position to attach the slider.

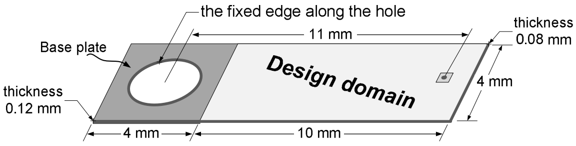

Fig.3 The initial suspension design model

The suspension is made up of material with the Young's modulus of 193×10^{9} N/m^{2}, 0.3 Poisson's ratio, and 8030 kg/m^{3} density.

In dealing with some numerical difficulties usually taking place during topology optimisation, the ground element filtering technique (GEF) (or approximate density distribution technique, ADD) [8] is employed to reduce the number of design variables, and to alleviate checkerboard patterns on resultant topologies. The GEF technique is a simple trick exploiting the idea that the (ground) finite elements and design variables grids of the design domain are set to have different resolutions. To prevent checkerboards, the design variables grid will be coarser. The transformation between the thickness distribution on the finite element domain ($\boldsymbol{\rho}^{e}$) and that on the design variables domain ($\boldsymbol{\rho}^{GEF}$) can be achieved as:

$$\boldsymbol{\rho}^{GEF} = round(\mathbf{T}\boldsymbol{\rho}^{e}+\boldsymbol{\rho}^{0}) \qquad (2)$$

where **T** is a transformation matrix which can be determined using surface spline interpolation. All the elements of $\boldsymbol{\rho}^{0}$ is set to be 0.25. For more details, see [8-9].

The design domain of the suspension structure herein is meshed to have 50×20 shell elements while the GEF design variables have 25×10 elements. The lower and upper bounds of the shell element thickness are set to be 0.00008 mm and 0.08 mm respectively.

PBIL is used to solve the problem (1) with 250 iterations and the population size of 50. The optimisation process is repeated for 4 simulation runs so as to test its searching consistency. As PBIL uses a set of binary strings for searching, the decoding process can be carried out in such a way that, binary design variables are transformed to be binary finite elements thickness distribution using equation (2). Elements of ρ^e which have the values of “1” is set to have 0.08 mm element thickness for the suspension shell finite element model whereas the rest are set to have 0.00008 mm element thickness.

Optimum topology results

The approximate Pareto fronts of the design problem (1) obtained from using PBIL 4 runs are displayed in Fig. 4 where their hypervolumes are given. It can be seen that PBIL has acceptable search consistency as the method can almost reach the same frontier for all 4 runs. The hypervolumes of the fronts are in between 0.64 and 0.75. The best front based on the hypervolume indicator is selected to perform further design. Fig. 5 displays the progress of non-dominated fronts of the best run at particular generations. The convergence history of the best run of PBIL depicted as the plot of hypervolume values against generation numbers is given in Fig. 6. It can be seen that the search converged since the 230th iteration.

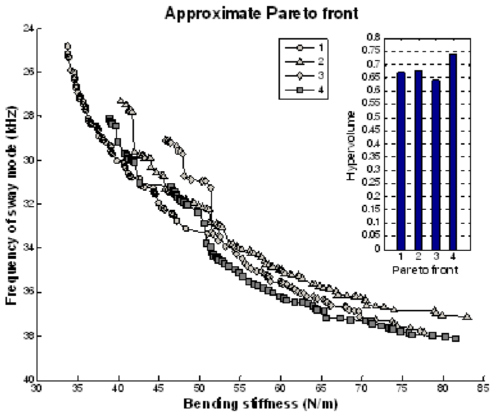

Fig. 4 Non-dominated front from 4 runs

Fig. 7 displays the Pareto front of the best run (out of the four optimisation runs). The HDD suspension topologies corresponding to the selected solutions in Fig. 7 are illustrated in Fig. 8. It is shown that various suspension layouts are obtained within one optimisation run.

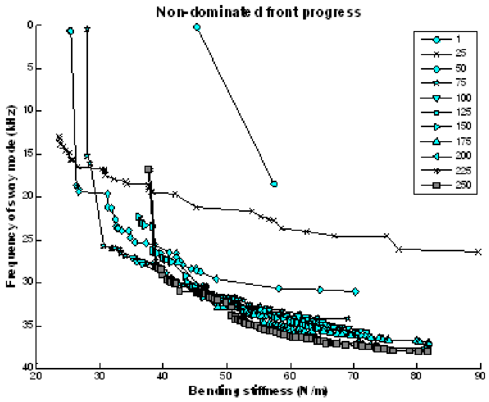

Fig. 5 Pareto front progress

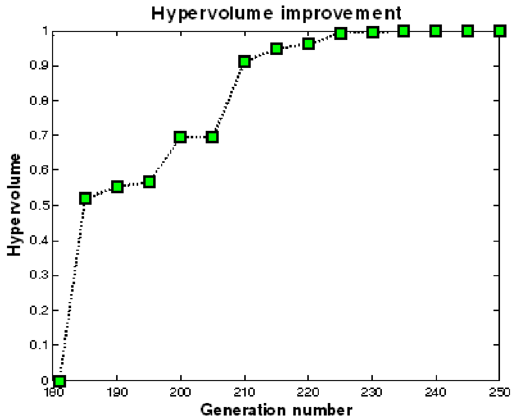

Fig. 6 Hypervolume versus generations

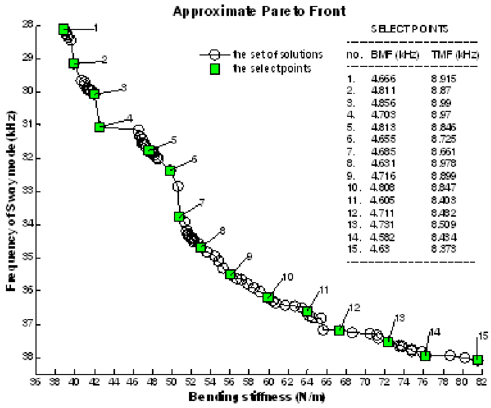

Fig. 7 Pareto front from the best run

The optimum topology that gives the highest first sway mode frequency in Fig. 8 is chosen for further design so as to fulfil the bending stiffness requirement (5 N/m $\leq K_{BS} \leq$ 15 N/m). Some part of the suspension topology is thinned and it becomes a suspension flexible hinge as illustrated in Fig. 9. The dynamic and static performances of the suspension in Fig. 9 are compared with the best results in [2] as shown in table 1. The comparative results reveal that the design approach presented in this paper is superior to that presented in [2] as the sway mode frequency which is the real objective to be maximised is higher whereas the other parameters fulfil the design constraints.

Table 1 Performance comparison of HDD suspensions

Mechanical parameters	Opt4 in [2]	Present work
Stiffness (N/m)	14.5	14.9
1st sway mode frequency (kHz)	5.5	35.3
1st bending mode frequency (kHz)	16.7	4.5
1st torsion mode frequency (kHz)	29.5	8.4

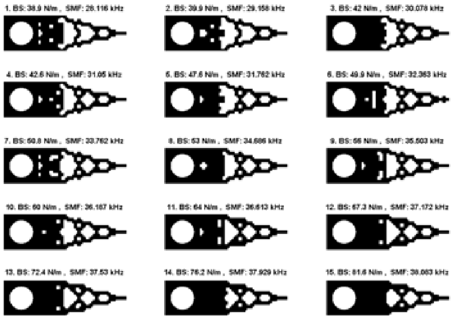

Fig. 8 Suspensions according to the front in Fig. 7

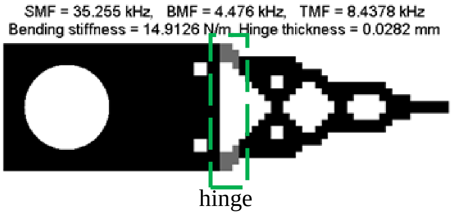

Fig. 9 Selected suspension

Conclusions and Discussion

From the comparative performance of the HDD suspensions obtained from the approach proposed in this paper and that from the literature, it can be said that multiobjective population-based incremental learning is a powerful optimizer for the conceptual design of a HDD suspension system. By using multiobjective PBIL, many optimal design solutions for decision making can be achieved within one optimisation run. The resulting topologies obtained from using PBIL are said to be practical (with further shape and sizing design phases). However, based on the total number of finite element analyses, the searching performance of PBIL is still inferior to its gradient-based counterparts e.g. the optimality criteria method. The future work will be the application of PBIL for unconventional topology optimization of a HDD suspension such as minimizing frequency response function amplitude, a design problem that is difficult or even impossible to use gradient-based optimizers. Moreover, the performance enhancement of multiobjective PBIL is still an issue to be tackled.

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