INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

MULTI-CRITERIA RELIABILITY-BASED DESIGN OPTIMIZATION FOR COMPLIANT MECHANISMS

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Keywords: robust design, reliability-based design optimization, optimal safety factor, compliant mechanism

1. 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 [Howell 2001] 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 [Howell 2011], [Ananthasuresh and Kota 1995], 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) [Howell 2011], [Larsen et al. 1997] 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 [Her and Midha 1987], [Howell and Midha 1994]. 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 [Bendsøe and Kikuchi 1988], 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 [1997] proposed a design approach using topology optimization based on the density method. Nishiwaki et al. [2001] proposed a design approach using topology optimization 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 fully optimal configurations can be yielded.

Topology optimization, however, has several inherent problems, such as numerical problems that typically result in checkerboards or hinge patterns and numerical difficulties in utilizing local physical quantities such as stress and displacement during the optimization process. Topology optimization also cannot easily handle large deformations and non-linear analysis, or make detailed shape decisions. Numerous methods have been developed to resolve these problems. We also developed a two stage design method consisting of topology and shape optimization [Kobayashi et al. 2009].

In a practical mechanical design, every parameter such as geometry, material property and load case can be deterministic during a design process. However, once a product is actually manufactured and used, they take on variations due to a number of reasons. The variations adversely affect the product properties, which leads to reduce the probability that the product functions well, i.e. reliability of the product. To overcome such uncertainty, safety factor is widely introduced in a traditional mechanical design. 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) [Kharmanda et al. 2004], one of reliability-based design optimization (RBDO), is introduced into a compliant mechanism design. In a compliant mechanism design, multiple criteria such as displacement and stress need to be considered but conventional OSF is to consider reliability of single criteria. Thus, before the introduction of OSF to a compliant mechanism design, OSF needs to be extended to allow for considering reliability of multiple criteria. In the case study, the proposed method is applied to the design of a thermal actuated compliant valve used for a micro water cooling system.

2. Multi-criteria reliability-based optimal design for compliant mechanisms

To design a reliable compliant mechanism, we propose multi-criteria reliability-based optimal design method based on OSF. The proposed method consists of the following 2 stages.
Stage 1: Design of an initial compliant mechanism
Stage 2: RBDO using extended OSF

2.1 Stage 1: Design of an initial compliant mechanism

In Stage1, an initial compliant mechanism is designed with no consideration for its reliability. Any methods can be used to design an initial compliant mechanism, our two stage design method is used in this research.

Two stage design method consists of topology and shape optimization. Topology optimization first creates an initial outline or concept of a compliant mechanism by considering only linear analysis and then shape optimization yields its detailed shape by considering non-linear analysis, stress constraints and making accurate quantitative performance evaluations. Using this method, a designer can more easily and efficiently create a practical compliant mechanism. See the reference [Kobayashi et al. 2009] for the details of two stage design method.

2.2 Stage 2: RBDO using extended OSF

In Stage 2, RBDO using extended OSF is executed to adjust design parameters of the compliant mechanism designed in Stage 1 in order to improve reliability. This section explains original OSF at first and then explains modification of OSF for considering reliability of multi valuation characteristics.

2.2.1 Optimal safety factor (OSF)

OSF is one of reliability-based design optimization (RBDO) proposed by Kharmanda et al [2004]. OSF calculate the reliable design point $\boldsymbol{x}$ from the design point $\boldsymbol{y}$ obtained by determistic structural optimization according to the following three steps.

First, the initial design point $\boldsymbol{y}$ is obtained by determistic structural optimization. In this research, this step is carried out as Stage1. Next, the reliable design point $\boldsymbol{u}$ in the normalized space is calculated by using sensitivities of the limit state curve with respect to the design variables and optimality condition as follows:

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

Where G is the limit state curve in the physical space. β is the target reliability index. the sign of ± depends on the sign of the derivative of G as follows:

$$\partial G/\partial y > 0 \Leftrightarrow +\ ,\ \partial G/\partial y < 0 \Leftrightarrow - \tag{2}$$

Figure 1 illustrates the relationship between an initial design point and an optimal point in cases of two design variables in the normalized space. Here, P_D is the initial design point, P_{Op} is the optimum point with reliability in mind, $H(u)=0$ is the limit state curve in the normalized space and β is a reliability index. Finally, the optimal point $\boldsymbol{x}$ in the physical space is caluculated from $\boldsymbol{u}$ in a normalized space. When random variables are subjected to normal distribution N($\boldsymbol{x}$, σ), the optimum point $\boldsymbol{x}$ can be written as follows:

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

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.

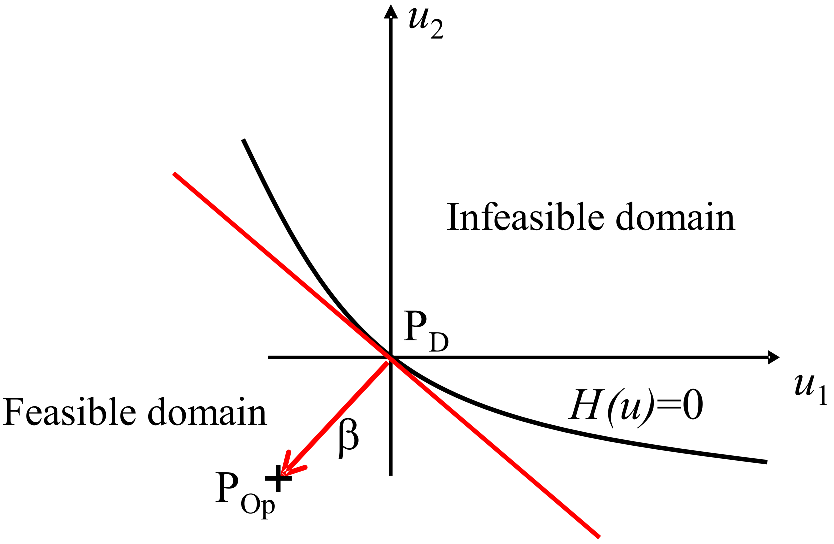


Figure 1. Initial and optimal design points in the normalized space

2.2.2 OSF considering reliability of multi valuation characteristics

Original OSF can consider only single reliability. However, in compliant mechanism design, reliability of multiple valuation characteristics such stress and output displacement needs to be considered in order to ensure the function of a compliant mechanism. Therefore, OSF is extended in order to consider reliability of multiple valuation characteristics.

The basic concept of the extended OSF is to find a new design point located the given β away from each limit state curve in a normalized space. The procedure of calculating the optimal point P_{Op} is described below using the example shown in Figure 2. In this example, there are two design variables u_1 and u_2 and three limit state curves H_1, H_2 and H_3 in a normalized space. P_D is the initial design point obtained in Stage 1. In this case, the initial design point P_D is located on every limit state curve.

First, the design points considering reliability of single valuation characteristic P_{Op1}, P_{Op2} and P_{Op3} are calculated by conventional OSF, as shown in Figure 3. Their limit state curves are with respect to the initial design point. Next two limit state curves are selected. In this case, H_1 and H_2 are selected. Next, the point of the intersection of the two lines, as shown in the left of Figure 4, are calculated and named P_{Op12}. The line perpendicular to β_{12} at P_{Op12} is named H_{12}. Finally, the procedure applied to H_1 and H_2 is then applied to H_{12} and H_3 in the same manner, as shown in the right of Figure 4. The optimal design point P_{Op}^* is obtained.

Using this method, since the optimal design point is separated the given β away from three limit state curves, the optimal design can satisfy reliability of three valuation characteristics.

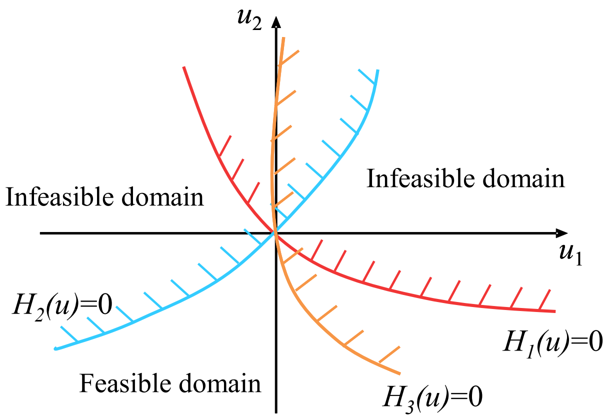


Figure 2. The case of three criteria

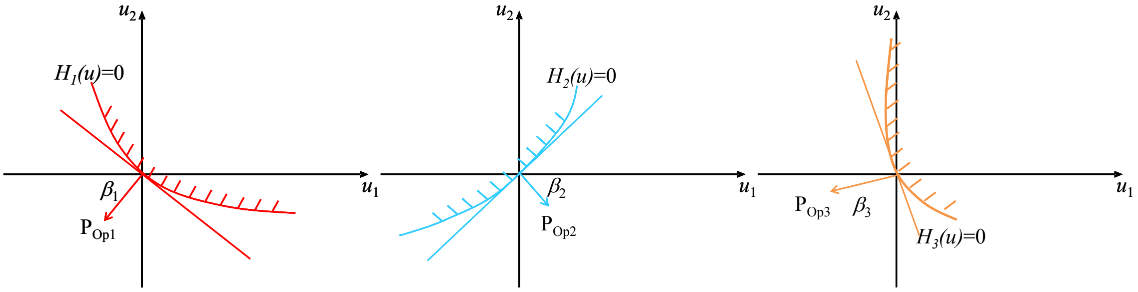


Figure 3. Calculation of P_{Op1}, P_{Op2}, P_{Op3} using conventional OSF

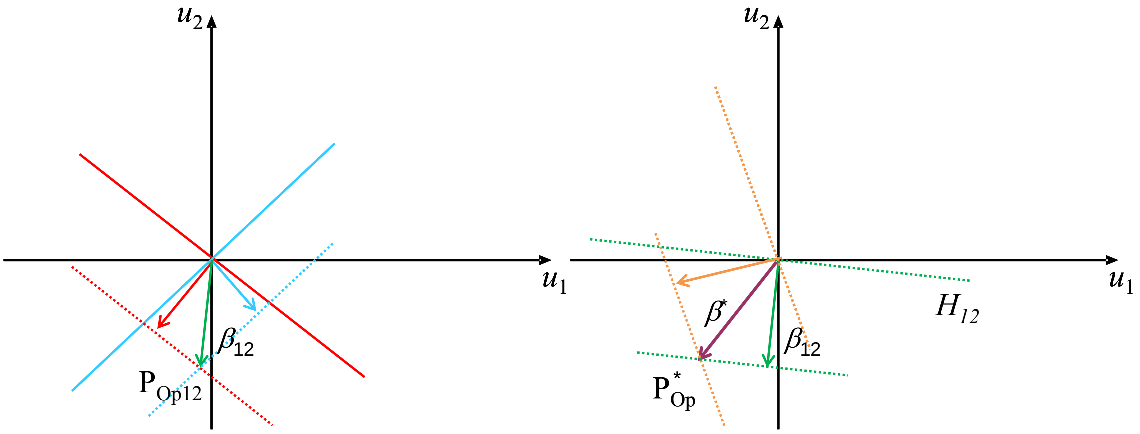


Figure 4. Calculation of P_{Op12} (Left) and $P_{Op}{}^{*}$ (Right)

3. Case study

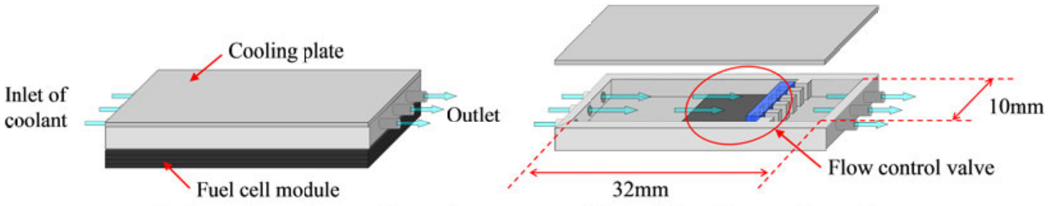
To demonstrate the flow of the proposed method, the proposed method is applied to design of a thermal actuated compliant valve used for a micro water cooling system.

3.1 Micro water cooling system with a thermal actuated compliant valve

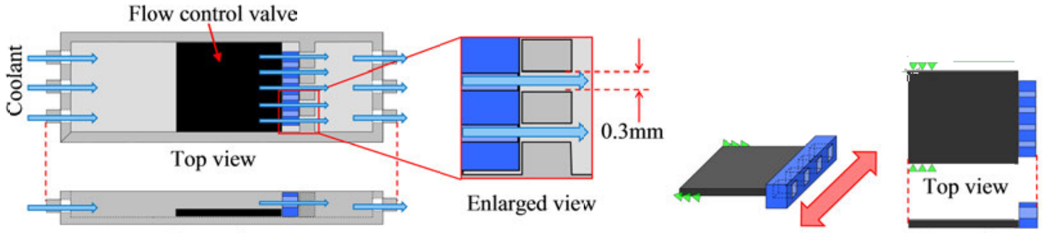
Recently there is a growing need for micro water cooling systems with the development of small-sized devices such as small-sized fuel cells for mobile electric devices. In general, a water cooling system requires a valve for controlling flow rate of coolant in order to keep targeted devices at an appropriate 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.

3.1.1 Diagram of micro water cooling system

Figure 5 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

3.1.2 Specification of thermal actuated compliant valve

A flow channel inside a cooling plate is 32 mm long and 10mm wide and maximum size of a valve is 12 mm long and 10mm wide. A valve is anchored in both sides of side walls. The width of slit channels in two blocks is 0.3 mm. 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 0.3 mm under the condition of increase in temperature of 75 degrees Celsius. The block fixed on the tip of the valve receives water pressure and the valve is deformed alongside the channel. This deformation hinders function of flow control.

Therefore, the deformation alongside the channel needs to be considered as a constraint condition in addition to stress.

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.

3.2 Stage 1: Design of an initial compliant mechanism

Using our two-stage design method, an initial compliant mechanism is designed. Figure 6 (a) shows the design conditions of topology optimization whereas Figure 6(b) shows the obtained optimal configuration. The optimal configuration is then converted into an initial shape optimization model shown in Figure 7(a). As shown in this figure, the block is attached on the tip of the model. Arrows shown in Figure 7(a) are control points of lines and curves. Their coordinates are used as design variables of shape optimization. Table 2 shows target and optimized values of the slide length X_{stroke}, Displacement alongside the channel Y and the Maximum von Mises stress σ_{max} when environmental temperature rises by 75 degrees Celsius. Figure 7 (b) shows the optimal structure. These table and figure show that the thermal actuated compliant valve that satisfies the given design requirements can be designed.

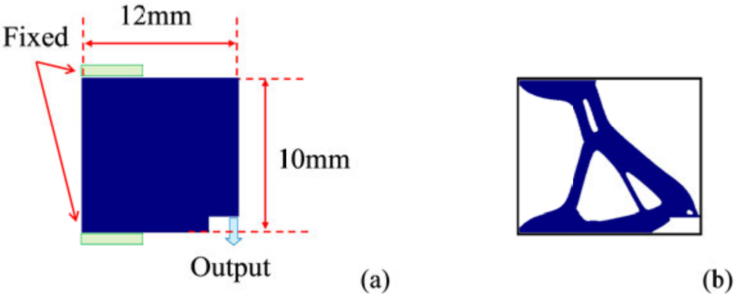


Figure 6. Design conditions (Left) & optimal configuration (Right) of topology optimization

Table 1. Target / optimized values of objective functions and constrained conditions

	Target	Optimized
Horizontal displacement (mm)	> 0.3	0.3
Vertical displacement (mm)	< 0.003	0.0019
Maximum von Mises stress (MPa)	< 10	8.6

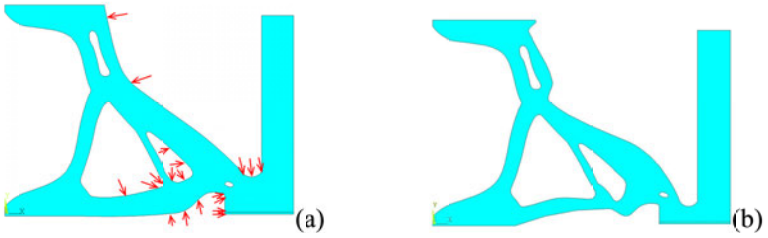


Figure 7. Initial shape optimization model (Left) & Optimal structure (Right)

Table 3 shows the reliability of the optimal structure evaluated by using Monte Carlo simulation. Reliability against stress, vertical displacement and horizontal displacement are evaluated. Coordinates of the control points of lines and curves that represent shape of the compliant mechanism are used as random variables. The standard deviation of their coordinates is given by σ=0.03mm. This table shows that the optimal structure possesses enough reliability against stress but not enough against vertical & horizontal displacement.

Table2. Reliability of the initial model against three valuation characteristics

Vertical displacement	Horizontal displacement	Stress
68.0%	78.7%	99.1%

3.3 Stage2: RBDO using extended OSF

RBDO using extended OSF is then applied to the initial compliant mechanism. The target reliability index for vertical displacement is: $\beta_1=3$, one for horizontal displacement is: $\beta_2=2$ and one for stress is: $\beta_3=2$.

Figure 8 shows the optimal structure resulting from RBDO. Table 3 shows the results of reliability evaluation. For the purpose of comparison, the reliability of the structures resulting from RBDO using original OSF is also shown in the same table. Since original OSF can only consider single valuation characteristic at a time, there is a possibility that reliability against the other characteristics becomes low. This table shows that the proposed method can obtain a compliant mechanism having higher reliability against stress, vertical displacement and horizontal displacement than original OSF.

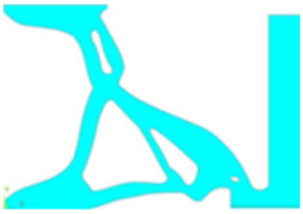


Figure 8. Optimal structure resulting from RBDO

Table 3. Comparison of the reliability (original OSF and proposed method)

Method	Vertical displacement	Horizontal displacement	Stress
Original OSF	28.6%	39.9%	99.9%
Proposed method	99.3%	95.6%	98.6%

4. Conclusion

In order to design a reliable compliant mechanism, we extend optimal safety factor (OSF) and develop a multi-criteria reliability-based design optimization that integrates two-stage design method and extended OSF. In the first stage of the he proposed method, two-stage design method that consists of topology and shape optimization creates an initial compliant mechanism. In the second stage, the extended OSF evaluates influence of variations in design parameters on multiple valuation characteristics such as output displacement and stress and adjusts 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.

Acknowledgements

This study was supported by Ministry of Education, Culture, Sport, Science, and Technology, Japan (MEXT) through special subsidies for private universities and institutions: Special funds for the creation of strategic research infrastructure, 2013-2017.

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