WCCM V
Fifth World Congress on
Computational Mechanics
July 7-12, 2002, Vienna, Austria
Eds.: H.A. Mang, F.G. Rammerstorfer,
J. Eberhardsteiner

Design of Heat-activated Compliant Mechanisms and Its Application to Product-Embedded Disassembly

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Key words: Compliant mechanisms, Topology optimization, Design for Disassebly, Integral Attachment

Abstract

Thermal transducers, which can be interpreted as thermally actuated compliant mechanisms, have found a wide range of applications, due to the reason of accessible source, easy controllability and reliability. During the past decade topology optimization techniques have been developed as efficient tools to design distributed type of complaint mechanisms. The generated results have been accepted and applied in practical applications. There has been research done to synthesize design of thermal actuation embedded electrical-thermal-compliant mechanisms, in which the non-uniform joule heating was generated through non-uniform electric current. In this research, time transient effect of heat transfer is proposed to produce the localized thermal actuation, while only simple forms of boundary heating is considered. Therefore non-uniform temperature distribution can be achieved by controlling the heating time before steady state is reached. This technique can be applied to design a novel type of integral attachment mechanisms to realized product-embedded disassembly. Design of heat-activated reversible snap-fit is posed as a topology optimization problem of compliant mechanism actuated with localized thermal expansion of materials through time transient heat transfer within the structure. Homogenization Design Method is utilized to calculate the effective material properties during the material distribution. Optimal configuration is presented, and in order to enhance manufacturability, simplification scheme and adjustment are applied to obtain realizable model. Final design is further verified with commercial FEA software.

1 Introduction

A complaint mechanism [1] is the mechanism that relies on its own elastic deformation to transfer or transform motion or force. Common compliant mechanisms function under the application of force at certain location (input) and generate desired force or deflection at another location (output). Thermally actuated compliant mechanisms are those compliant mechanisms onto which thermal loading is applied as input instead of force.

The most well known type of thermally actuated compliant mechanisms is the so-called "electro-thermal-compliant" (ETC) micro-actuators used in micro-electrical-mechanical system (MEMS). The mechanisms are made of conductive materials that are actuated through joule heating effect by an electrical current. Early thermal actuators are mostly bimorph actuators made of two materials with dissimilar thermal expansion coefficients. Recently idea of embedded actuation in one single material has been introduced to design ETCs. One example is the Guckel actuator [2], which is a folded U-shaped beam with thin and thick arms. When current passes between the two anchors, larger current density in the thinner beam cause a larger thermal expansion than that in the thick beam thus forms the pseudo-bimorph type of thermal actuator. Another successful design is the so-called bent-beam electro thermal actuator [3], which comprises of V-shaped beams anchored at both end. Each individual beam is heated through an electric current and the thermal expansion caused by joule heating pushes the apex outward. Other design methods have been developed involving topology optimization techniques by several different research groups [4][5]. The basic idea is to distribute material in a certain design domain to form a compliant structure to be heated and deform in a desirable manner.

In this research, we introduce the time transient effects to thermal actuator design. Unlike in ETC cases, where non-uniform temperature distribution is caused by non-uniform joule heating, this work proposes to utilized the non-uniform temperature distribution due to time transient response of heat transfer. In other words, during a certain period of time of heat transfer process, significant temperature difference exists between different parts of the mechanisms. In this case the thermal loading condition can simply be a boundary heating. It is necessary to understand that this proposed approach is not generally applicable to micro-systems, due to the short steady state time constant associated with micro-scale systems. Based on the topology optimization technique for compliant mechanisms, the time transient heat transfer analysis is integrated with thermal-mechanical analysis to formulate the design optimization problem. With this proposed design synthesis, the mechanism layout is generated by conducting the heat to the portion of mechanisms to be thermally expanded in favor of the desired mechanism motions. The easiness of time and temperature control makes the time transient effect realizable in practice and at the same time simplifies the manufacturing requirements. Especially, in macro-scale systems, mature actuation state does not depend on the steady state, which can be a save of actuation time and manufacturing cost. Numerical examples of a snap-fit mechanism design will be presented to show its application and benefit to product-embedded disassembly.

2 Topology optimization problem

2.1 Background

Homogenization based topology optimization is the basis for the design technique proposed in this research. The topology optimization problem is formulated as a problem of finding the optimal distribution of materials in an extended fixed domain where some structural cost function is maximized. To relax the problem a microstructure proposed by Bendsϕe and Kikuchi [6] is defined at each point of the domain, which is a unit cell with a rectangular hole inside. The design variables are the dimensions α, β and the orientation θ of the micro-hole. In this sense the problem is to optimize the material distribution in a perforate domain with infinite, infinitesimally small microscope voids. The effective properties of the porous material, for instance, effective material stiffness coefficient matrix $\mathbf{E}^{H}$ and effective thermal conductivity vector $\mathbf{?}^{H}$, are calculated using the homogenization methods[7]. In this research, HDM is used with square holes (a=ß=x) microstructure because of the requirement of isotropic thermal conductivity to avoid extreme anisotropic thermal property.

Compliant mechanisms can be characterized into two categories: partially compliant mechanisms and fully compliant mechanisms[8]. The design synthesis of partial ("lumped") compliant mechanisms has been developed as undulating elastica approach[9], kinematics synthesis approach[10] and more recently pseudo-rigid body model approach[11], while the fully ("distributed") compliant mechanisms is design using continuum synthesis approach based on topology optimization for solid structures [12][13] and truss-like structures[14][15].

2.2 Problem Formulation

In heat-activated compliant mechanisms, the deformation is caused by thermal expansion of material due to change of temperature distribution. The difference with thermal actuation is, instead of elastic strain energy, what the system stores is the thermal strain energy.

In this research we make use of the time transient effect of heat transfer to generate non-uniform temperature distribution, which means a certain time period, must be specified before the system reaches the steady state. Let t_f denote the actuation time specified, and its value is selected so that the design domain has a diversity of temperature distribution and significant temperature gradient. According to strain-displacement relation and thermal strain definition, the equivalent thermal body force is defined as:

$$\mathbf{f}_t = \mathbf{E}\mathbf{a}\Delta f \mathrm{L} \qquad (1)$$

where $\mathbf{E}$ is the material stiffness coefficient matrix and $\mathbf{a}$ is thermal expansion coefficient in vector form and $\Delta f(t_f)$ denotes the temperature change at actuation time t_f obtained from heat transfer analysis and L denotes the differential operator from strain-displacement relation:

$$\mathbf{e} = \frac{1}{2}(\nabla^{T}\mathbf{u} + \mathbf{u}\nabla) = \mathrm{L}\mathbf{u} \qquad (2)$$

The topology optimization of compliant mechanisms with heat actuation shares the similar design criteria as the general compliant mechanisms. Two types of design criteria are considered to formulate an optimization problem: flexibility requirement and stiffness requirement. The flexibility requirement, also called mechanisms requirement means the designed compliant object must have be deformed in a favorable manner to complete its functionality. Mathematically this requirement is captured using the concept of mutual mean compliance[16][17] based on the reciprocal theorem for linear elasticity.

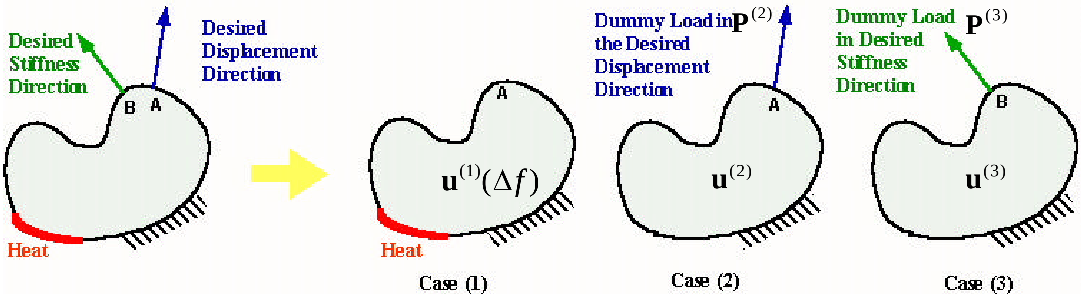


Figure 1: Design requirements of compliant mechanism

Consider the loading cases shown in Figure. If displacement field in case (1) $\mathbf{u}^{(1)}$ caused by temperature change is used as the virtual displacement for equilibrium equation under the dummy loading case (2), the principle of virtual work can be expressed as the following:

$$\int_\Omega \mathbf{e}^T(\mathbf{u}^{(1)})\mathbf{s}^{(2)}d\Omega = \int_\Omega \mathbf{e}^T(\mathbf{u}^{(1)})\mathbf{E}\mathbf{e}(\mathbf{u}^{(2)})d\Omega = \mathbf{P}^{(2)^T}\mathbf{u}_A^{(1)} \tag{3}$$

And if $\mathbf{u}^{(2)}$ is used as the virtual displacement for case (1), we have:

$$\int_\Omega \mathbf{e}^T(\mathbf{u}^{(2)})\mathbf{E}\mathbf{e}(\mathbf{u}^{(1)})d\Omega = \int_\Omega \mathbf{f}_t^T(\Delta f^{(1)})\mathbf{u}^{(2)}d\Gamma \tag{4}$$

The bilinear form $a(\mathbf{u}^{(1)},\mathbf{u}^{(2)}) = \int_\Omega \mathbf{e}(\mathbf{u}^{(1)})\mathbf{E}\mathbf{e}(\mathbf{u}^{(2)})d\Omega$ defines the mutual mean energy between case (1) and case (2). If P in case (2) is a unit dummy load, this mutual mean energy equals to the displacement at A $\mathbf{u}_A^{(1)}$ in the desired direction due to temperature change.

The stiffness requirement provides the compliant mechanisms with the internal ability to resist an external loading. Mathematically it can be formulated as the well-know concept in structural optimization, compliance. Consider loading case (3) in Figure 2, if a external force is to be loaded to the mechanisms, in the form of resistive force or functioning disturbance force (as discussed in later session), the stiffness required to sustain the loading is characterized by the displacement at the loading location. Using the same displacement field as the virtual displacement:

$$a(\mathbf{u}^{(3)},\mathbf{u}^{(3)}) = \int_\Omega \mathbf{e}^T(\mathbf{u}^{(3)})\mathbf{E}\mathbf{e}(\mathbf{u}^{(3)})d\Omega = \mathbf{P}^{(3)^T}\mathbf{u}_B^{(3)} \tag{5}$$

The multi-objective optimization problem is formulated as:

$$\max_{x,j} f = \frac{a(\mathbf{u}^{(1)},\mathbf{u}^{(2)})}{a(\mathbf{u}^{(3)},\mathbf{u}^{(3)})}$$

$$\text{Subject to:} \quad a(\mathbf{u}^{(i)},\mathbf{u}^{(j)}) = \int_\Omega \mathbf{e}^T(\mathbf{u}^i)\mathbf{E}\mathbf{e}(\mathbf{u}^j)d\Omega \tag{6}$$

$$V = \int_\Omega (1-x^2)d\Omega \le \overline{V}$$

$$0 \le x \le \overline{x} < 1$$

where $\overline{V}$ is the volume constraint and x is the size of the square micro-void in proposed microstructure, which is a measure of density.

2.3 Optimization Procedure

Figure 3 shows a flow char of optimization procedure. Sequential linear programming (SLP) is used as an optimizer. Each iteration consists of, in sequence, a time transient heat transfer analysis, and a thermal-mechanical analysis and sensitivity analysis to both finite element procedures. The termination criteria are convergence of objective function or a maximum iteration time.

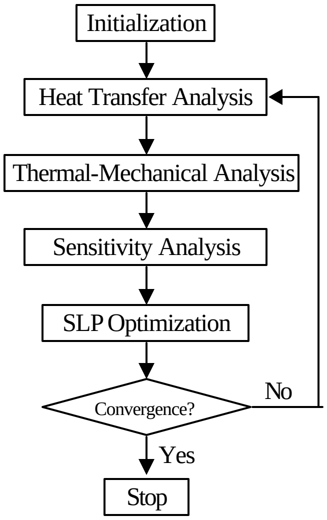


Figure 2: Optimization Procedures

The finite element equilibrium equations that need to be solved are[18]:

$$\begin{aligned} &\mathbf{C}\dot{\mathbf{F}} + \mathbf{K}_t\mathbf{F} = \mathbf{?}_t \\ &\mathbf{K}\mathbf{U}^{(i)} = \mathbf{F}^{(i)}, i = 1,2,3 \end{aligned} \tag{7}$$

where $\mathbf{C}$, $\mathbf{K}_t$ and $\mathbf{P}_t$ are heat capacity matrix, stiffness matrix and heat source vector respectively in time-transient heat transfer finite element analysis, while $\mathbf{K}$ and $\mathbf{F}^{(i)}$ force vector in mechanical analysis for the three loading cases described earlier. In particular, $\mathbf{F}^{(1)} = \mathbf{F}_t$ is the equivalent thermal force vector in thermal-stress analysis, calculated from temperature distribution result $\mathbf{F}(t_f)$. For example, for general 2D problem:

$$\mathbf{F}_t = \int_{\Omega} \mathbf{B}^T \mathbf{E} \mathbf{a} \Phi [1,1,0]^T \, d\Omega = \mathbf{AF} \tag{8}$$

where $\mathbf{A}$ denotes the transformation matrix between nodal temperature and nodal equivalent thermal force, while $\mathbf{B}$ is the strain-displacement matrix calculated from relation (2). It should also be noticed that the stiffness matrices are calculated from the homogenized material properties $\mathbf{E}^H$ and $\mathbf{?}^H$. The backward finite difference is used as the time integration scheme for transient heat transfer analysis.

Sensitivities are calculated as:

$$\frac{\partial}{\partial x}(\mathbf{U}^{(i)^T}\mathbf{K}\mathbf{U}^{(j)}) = -\mathbf{U}^{(i)T}\frac{\partial \mathbf{K}}{\partial x}\mathbf{U}^{(j)} + \frac{\partial \mathbf{F}^{(i)^T}}{\partial x}\mathbf{U}^{(j)} + \mathbf{U}^{(i)T}\frac{\partial \mathbf{F}^{(j)}}{\partial x} \tag{9}$$

where each terms are calculated from the following equations:

$$
\begin{aligned}
\frac{\partial \mathbf{K}}{\partial x} &= \int_{\Omega} \mathbf{B}^{T} \frac{\partial \mathbf{E}}{\partial x} \mathbf{B} d\Omega \\
\frac{\partial \mathbf{F}_t}{\partial x} &= \int_{\Omega} \mathbf{B}^{T} \frac{\partial \mathbf{E}}{\partial x} a\Phi \left[1,1,0\right]^{T} d\Omega + \int_{\Omega} \mathbf{B}^{T} \mathbf{E} a \frac{\partial \Phi}{\partial x} \left[1,1,0\right]^{T} d\Omega \\
&= \frac{\partial \mathbf{A}}{\partial x} \mathbf{F} + \mathbf{A} \frac{\partial \mathbf{F}}{\partial x} \\
\mathbf{C} \frac{\partial \dot{\mathbf{F}}}{\partial x} + \mathbf{K}_t \frac{\partial \mathbf{F}}{\partial x} &= -\frac{\partial \mathbf{C}}{\partial x} \dot{\mathbf{F}} - \frac{\partial \mathbf{K}_t}{\partial x} \mathbf{F} + \frac{\partial \mathbf{?}_t}{\partial x}
\end{aligned}
\qquad (10)
$$

3 Snap-fit Mechanism Design for Product-Embedded Disassembly

To demonstrate a result of the proposed design technique, a numerical result related to practical application is presented in this section. Integral snap-fit attachments [20][21][22][23] have been widely used as substitutes for separate fasteners for the purpose of design for assembly (DFA)[24][25]. However, snap fits are not necessarily a favored choice fore design for disassembly since they are often difficult to disengage without inherent destruction of the components[26]. While some snap-fits are designed to be reversible (*e.*g., battery covers for cellular phones), they require the application of auxiliary forces in a direction different from the insertion deliration in order to unlatch the snapping features.

3.1 Design for Disassembly

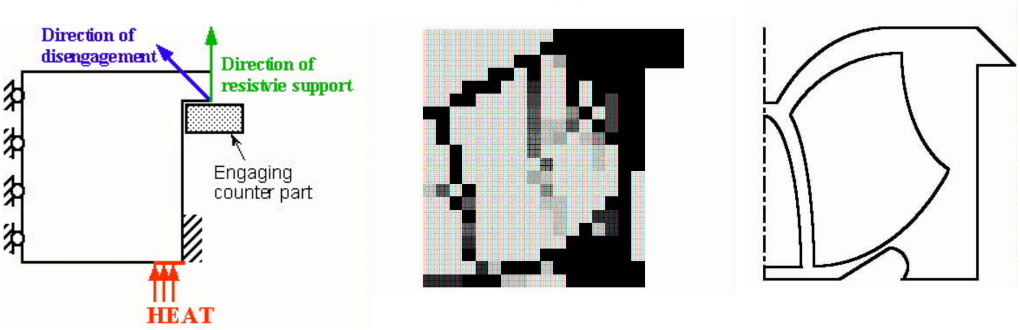
Academic investigations into the concept of "design for disassembly" began in the late 1980s, largely driven by successes with "design for assembly" earlier in the decade. Unfortunately, many guidelines suggested by the "design for assembly" methodology do not apply to "design for disassembly," for instance [26][27][28][29]:

- Rapid attachment fasteners employed in assembly may not be suitable for disassembly. For example, glue can be used to easily join two plastic parts, but the resulting joints cannot be detached without damaging both parts.
- Products designed for assembly may not allow easy access to the specific components to be recovered. For example, a product may require the removal of *100* components to reach *one* component with high recycling value. In such cases, disassembly may not be economically feasible.
- The condition of products at disassembly may be different from the conditions under which the products were initially assembled. For example, wear or corrosion may make bolted joints extremely hard to detach.
- Due to the significant spatial and temporal distance between the assembly and disassembly processes, it may not be immediately obvious how to disassemble a part.
- Parts that appear similar may require completely different approaches to disassembly.

Efforts to overcome these disassembly obstacles through the concept of *"product-embedded disassembly,"* or *"self-disassembly,"* have recently stated appearing in the literature. Product-embedded disassembly gives a product the ability to take itself apart. Chiodo *et al* [30]demonstrated the feasibility of a self-disassembly strategy for consumer electronic products using fastener screws made of a special shape memory alloy (SMA) polymer. Masui *et al* [31] demonstrated the self-disassembly of a CRT using nichrome wire embedded in the component glass along the desired boundary for separation. Although these examples were effective in the particular cases presented, both methods lack generality since they require the use of specialized and costly materials such as SMA polymers.

3.2 Problem Statement

A snap-fit mechanism can be engaged by simply pushing the two counter parts together, while disengaging is a problematic process. Automatic application of disengaging force is challenging task. Using heating as disengaging actuation can be an advantage. Furthermore, a uniform temperature change or steady state temperature distribution takes time to obtain, and also tend to generate excessive thermal expansion, but a limited actuation time is necessary and realistic. Besides, the control of heating time is trivial in practice. Therefore, the design of snap-fit mechanisms can be formulated as topology optimization problem considering time transient heat transfer. As discussed in section 3, two design criteria are considered, as illustrated in Figure 3a (only half of the symmetric geometry is considered). The flexibility requirement is that when the object is heated as specified, the induced deformation should be in favor of disengagement of the snap-fit. The stiffness requirement is to provide retention force, i.e. the undesired disengagement.



(a) Design Domain (b) Optimal Configuration (c) Extracted Geometry

Figure 3: Design domain and result

3.3 Result Simplification and Verification

Topology optimization result of the design domain is shown in Figure 3b. Although there are some intermediate density values visible in the result, the basic layout can be extracted and easily understood by intuition. The simplified model is verified using commercial software ABAQUS. Both deformation pattern and temperature distribution are shown in Figure 4.

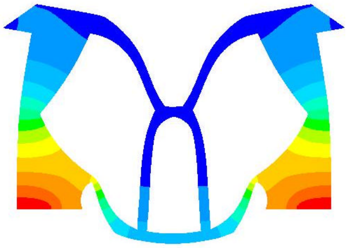
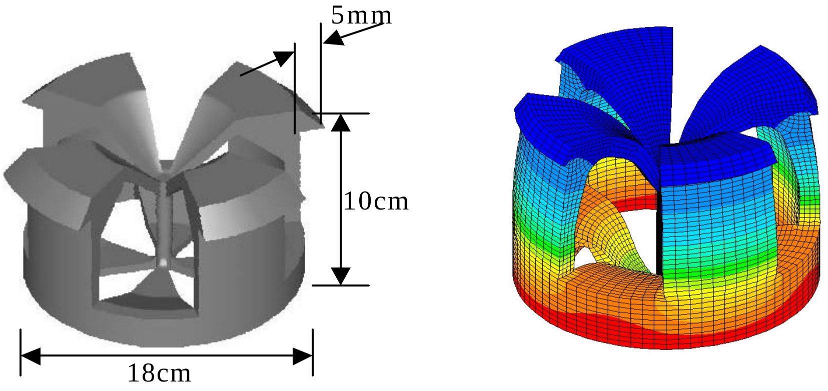


Figure 4: ABAQUS verification of 2D result

Since the final 2D geometry contains internal holes, it cannot be practically injection molded. To overcome this difficult, further simplification needs to be conducted and the 2D geometry can be swept axially into 3D to avoid internal holes. Figure 8a shows a three-dimensional CAD model after the modification. Although the geometry is further simplified, the basic functioning members still remain and ABAQUS simulation verifies that the desirable deformation pattern can be achieved Figure 5b.



(a) 3D CAD Model (b)ABAQUS Verification

Figure 5: Realized 3D model and verification result

4 Discussions and Conclusions

In this research, topology optimization synthesis for design heat-activated compliant mechanisms considering time transient effect has been proposed. Examples have shown that novel compliant mechanisms of macro-scale can be designed.

The design proposed in this paper has its certain advantages over the existing type thermal actuators:

- There is no restriction to material properties as long as the material has an appreciated thermal expansion coefficient. This type of thermally actuated mechanisms can be made from any type of material.
- Usually the when a mechanism is in function, it would have a physical contact with another system components. To avoid high temperature at the external contact portion, Yin et al. [5] proposed to use two different materials. However, in design synthesis proposed in this research, the desired output portion is usually placed away from the heating location, and high temperature change is automatically avoided.
- Compared to the embedded actuation idea, it is believed that this design synthesis based on temperature distribution pattern is less sensitive to post design modification.
- While designing relatively large-scale mechanisms, this design synthesis saves time by allowing system to function during an actuation time instead of waiting for steady state.
- The specified actuation time and heating location avoid the incurrence of undesired actuation.

Since thermal actuation has attracted more and more attention in practical applications, proposed design proposed and presented results in this paper are expected to be constructive towards novel designs of mechanical systems.

Acknowledgements

The authors gratefully acknowledge the Institute for Environmental Sciences, Engineering and Technology (IESET) at the University of Michigan, for a partial support from awarded research grant.

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