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Synthesis of a discrete-action thermo-bimetallic actuator with a tongue

A Nikolaeva¹, AJ McMillan², S Gavriushin¹

¹ Bauman Moscow State Technical University, 5/1, 2nd Baumanskaya, Moscow, 105005, Russia.

² Wrexham Glyndwr University, Mold Road, Wrexham, LL11 2AW, UK.

nikolaeva@bmstu.ru

Abstract. The selection of suitable parameters, by experimental or intuitive processes for snap-through actuation of a bimetallic actuator at a prescribed temperature is an extremely time-consuming task. This paper describes a new methodology for the optimization of a discrete action thermo-bimetallic actuator with a tongue. This methodology makes it possible to solve the optimization task with higher efficiency. The requirement is to find optimal parameters values so that the actuator will make a snap-through at a given temperature. The constrained optimization task was performed using an evolutionary algorithm and surrogate modelling and this was coded in Matlab. Functional relationships between the criteria and parameters were not set explicitly, but they were calculated using finite element method, each simulation of which was performed in Abaqus.

1. Introduction

Discrete action actuators are used in industry. In particular they can be used as thermo-sensitive electrical switches for overload protection of electric circuits, for important elements temperature control and regulation, in optical components, as a manipulator for object transportation in micro-systems.

Dome plate bimetallic actuators are well known [1]. They change curvature direction, making a snap-through at a critical temperature [2-4]. Despite the ease of fabrication, they have several disadvantages. For example, their temperature of a snap-through is unstable and the component experiences high stresses, in some cases exceeding the elasticity limit. In the latter case, the value of the critical temperature changes over as a result of the evolution of the zone of plastic deformations. As a result the service life of such actuators, relays and switches is limited. Another disadvantage is the emergence of cracks on the actuator surface after multiple switches, leading to actuator failures.

Another well-known type of actuators is that of actuators with a tongue [5]. Their effective displacement is higher compared with the dome actuators, so they can ensure required contact forces and avoid bounce. Required contact force ensuring makes it possible to transform the mechanical displacement of the actuator into the proper performance of the following part of the micro-electro-mechanical system (MEMS). Due to the displacement paucity, contacts can “bounce” upon closure before coming to a full rest and providing unbroken contact, which is inadmissible in electric circuits.



Bimetallic actuator parameter optimisation using current state-of-the-art optimisation and finite element modelling (FEM) analysis software (such as ANSYS, Abaqus, iSight) is an extremely time-consuming task, as it requires multiple meshing after geometrical design parameter variations. The formal use of these programs for the analysis of bimetallic actuators deformation processes without correct design strategy can often be unsuccessful (especially in the case of deformation with a snap-through).

The snap-through behaviour and large deflections of thin-walled shells has been studied by many authors [6-12]. Other recent research papers [13-14] describe computational algorithms for non-linear deformation. Optimization plays a key role in the design of actuators [15-18], however, most MEMS design optimization (exploration) methods depend either on analytical / behavioural models or on time consuming numerical simulations. Surrogate modelling techniques have been introduced to integrate generality and efficiency [19].

In the present paper, a technique is presented for determining geometry parameters for a discrete action micro-actuator, operating under snap-through. The actuator consists of two regions: hemispherical shell with a central hole and tongue configuration (Figure 1). The actuator is comprised of two layers. The parameters are shown in figure 1. It is required to find optimal parameters values so that the actuator will make a snap-through at a given temperature. This constrained optimization task was performed using an evolutionary algorithm and surrogate modelling [19] and implemented in MATLAB R2013a [20]. Functional relationships between the criteria and the parameters are not set explicitly, but they are calculated using a finite element method [21], each simulation of which is performed in Abaqus finite element software [22].

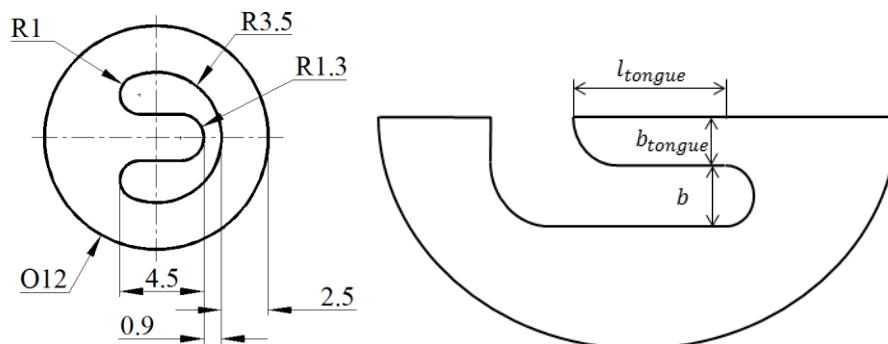


Figure 1. Actuator - geometry and parameters for the optimization task.

2. The method adopted

The hemi-spherical thin-walled micro-actuator is designed to perform mechanical switching. Let us suppose that its deflection is required to take a given value d^* when the critical temperature T^* is applied. The elastic characteristic of the micro-actuator which includes a snap-through mechanism and the deformed shape of the actuator are shown schematically in figure 2.

The shell curvature changes after applying temperature. This part of the process is illustrated by the DA part of the curve. The shell instantly changes the direction of the deflection at the point A (the upper critical point) – the snap-through at point A. Then the shell continues its deformation from the point B of the stable part of the elastic characteristic. The deflection of the shell decreases if the pressure decreases (BC) until the point C (lower critical point) and the CD snap-through.

The initial data for the research is given in table 1. The required outcome of the optimisation process is the selection of values l_{tongue} , b_{tongue} , b , subject to the value of critical temperature T^* being

equal to the customer's requirements. The acceptable ranges of variation of these parameters are also given. The functional relationships between the criteria and parameters are not set explicitly, but are calculated using Finite Elements in Abaqus as described below.

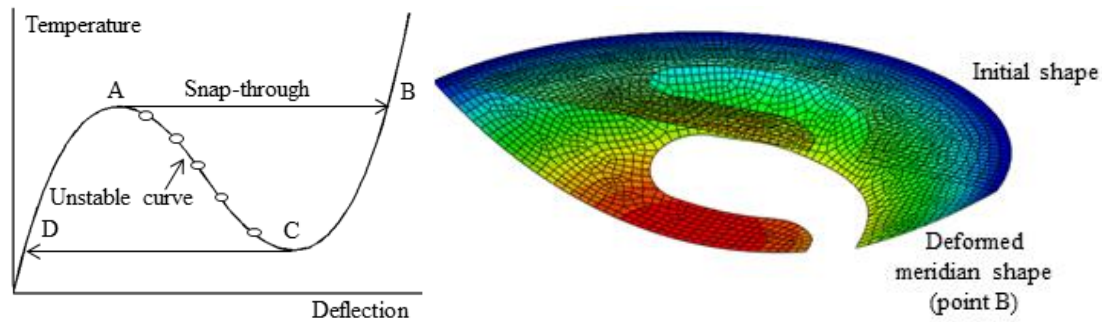


Figure 2. Schematic of the discrete elastic response and deformed shape of the actuator.

The shell is modelled using shell elements. The material of the shell is linearly elastic. The shell is simply-supported around the edge and is loaded by temperature. The analysis is performed using the parameter continuation algorithm arc-length method for a problem with large displacements. In this method the length of the arc [23] along the elastic characteristic curve is used as a parameter in the parameter continuation method, rather than displacement in the displacement - controlled mode or temperature in the temperature-- controlled mode. This makes it possible to overcome computational stability difficulties. The evolutionary algorithm and surrogate modelling method implemented in Matlab are used for the solution of the optimization problem [21].

There is one objective function, specified as

$$F_1 = |T - T^*| \quad (1)$$

Table 1. Problem specification data

Parameter		Value	
Length of the tongue	l_{tongue}	$1.5 - 4 \times 10^{-3}$ m	
Width of the tongue	b_{tongue}	$1.3 - 2 \times 10^{-3}$ m	
Hole parameter	b	$1.2 - 2 \times 10^{-3}$ m	
Desired temperature	T^*	40°C	
		Layer 1	Layer 2
Shell thickness	h	1×10^{-4} m	1×10^{-4} m
Young's modulus	E	190×10^9 Pa	150×10^9 Pa
Poisson's ratio	ν	0.3	0.3
Thermal expansion coefficient	α	$18 \times 10^{-6}, 1/^\circ\text{C}$	$1 \times 10^{-6}, 1/^\circ\text{C}$

At each iteration, new values for the variables were substituted into the Abaqus file, and the finite element analysis was repeated. The calculated values for the critical temperature, T , were extracted from the Abaqus results database. The Optimizer continues to test different parameter values until the

value of T matches that of T^* to within the tolerance requirements. Penalty functions were used to implement the constrained optimization.

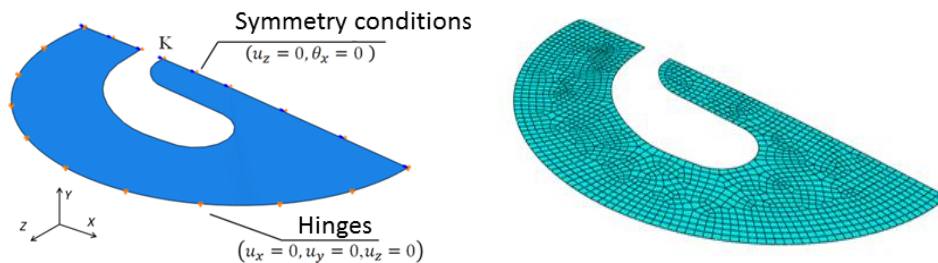


Figure 3. Mathematical and finite element models of the actuator

3. Evolutional algorithm and surrogate modelling

The evolutionary computation algorithm imitates the biological mechanisms of evolution to approximate the global extremum problem [15]. The main feature of the evolutionary algorithm (EA) is the use of individual populations that are processed by a set of operators (*crossover*, *mutation*, *selection*) and are evaluated using the fitness function. The goal of the operators is to find candidates with higher fitness function values [16]. The fitness function shows "how well" a candidate succeeded and determines the probability of its survival. The process of solving the problem consists of generating new populations and testing them: the candidate with the higher fitness function has a higher chance of being saved and being used as the "parent" when creating the next candidate solutions. First, populations (each population consists of individual specimens – actuators, which are characterized by a vector of parameters) are randomly generated. Then, the procedure of *crossover* is carried out: different candidates share their binary strings parts to create new child populations (binary genetic algorithm [24]). The purpose of this step is the exchange of information by parents. If the useful information is combined, the functional adaptation of the new candidate populations is more likely to have high value. The next step is the *mutation*. The purpose of mutation is to present new information to the population to provide a global search. New populations are generated after the mutation stage. Candidates with a higher fitness function receive a greater likelihood of promoting successful generations on the *selection* stage. The best solution is displayed, if the stopping criterion is satisfied, *i.e.* the maximum number of populations is reached, otherwise, a new iteration starts.

Surrogate models are used to replace models which require time-consuming calculations? For example the computationally demanding FEM snap-through analysis. The purpose of the surrogate model is to significantly increase the efficiency of the optimization by replacing time-consuming computational steps with simpler models which are sufficiently representative the true values. In this study, the critical temperature for new parameter values is determined using a surrogate model of the surface of equilibrium states without extra running the finite-element program.

4. Results

The optimal parameters of the actuator are shown in the table 2. The elastic characteristic for the optimal geometry is shown in figure 4. The average time cost is 3.6 hours (wall clock time) which is five times quicker than optimization task solution using a standard differential evolution algorithm.

5. Discussion

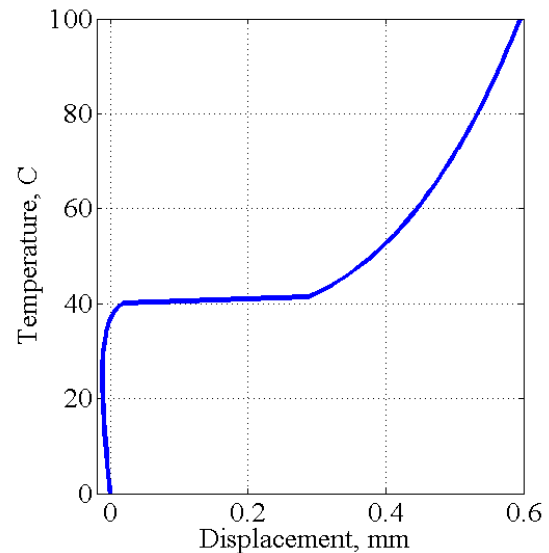
Surrogate model-based methods are used in actuator design optimization to combine generality and efficiency. An initial random sampling is first carried out. The black-box surrogated model is prepared to approximate the performance of the actuator using the sampled design variables as the

input and the critical temperature via numerical simulations as the output. It is used to replace computationally expensive numerical simulation model in the optimization process. The developed algorithm made it possible to achieve the results comparable with methods which directly embed numerical simulations to a standard evolutionary algorithm for actuator optimization.

Table 2. Optimal parameters

Parameter	Value
l_{tongue}	3.87×10^{-3} m
b_{tongue}	1.39×10^{-3} m
b	1.28×10^{-3} m

Figure 4. Elastic characteristic of an actuator with optimized geometry



The surrogate modelling method is Gaussian Process, providing an approximation model for the MEMS performance using existing training data points. For off-line surrogate model-based methods, prediction results are used as results based on real simulation in the optimisation process. Thus, its accuracy needs to be verified, or wrong convergence may happen; however, the surrogate model here is an on-line model. Promising candidates using prescreening methods are selected and are then verified by finite element analysis. In other words, the surrogate model only serves for looking for "promising" solutions, but the prediction result itself is not used as the performance. The surrogate model assisted evolutionary algorithm used here is a state-of-the-art method [25].

The efficiency of the optimization process by using surrogate modelling was improved by up to five times. Actuator optimization problems with several design variables and without any initial solutions were solved.

6. Conclusion

A technique for determining geometric parameters for a discrete action actuator with a tongue, to translate a prescribed critical temperature into deflection has been described. The three geometry variables considered were the tongue length, tongue width and the hole parameter. The mechanical analysis was performed using Finite Element Analysis to obtain the temperature of a snap-through. The optimization process was performed using an evolutionary algorithm and surrogate modelling in Matlab program. The proposed methodology followed has been demonstrated to be effective, a number of opportunities for methods development have been identified, and these will form the basis for further more challenging design optimization studies. Compared with other state-of-the-art methods, the proposed technique showed clear advantages in efficiency and accuracy.

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