Design Optimization of Actuators Using ANSYS

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ABSTRACT
Research and development on actuators has been accelerated with the aid of virtual prototyping software, like ANSYS. This is illustrated with two successful cases using ANSYS to design and optimize micro-electro-mechanical actuators. The first case is topology optimization of head suspension assembly for hard disk drive. The second case is design optimization of polymeric thermal micro-actuator. Both cases shows that virtual prototyping makes design optimization possible before real prototyping. It therefore increases the chance of successful product development as well as design innovation.

Keywords: virtual prototyping, design optimization, topology optimization, micro-actuators, MEMS, hard disk drive

1. INTRODUCTION
Micro-electro-mechanical systems (MEMS), which incorportes sensors, actuators, and electronics together, can deliver intelligent functions. Some of its successful examples include micro-accelerometers, and micro-positioner for head disk drive (HDD). Micro-acceleromerers enable precise and timely activation of air-bag to cushion driver upon sensing impact of a car crash, whereas micro-positioner can moves a read/write head of HDD to the right data track precisely against external disturbence. Functioning of MEMS relies on many components, both mechanical and electrical. The components must be designed, modeled and refined before their final integration and micro-fabrication can be done. Therefore, tools of virtual prototyping is indispensable in the loop of design and development of a successful MEMS product.

This paper will present use of virtual prototyping and design automation for actuator development. Here, ANSYS is used as a tool for virtual prototyping and it serves also as a platform for design automation methodology, which is developed in-house to innovate structural and mechanism design without human interrupt. ANSYS is selected for the development because it allows scripting by APDL (ANSYS Parametric Design Language) and access to its binary data file, which contains element stiffness matrix and results. In the subsequent sections, this paper will demonstrate use of the design automation method developed to design a mechanical component in HDD, i.e. a head suspension assembly (HSA) which carries a read/write head. In addition, this paper will present multiphysics modeling and parametric optimization of a recently developed polymeric micro-actuator with embedded skeleton.

2. DESIGN CASE I: HDD SUSPENSION
In a hard disk drive (HDD), a magnetic read/write (r/w) head on a carriage (called slider) is floating above a spinning disk, on which data are stored in concentric tracks. The r/w head is moved by a voice coil motor through a swing arm and suspension assembly. A suspension assembly carries the r/w head and connect it to the front of the swing arm (see Fig. 1 ) [Ref.5]. It serves to cushion the flying r/w head while precisely following trajectory of the swing arm. To achieve these functions, a suspension design needs to be flexible vertically with respect to the plane of a spinning disk, but dynamically stiff in a lateral direction across data tracks. In addition, a suspension should not twist when moving the r/w head laterally across data track. Otherwise, it may adversely causes off-track read error. These design requirements are conflicting to each other, and they are hard to meet simultaneously.

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On the other hand, form factors of HDD have decreased from 5.25 inch in 1980, 3.5 inch in 1984, 2.5 inch in 1984, 1.8 inch in 1993, down to 1 inch in 1999. Likewise, slider and suspension decrease in size. Down sizing does affect suspension design and this is evidenced with its design evolution. An early design of suspension has a large length while a recent design has a shorter length. The design requirements for suspension remains similar but becomes more demanding for better dynamic performance. Over the years, suspension design has improved in terms of the first sway and torsional frequencies (see Fig. 2) and better shock resistance.

There are variety profiles and layouts of suspension design. An early suspension design is simply a leave spring with a square profile by Wanlass (see Fig. 2a). It has a large width and a small thickness to achieve a high lateral frequency but a small vertical stiffness. On the other hand, a suspension design by Zarouri (see Fig. 2b) has a narrow width to achieve a high torsional frequency. Recently, a balanced design of suspension is conceived of by Tangren. It has varying width, which is large at the root but small at the tip (see Fig. 2c). Width of the balanced design lies between the wide profile that maximizes the lateral frequency and the narrow profile that maximizes the torsional frequency. In this way, the balanced design could achieve adequately high lateral and torsional resonant frequencies simultaneously.
The design of suspension is tedious and time consuming, involving trial and error. In practice, a mechanical designer modifies a prior design so as to satisfy the most recent requirements set from a system designer. The modified design is then evaluated by virtual prototyping, such as finite element simulation using ANSYS. The first modified design may not meet the requirement at once, and it is subjected to more revisions in subsequent design iterations before eventually meeting the design requirements. Cost incurred to the design cycles is tremendous though the design procedures are repetitive. However, chance to conceive of a radically new but effective design is slim because a human designer relies very much on his/her experience, sometimes intuition, to improve the design. As a result, a design automation methodology and software is very much in need to shorten the design cycle and possibly innovate the design of suspension assembly.

2.1 Automated Design Methodology

The methodology adopted in the design automation is based on topology optimization method that distributes materials (solid or hole) over a design domain to find out the shape or layout that delivers the desired output function (such as motion or eigenvalues) given the prescribed input and boundary conditions. In the design automation procedure (see Fig. 3), the desired output function is taken as the design goal. The design goal is evaluated using finite element method for each design. In addition, its sensitivity with respect to material change (solid or void) is evaluated at each location over the whole design domain. Afterwards, the sensitivity is used to determine where solid materials are to be distributed. The end results of such design automation procedure is a topological image, which indicates solid/void distribution the design domain. The topological image can suggest layout or profile of a structure or mechanism. It can readily be translated into a physical design of suspension simply by etching away the void region from a stainless steel shim. In addition, the procedures can also determine region of half thickness, an intermediate state between solid and void, to improve the dynamic performance.

The present procedures of topology optimization consider one or more of the following design criteria: the first lateral resonant frequency, the first torsional resonant frequency, the vertical spring constant, and shock resistance (by means of relative mass). To identify the correct mode shape of resonant vibration, the
procedures adopt mode-track techniques, such as mode assurance criteria (MAC)\textsuperscript{17,23} and modal participation factor.\textsuperscript{21} In this way, we manage to optimize the topology for a particular mode shape. For example, topology optimization can track and improve the first lateral resonant frequency, which may fluctuate below or above the first torsional resonant frequency throughout design iterations.

<table>
<thead>
<tr>
<th>Suspension alone</th>
<th>Head suspension assembly (including gimbal &amp; sliders)</th>
</tr>
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<tbody>
<tr>
<td>Maximize the 1\textsuperscript{st} torsional frequency (T1)</td>
<td>![Image]</td>
</tr>
<tr>
<td>Maximize the 1\textsuperscript{st} lateral frequency (L1)</td>
<td>![Image]</td>
</tr>
<tr>
<td>Maximize both frequencies (T1 and L1)</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

Figure 4. Optimized designs of suspension or suspension assembly for various design goals: (row 1) maximize the first torsional frequency; (row 2) maximize the first lateral frequency; (row 3) maximize both torsional and lateral frequencies.

<table>
<thead>
<tr>
<th>Constraint of low spring constant</th>
<th>Constraint of low relative mass</th>
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<tbody>
<tr>
<td>Initial design of head suspension assembly (HSA)</td>
<td>Optimized suspension that maximizes both lateral and torsional frequencies of HSA</td>
</tr>
<tr>
<td>![Image]</td>
<td>![Image]</td>
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</tbody>
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Figure 5. Optimized designs of head suspension assembly, that fulfill an additional constraint: (row 1) a low spring constant in vertical direction; (row 2) a low relative mass at the tip for better shock resistance.

\textbf{2.2 Results}

Optimized design of a bare suspension varies with design goals (see Fig. 4). For example, the design that maximizes the first torsional frequency has a slender profile and its width tapers from the root to the tip. Whereas, the design that maximizes the first lateral frequency has a wide profile and its width tapers and thickness reduces from the mid-span towards the tip. On the other hand, a balance design that maximizes both the first torsional and lateral resonant frequencies has a width profile in between the two profiles. This
Figure 6. Design of head suspension assembly for improved shock resistance: (left) initial and optimized designs; (right) comparison of tip reaction induced by a half-sine shock acceleration of 300 G for a duration of 0.5 ms

Table 1. Performance of initial and optimized designs (see Fig. 6) of suspension against shock

<table>
<thead>
<tr>
<th>Performance</th>
<th>Units</th>
<th>Initial design</th>
<th>Optimized design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st bending freq.</td>
<td>kHz</td>
<td>0.242</td>
<td>0.385</td>
</tr>
<tr>
<td>2nd bending freq.</td>
<td>kHz</td>
<td>2.70</td>
<td>2.64</td>
</tr>
<tr>
<td>1st torsional freq.</td>
<td>kHz</td>
<td>2.11</td>
<td>5.88</td>
</tr>
<tr>
<td>1st sway/lateral freq.</td>
<td>kHz</td>
<td>14.82</td>
<td>19.67</td>
</tr>
<tr>
<td>Effective mass</td>
<td>mg</td>
<td>15.23</td>
<td>6.204</td>
</tr>
<tr>
<td>Relative mass</td>
<td>1</td>
<td>0.506</td>
<td>0.316</td>
</tr>
<tr>
<td>Lift-off acceleration</td>
<td>G</td>
<td>242</td>
<td>829</td>
</tr>
<tr>
<td>Spring constant</td>
<td>N/m</td>
<td>25.98</td>
<td>22.70</td>
</tr>
</tbody>
</table>

appears like re-invention of the patented suspensions design (see Fig. 2), as disclosed by Tangren, because the optimized suspension profiles show a similar dependence on the design goals. Beside design of a bare suspension, topology optimization can be applied to design a complete suspension assembly with slider and gimbal included. The optimized suspension for the assembly is reinforced near the tip to support the added mass of slider and gimbal.

Besides the design goals of high resonant frequencies, we can design the suspension to conform additional design constraints. For example, imposing a constraint of a lower spring constant leads to an optimized suspension design with a cut-out near the root (see Fig 5). This feature correlates well to the present suspension with a low spring constant. On the other hands, imposing a constraint of a lower effective mass at the tip leads to an optimized design that has a thinned and tapered front (see Fig. 5). The relative mass is defined as the proportion of shock-induced inertial force imparted to the head. The optimized design is touted for better shock resistance by suppressing the tendency of head lift-off. The optimized topological image is translated into a suspension design with two thickness levels, i.e. full thickness and half thickness. The evaluation of the translated design confirm that the optimized suspension could withstand an acceleration of 829 G without lift-off as compared to 242 G of an initial design with a rectangular profile.

Topology optimization of resonant frequencies leads to various topological images. Among them, we observed that most optimized topological images have intermediate thicknesses, in addition to solid and void. The inter-
Figure 7. An integral suspension\textsuperscript{18} that incorporates functions of a gimbal and a suspension. This design employs half thickness at the two rims and spring region near the root to improve dynamic performance. This design is inspired from the observation that intermediate thickness repeatedly appears in the optimized topological images for maximum torsional or lateral resonant frequencies. Top image is a finished prototype of the integral suspension made of stainless steel; bottom images are a photo of experimental setup for mode shape measurement and three mode shapes measured with positive and negative vertical velocity indicated as scaled green or red colors.

mediate thickness usually occurs at the rims of solid region or the front region at which the slider is mounted. The prevalence of intermediate thickness strongly suggests that an optimum suspension design for dynamic performance is preferred to have more than a thickness level. This inspires a design of an integral suspension (see Fig. 8) employing half thickness at the rims and spring region near the root in order to improve its dynamic performance. Finite element evaluation shows that the suspension with thin rims on two sides has a higher torsional resonant frequencies than the one with uniform thickness or two side flanges.\textsuperscript{18} This finding is in contrary to the common wisdom that side flanges make the suspension stiffer against torsional vibration.

In short, topology optimization could shorten the time spent on suspension design. In addition, it could innovates the suspension design based on the design criteria, but not modification from the prior designs.

3. DESIGN CASE II: THERMAL MICRO-ACTUATORS

This section presents modeling and optimization of a new class of polymeric thermal micro-actuator with a meander-shaped silicon skeleton (see Fig. 9). This actuator is recently developed\textsuperscript{24} and demonstrated with powerful actuation (at 1.30 MPa/°C) at a relatively low driving temperature (below 200 °C) as compared to its homogeneous constituent materials. This powerful actuation is mainly attributed to the synergetic integration of multiple materials that improves the apparent behaviors. Among the three constituent materials, the thermal expander and skeleton dominates the thermo-elastic behavior while the heater and skeleton determines the electrothermal response. The polymer expander contributes mainly to thermal expansion. The skeleton plays a pivotal role in improving the heat transfer and apparent stiffness of the polymer expander, which is insulating and compliant. Typically, 50 \% volume fraction of the actuator is comprised of the thermal expandable polymer while the rest is comprised of the skeleton.

Each constituent material and its associated geometry is supposed to influence its functional role as it was designed. For example, volume fraction of polymer determines the apparent thermo-physical properties; skeleton geometry affects the structural reinforcement and heat transfer; whereas, the length of heater and skeleton determines the thermal response time. However, the aforementioned geometric parameters are related or coupled to each other. They may together affect the overall actuator performance, but to different extent and trend. For example, interplay of polymer volume fraction and the heater length determines ultimately the overall thermal response time.
Modeling and optimization of the present actuator is challenging because it involves complex geometry, multiple materials, and multi-physical fields (namely, electrical, mechanical and thermal). Fortunately, ANSYS is available and capable of multi-physical modeling and parametric study. Three-dimensional (3-D) finite elements, either structural (SOLID45) or thermal (SOLID70), are used to build the finite element model. Three types of analyzes are conducted, namely the thermo-elastic response under uniform heating, structural response under mechanical loading, and transient thermal response during cooling.

Important design parameters are identified as the polymeric volume fraction ($\phi$) and the heater length ($L$). Parametric study suggests that an design with 70% SU-8 optimizes the actuation work density. The optimized work density is 20.5% higher than that for a reference design with 50% SU-8. In addition, the optimized design also exhibit a roughly 20% shorter thermal characteristic time constant because the heater length, which depends
on the volume fraction, is shortened.

In short, virtual prototyping using finite element method can improve the actuator performance as much as 20% by geometry change, even without changing the constituent materials.

4. CONCLUSIONS

ANSYS serves well as a tool for virtual prototyping. It can performs multiphysics simulation and allows parametric programming. We have used it to simulate dynamic response of HDD suspension and multiphysical response of a thermal micro-actuator. Current version of ANSYS allows parametric study, but it does not have strong capability to perform design automation and innovation. The built-in topology optimization in ANSYS has limited options for real-life design. Despite this, ANSYS remains a useful platform for user-defined program. On this platform, we have developed topology optimization method to automate and innovate the design of HDD suspension.

Topology optimization developed at NTU has led to variety of optimized designs of suspension that serve various design criteria. In addition, it leads us to insight that optimization for high resonant frequency may result in optimized design with reduced thickness, in other words, intermediate thickness, in addition to solid and void. This finding differs from conventional wisdom that suggests added materials like side flanges could increase the dynamic torsional stiffness. Furthermore, the topology optimization method successfully found the optimized design that improves shock resistance.

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