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Reliability-Based Optimal Design of Thermal Actuated Compliant Valves

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Abstract
In recent years, compliant mechanisms have been paid to attention as new mechanisms to replace traditional rigid link mechanisms. Compliant mechanisms achieve a specified motion by deforming the structure elastically instead of relying on joint movements. Compared to traditional mechanisms, compliant mechanisms have several merits due to their monolithic structure without joints. Thus, the use of compliant mechanisms in mechanical products, medical instruments and MEMS can be expected to increase. For such promising compliant mechanisms, although many design methods have been developed, their reliability is not sufficiently considered. Since compliant mechanisms are quite different from traditional mechanisms, it is difficult to configure safety factor empirically. Thus, in this research, optimal safety factor, one of reliability-based design optimization (RBDO), is introduced into compliant mechanism design. In compliant mechanism design, there are two important criteria: output displacement and stress, but traditional OSF considers only single reliability. Thus, existing OSF is extended to allow for considering multiple reliabilities. In the case study, the proposed method is applied to a design of a thermal actuated compliant valve used for a micro water cooling system.

Keywords: Robust Design, Reliability-Based Optimization, Compliant Mechanism.

Introduction
In mechanical design, mechanisms consisting of rigid parts linked to moveable joints are often used, and in such mechanisms, the relative motion of the links is constrained by the joints. On the other hand, compliant mechanisms [1] utilize a structure's flexibility to achieve a specified motion, by deforming the structure elastically instead of relying on joint movements. Such compliant mechanisms often consist of fewer parts than rigid link mechanisms, or can even be monolithic, and, compared to rigid link mechanisms, they have several merits [1] [2], such as reduced wear and operation noise, zero backlash, freedom from lubrication requirements, weight savings, manufacturing advantages, and ease of miniaturization. Therefore, the use of compliant mechanisms in mechanical products such as robot arms, space instruments, medical instruments and MEMS (Micro-Electro Mechanical Systems) [1] [3] can be expected to increase.
For such promising compliant mechanisms, many design methods have been developed over the past few decades. These methods can be classified into the following two types. The first type is based on kinematics, where a designer creates a traditional rigid-link mechanism consisting of rigid parts and joints and then creates a compliant mechanism by converting the joints to flexural parts [4] [5]. However, such methods require trial and error processes on the part of a designer, to find the best conversion, and the best traditional mechanism does not

always result in the best compliant mechanism. The second type is based on topology optimization [6], where a designer configures the design domain, boundary conditions and the location and direction of the input and output forces of the target mechanism, and then the topology optimization is conducted to calculate an optimal shape under these conditions. Sigmund [7] proposed a design approach using topology optimization based on the density method. On the other hand, the approach proposed by Nishiwaki et al. [8] is based on the homogenization design method. The advantage of a topology optimization based approach is that knowledge of kinematics and designer's trial and error processes are not required, and this approach can yield fully optimal configurations.

In practical mechanical design, safety factor is widely introduced against uncertainties concerning geometry and material properties in manufacturing processes and applied load in use. However, since compliant mechanisms are quite different from traditional mechanisms, it is difficult to configure safety factor empirically. Thus, in this research, optimal safety factor (OSF) [9], one of reliability-based design optimization (RBDO), is introduced into compliant mechanism design. In compliant mechanism design, there are two important criteria: output displacement and stress, but traditional OSF considers only single reliability. Thus, OSF is extended to allow for considering multiple reliabilities. In the case study, the proposed method is applied a design of a thermal actuated compliant valve used for a micro water cooling system.

Reliability-based optimal design of a compliant mechanism

In order to design a reliable compliant mechanism, we extend OSF and integrate it into our two-stage design method consisting of topology and shape optimization. The proposed method consists of the following 3 stages:

Stage1: Topology optimization
Stage2: Shape optimization
Stage3: RBDO using OSF

In Stage1, topology optimization creates an initial outline of a compliant mechanism. In Stage2, shape optimization yields detailed shape of the compliant mechanism based on the initial outline obtained in Stage1. In Stage3, OSF evaluates reliability of the compliant mechanism obtained in Stage2, i.e., influence of variations in its design parameters on output displacement and stress, and adjusts its design parameters in order to improve their reliability. Due to space limitations, stages1 and 2 are briefly explained while stage3 is be described more fully in the following sections. Since stages 1 and 2 are exactly the same as ones of two stage design method, see the reference [10] for their details.

Stage1: Topology optimization

In Stage1, topology optimization creates an initial outline of a compliant mechanism. To create a compliant mechanism using topology optimization, a fixed design domain D that includes the optimal structure Ω_d, boundary conditions Γ_d and a direction of flexibility (location and direction of input force t_1 and output force t_2) need to be configured as shown in Figure 1(a). In the case of thermal actuator design like the case study, temperature increase Δt is applied to a fix design domain D instead of input force $t_1$as shown in Figure 1(b).

In this research, the level set based topology optimization proposed by Yamada et al. is used.

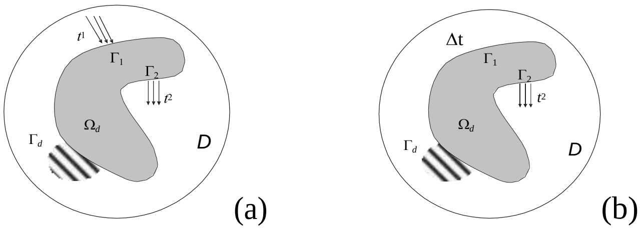


Figure 1. Design conditions of topology optimization

Stage2: Shape optimization

In Stage2, shape optimization yields detailed shape of a compliant mechanism based on the optimal configuration resulting from topology optimization in stage1. In topology optimization, geometry is represented as raster-like image. Meanwhile, in shape optimization, geometry is represented by lines and curves. Thus, an optimal configuration of topology optimization needs to be converted into an initial shape optimization model. Figure 2 shows its procedure. First, hinges and lumps that characterize the behaviour of a compliant mechanism are recognized. Next, control points of lines and curves are assigned them. Finally, lines and curves are drawn by connecting assigned control points. Coordinates of these control points are handled as design variables of shape optimization.

In this research, ANSYS is used as structural analysis and shape optimization software.

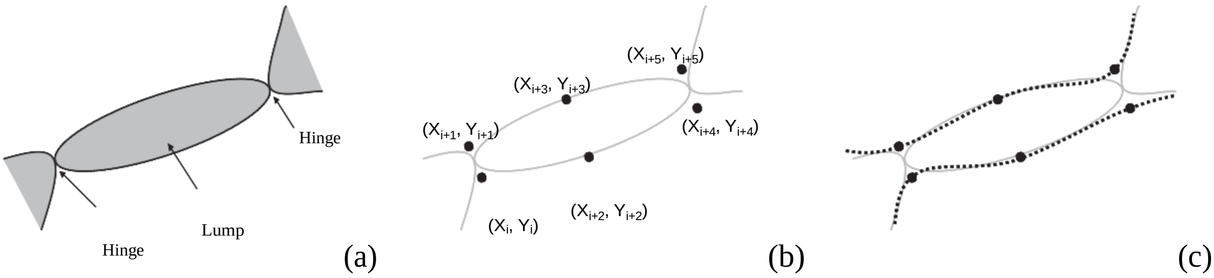


Figure 2. Flow of modeling an initial shape optimization model

Stage3: RBDO using OSF

In Stage3, OSF evaluates reliability of the compliant mechanism obtained in Stage2 and adjusts its design parameters in order to improve reliability. This section explains original OSF at first and then explains modification of OSF for considering two reliabilities.

Optimal safety factor (OSF)

OSF is one of reliability-based design optimization (RBDO) proposed by Kharmanda et al [3]. OSF consists of the following 3 steps. First, optimize with deterministic variables in a physical space and calculate a design point y_i. In the proposed method, this step is carried out as Stage2. Next, design point u_i in a normalized space is calculated by using sensitivities of the limit state function with respect to the design variables and optimality condition as follows:

$$u_i = \pm\beta\sqrt{\left(\frac{\partial G}{\partial y_i}\right)^2 \Bigg/ \sum_{i=1}^{n}\left(\frac{\partial G}{\partial y_i}\right)^2}\ , i=1,...,n \qquad (1)$$

Where the sign of ± depends on the sign of the derivative as follows:

$$\partial G/\partial y > 0 \Leftrightarrow +,\ \partial G/\partial y < 0 \Leftrightarrow - \qquad (2)$$

Figure 3 illustrates the relationship between a design point and an optimal point in cases of two design variables in the normalized space. Here, P^* is the design point, optimum point is corresponding to the origin, $H(u)$=0 is a limit state curve and β is a reliability index. Finally, optimal point is transformed from normalized space into physical space. When random variables are subjected to normal distribution $N(x, \sigma)$, optimum point can be written as follows:

$$x_i = y_i - \sigma_i u_i \text{ , } i=1,...,n \tag{3}$$

OSF uses one-level loop problem of the shape optimization and calculation considering uncertainties are out of the loop. Therefore it successfully reduces the computational time in comparison with the conventional nested problems.

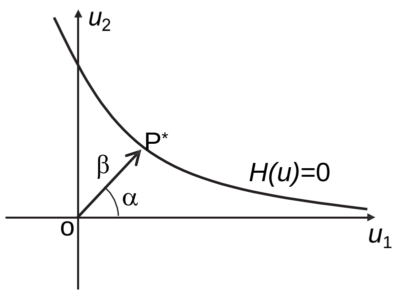


Figure 3. Design point in normalized space

OSF considering two reliabilities

Original OSF can consider only single reliability. However, in compliant mechanism design, reliabilities of stress and output displacement need to be considered in order to ensure function of a compliant mechanism. Therefore, this paper develops OSF considering two reliabilities. Figure 4 shows its basic concept in case of two variables in the normalized space. First, design points considering single reliability P_1^*, P_2^* are calculated by conventional OSF. Next, linearize the limit state curves with respect to the design point. Finally, new design point P^* is the point of the intersection of the two lines and minimum distance from the origin. In this way, optimal point (origin) is separated from two limit state curves. Optimal point can satisfy two reliability constraints.

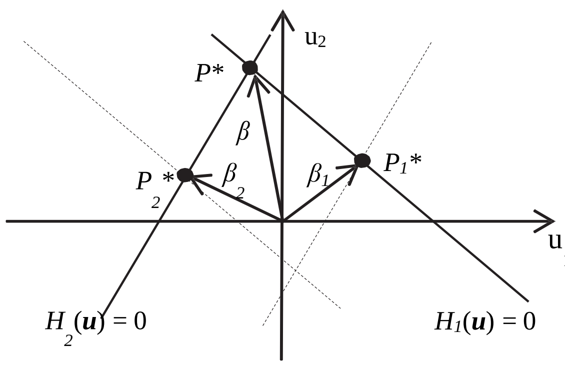


Figure 4. Basic concept of OSF considering two reliabilities

Case study

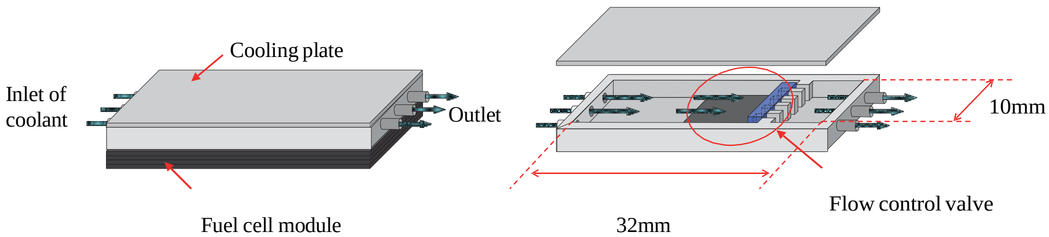
To demonstrate the flow of the proposed method, the proposed method is applied to design of a thermal actuated compliant valve used for a micro water cooling system.

Micro water cooling system with a thermal actuated compliant valve

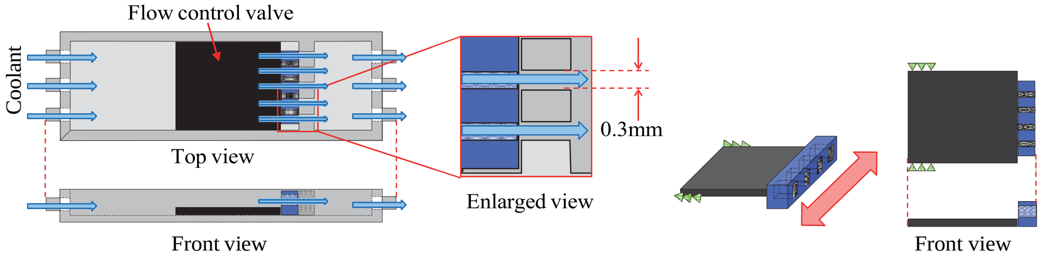
Recently there is a growing need for micro water cooling systems with the development of small-sized devices such as small-sized fuel cells for mobile electric devices. In general, a water cooling system requires a valve for controlling flow rate of coolant in order to keep targeted devices at an appropriate temperature and traditional type of a flow control valve is driven by an external power source and a control system. However, for the realization of small-sized fuel cells, it is desirable that whole water cooling system is sufficiently small and can be driven by very little electricity. Thus, as the successor to a traditional type of a flow control valve, we focus on a thermal actuator in this research. A thermal actuator is a device which can generate motion using amplified thermal expansion effects. Thermal actuator can be driven by heat flowing into it and amount of its deformation is decided by its temperature. In addition, a thermal actuator can be designed as a compliant mechanism. A compliant mechanism can be monolithic structure, which also contributes miniaturization of a device. Therefore, a thermal actuated compliant valve can be downsized compared to a traditional valve and work with neither an external power source nor a control system. This is why we consider a thermal actuated compliant valve is suitable for a flow control valve for the realization of micro water cooling system.

Diagram of micro water cooling system

Figure 5(a) – (d) shows the overview of a micro water cooling system used for a small-sized fuel cell. As shown in Figure 5(a), a cooling plate of a micro water cooling system is about the same size as a fuel cell module and attached to it. As shown in Figure 5(b), inside of the cooling plate is a flow channel of coolant and a thermal actuated compliant valve is placed on the channel. The valve is in close contact with a fuel cell module through an exterior wall of the cooling plate, so heat from the fuel cell module is directly transferred to the entire valve. Therefore, it can be assumed that temperature of the entire valve is uniform and the temperature is same as the temperature of the fuel cell module, which means that there is no necessity to consider heat transfer between the valve and the fuel cell module. Blocks with many slit channels are fixed on both middle of the channel and tip of the valve, as shown in Figure 5(c). Flow of coolant is controlled by the relative position between the above two blocks. Figure 5(d) shows a design domain of the thermal actuated compliant valve. Outer shape of the valve is enclosed by the black area shown in this figure. This mechanism can avoid the need for large displacement of a valve, so it is suitable for a compliant valve.



(a) Exterior of a cooling plate (b) Inside of a cooling plate



(c) Mechanism of flow control (d) Thermal actuated compliant valve

Figure 5. Diagram of a small-sized fuel cell for a mobile electric device

Specification of thermal actuated compliant valve
A flow channel inside a cooling plate is 32mm long and 10mm wide and a fixed design domain of a valve is 12mm long and 10mm wide. A valve is anchored in both sides of side walls. The width of slit channels in two blocks is 0.3mm. A valve is fully closed at a temperature of 25 degrees Celsius and fully opened at a temperature of 100 degrees Celsius. Therefore, design requirement of a valve can be summarized as follow: slide length of the valve reaches 0.3mm under the condition of increase in temperature of 75 degrees Celsius.
To gain large displacement with limited temperature increase, a material with high coefficient of thermal expansion is desirable. In the case study, high-molecular-weight polyethylene (HMW polyethylene) is adopted. Table 1 shows its material properties.

Table 1. Material properties of HMW polyethylene

Coefficient of thermal expansion	130*10-6 [1/°C]
Operating temperature limit	121 [°C]
Young’s modulus	887 [MPa]
Poisson's ratio	0.35
Density	960 [kg/m3]
Allowable stress	40 [MPa]

Stage1: Topology optimization
First, topology optimization is executed under the design conditions shown in Figure 6(a). The volume constraint is set at 25%. Figure 6(b) shows the obtained optimal configuration.

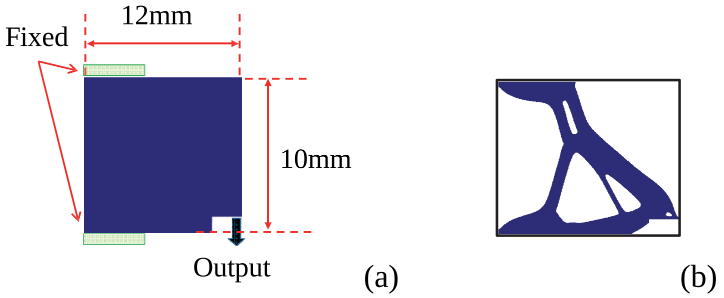


Figure 6. Design conditions (Left) & optimal configuration (Right)

Stage2: Shape optimization
Next, the optimal configuration obtained by topology optimization is converted into an initial shape optimization model. Figure 7(a) shows the created initial shape optimization model. As shown in this figure, the block is attached on the tip of the model. The details of the block are described in the previous section. In this stage, slit channels in the block are omitted from the model for making shape optimization easy. Arrows shown in Figure 7(a) are control points of lines and curves used as design variables of shape optimization.
Table 2 shows initial, target and optimized values of the slide length X_{stroke} and the Maximum von Mises stress σ_{max} when environmental temperature rises by 75 degrees Celsius. Here, initial values are the analytical results of the initial shape optimization model whereas optimized values are the ones of the optimized one. Figure 7(b) shows the optimal structure of a thermal actuated compliant valve. These table and figure show that the thermal actuated compliant valve that satisfies the given design requirements can be designed.

Table 2. Initial / target / optimized values of objective functions and constrained conditions

	Initial	Target	Optimized
Displacement X_{stroke} (mm)	0.26	0.3	0.30

Maximum von Mises stress σ_{max} (MPa)	47.7	<30	37.5

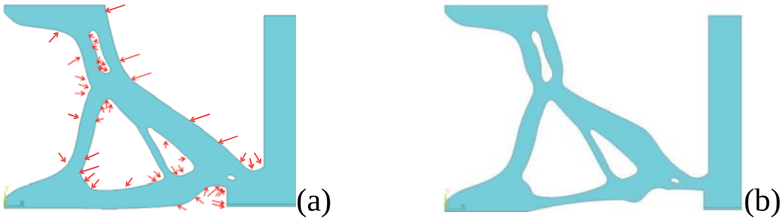


Figure 7. Initial shape optimization model (Left) & optimal structure (Right)

Table 3 shows the reliability of the optimal structure evaluated by Monte Carlo simulation. Reliability against stress, displacement and both are evaluated. This table shows that the optimal structure possesses enough reliability against displacement but not enough against stress.

Table 3. Reliability of the optimal structure

Reliability against stress	Reliability against displacement	Reliability against both
68.3%	98.8%	67.1%

Stage3: RBDO using OSF

Finally, RBDO using OSF is executed based on the optimal structure obtained in stage2. Coordinates of the control points used as design variables of shape optimization is used as random variables. The standard deviation of the width of the structure is given by σ=0.03mm. The target reliability index for stress is: β_1=3 and one for displacement is: β_2=2.

Figure 8 shows the optimal structure resulting from RBDO. Table 4 shows its reliability. For the purpose of comparison, the reliability of the structures resulting from original OSF is also shown in the same table. This table shows that the proposed method can obtain a compliant mechanism having higher reliability against both stress and displacement than original OSF.

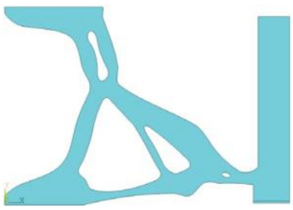


Figure 8. Optimal structure resulting from RBDO

Table 4. Comparison of the reliability of each result (original OSF and proposed method)

Reliability considered in OSF	Reliability against stress	Reliability against displacement	Reliability against both
Only stress	71.6%	56.2%	50%
Only displacement	20.2%	99.6%	20.2%
Both	94.3%	98%	93.2%

Conclusion

In order to design a reliable compliant mechanism, we developed a three-stage design optimization method consisting of topology optimization, shape optimization and optimal safety factor (OSF). In Stage1, topology optimization creates an initial outline of a compliant mechanism. In Stage2, shape optimization yields detailed shape of a compliant mechanism. In Stage3, OSF evaluates reliability of the compliant mechanism obtained in Stage2, i.e., influence of variations in its design parameters on output displacement and stress, and adjusts its design parameters in order to improve reliability. In the case study, to demonstrate the flow of the proposed method, the proposed method is applied to a design of a thermal actuated compliant valve used for a micro water cooling system.

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