234.37, 160.88, 360.26, -131.38, 0 deg, 83.12 deg, and $\theta_1, \ldots, \theta_9$ are 34.96 deg, 70.67 deg, 100.18 deg, 154.33 deg, 196.60 deg, 211.93 deg, 241.58 deg, 290.80 deg, and 325.04 deg, respectively. The corresponding motion characteristics are shown in Figs. 4 and 5. The required ram motion can be achieved when the input link is running at the given speed trajectory. It is noticed that the input speed variation in Fig. 4 is reduced from that in Fig. 3 since the geometric dimensions are also considered in optimization.

7 Conclusions

This paper presents a concept of using a servo approach for Stevenson-type presses. The motivation is to come up with a new generation of presses that can be used for various types of press works to upgrade an existing press. It uses a servomotor as the power input. By properly designing the input speed, the output motion can pass through a desired trajectory. The input motion characteristics are planned with Bezier curves containing undetermined control points that are selected by optimization methods to satisfy the design constraints and improve the performance of the system. The guidelines for transferring the design problem into the optimization problem are discussed. Additional dimensional synthesis is also discussed to reduce input speed variation. Examples are given. The success of these examples demonstrates the practicability of this idea of multi-function presses. As long as the servomotor can generate sufficient torque to keep the input speed along the pre-determined speed trajectory, the output motion for multi-action is then achievable.

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Design of a PZT Bimorph Actuator Using a Metamodel-Based Approach

David J. Cappelleri
Graduate Research Assistant

Mary I. Frecker
Assistant Professor

Timothy W. Simpson
Assistant Professor

Pennsylvania State University, Department of Mechanical and Nuclear Engineering, University Park, PA 16802

Alan Snyder
Associate Professor, Pennsylvania State University, Department of Surgery, Hershey, PA 17033

The design of a variable thickness piezoelectric bimorph actuator for application to minimally invasive surgery is proposed. The actuator is discretized into five segments along its length, where the thicknesses of the segments are used as design variables in the problem of optimizing both the force and deflection at the tip. Metamodeling techniques are used to construct computationally inexpensive approximations of finite element simulations and to rapidly explore the design space and the Pareto frontier. A prototype device and experimental verification of the analytical results are also discussed. [DOI: 10.1115/1.1446866]

Keywords: Piezoelectric Bimorph, Minimally Invasive Surgery, Sizing Optimization, Metamodeling

1 Introduction

A piezoelectric bimorph actuator consists of a thin passive beam sandwiched between layers of piezoelectric ceramic material (PZT). When opposing voltages are applied to the two ceramic layers, a bending moment is induced in the beam (Fig. 1) [1]. A pair of cantilevered piezoelectric bimorph actuators can be used as a simple grasping device, where the bimorph actuators act as ''fingers'' (Fig. 2). Similar grasping designs have been developed for MEMS and robotics by Chonan et al. [2] and Seki [3]. Bar-Cohen et al. [4] and Lumia and Shahinpoor [5] have designed bimorph actuator grippers using electroactive polymers.

The focus in this paper is on the design of a PZT bimorph grasper for application to minimally invasive surgical (MIS) procedures. During MIS, small surgical tools and viewing equipment are introduced into a body cavity through several 3-10 millimeter incisions. MIS reduces tissue trauma and patient recovery time compared to open surgery [6,7]; however, there is a need for improved dexterity and control in MIS tools [8–11]. We propose the use of an active end-effector such as a PZT bimorph grasper, where the localized actuation at the working jaws of the end-effector allows for precise control of its position.

The tip deflection and force are critical in such a design, as the jaws of the grasper must deflect to close completely while exert-

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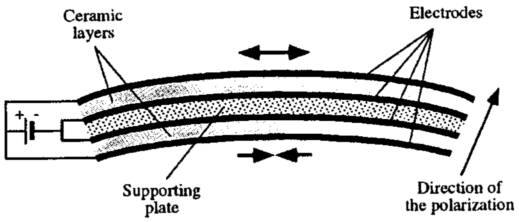

Fig. 1 PZT bimorph

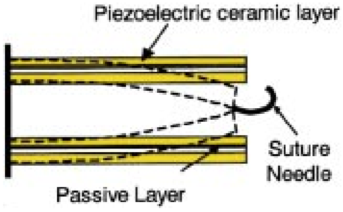

Fig. 2 Bimorph grasper

Fig. 3 Finite element model of variable thickness bimorph actuator

ing a large force to secure tissue or a suture needle. The deflection and force are determined by the geometry of the actuator, the material properties, and the applied voltage. Since the operating frequency is low (on the order of 1–2 Hz) in MIS applications, only quasi-static response is considered. Using simple models of a standard bimorph actuator with constant layer thicknesses, the blocked force available at the tip (force exerted with no deflection), and the free tip deflection were calculated. It was determined that a standard bimorph of appropriate size for MIS provides insufficient grasping force and tip deflection [12]. To improve the deflection and force performance of the bimorph actuator, a variable thickness design is proposed where the thickness of the piezoceramic layers is varied along the length. The finite element model for the bimorph actuator is described next.

2 Finite Element Model

Finite element analysis of the bimorph actuator is performed using ABAQUS [13] to predict the free tip deflection and the blocked force while subjecting the actuator to a prescribed input voltage. The actuator is modeled as composite beam with a thin steel passive layer sandwiched between layers of PZT5H [14]. The bimorph actuator is 54.0 mm long and 3.0 mm wide. The PZT layers are discretized into five sections, where the thickness of the sections, t_i $(i=1,...,5)$, are the design variables. Posing the problem in terms of discrete section thicknesses rather than a continuously varying shape limits solutions to those that are easily fabricated from commercially available PZT ceramic material. The finite element model consists of 1944 eight-node three-dimensional (brick) elements with cantilever supports at the root nodes (Fig. 3). Each PZT section has three elements across its height and width and 10 elements along the length. As the thickness of the PZT sections is varied in the optimization procedure, the number of elements remains constant.

In the FEA simulations, each PZT section is driven at its saturation voltage so that the maximum induced strain in each PZT section can be obtained. The saturation voltage is the maximum allowable voltage and is proportional to the thickness of the PZT material. By operating each segment at its saturation voltage, the voltage is varied along the length of the bimorph actuator, resulting in dramatic improvements in the tip deflection and force compared to the same bimorph operated at a constant voltage.

3 Solution Approach

A metamodel-based approach is employed in this study to simultaneously maximize tip deflection and blocked force of the bimorph actuator. Metamodeling involves the use of design of experiments [15] and metamodels (e.g., response surfaces [16]) to sample a design space and construct inexpensive-to-run approximations of a computationally expensive computer analysis like ABAQUS. The approximations are then used in lieu of ABAQUS to rapidly explore the design space during optimization; a detailed explanation of our approach is given in [17].

For this study, a half-fraction central composite face-centered (CCF) design [16] is used to sample each design variable at one of three levels: 1.0 mm, 2.0 mm, and 3.0 mm. The CCF design allows us to sample the free deflection and blocked force of the PZT bimorph actuator at 27 points in ABAQUS to generate enough data to build approximations for tip deflection and blocked force. Two different types of metamodels—response surface models and kriging models—are employed to construct approximations from this sample data. The response surface models used in this study are second-order polynomial models of the form:

$$\hat{y}(t)=\beta_0+\sum_{i=1}^{5}\beta_i t_i+\sum_{i=1}^{5}\beta_{ii}^2 t_i^2+\sum_{i=1}^{5}\sum_{j=1}^{5}\beta_{ij}t_i t_j \tag{1}$$

where $\hat{y}(t)$ is the predicted response, t_i are the design variables, and β_{ij} are the coefficients used to fit the model. A complete description of response surface modeling can be found in, e.g., [16]. Note that although the metamodels are constructed using a set of points at three discrete levels, the optimization solutions found using the metamodels need not be restricted to these discrete values.

Since response surface models are typically second-order polynomial models, they have limited capability to accurately model non-linear functions of arbitrary shape. Therefore, as part of this study we are investigating kriging models as alternatives to response surface models. Kriging models are interpolative approximations based on an exponentially weighted sum of the sample data [18,19]. The kriging models used in this study consist of constant underlying "global" models combined with Gaussian correlation functions based on the results of our previous studies [20,21]. To ensure that both sets of approximations are sufficiently accurate for use during optimization, the metamodels are validated using 25 additional points from ABAQUS [12].

4 Optimization Results

One advantage of using approximations such as response surface and kriging models is that the design space can be rapidly explored to examine the tradeoff between competing design objectives. For this example, a 5^5 search grid (3125 points) is used to explore the design space and predict the Pareto frontier. The Pareto frontier can be thought of as a "trade-off curve" of design points in the performance space, beyond which it is not possible to improve both objectives. A formal procedure for efficiently estimating the Pareto frontier using metamodels is presented in [17]. As seen in Fig. 4, the Pareto frontier can be readily captured using the metamodels themselves without using any optimization or a weighted-sum of the objectives with varying weights. The kriging model is a better predictor of force and deflection, while the response surface models are poor predictors of designs with large deflections.

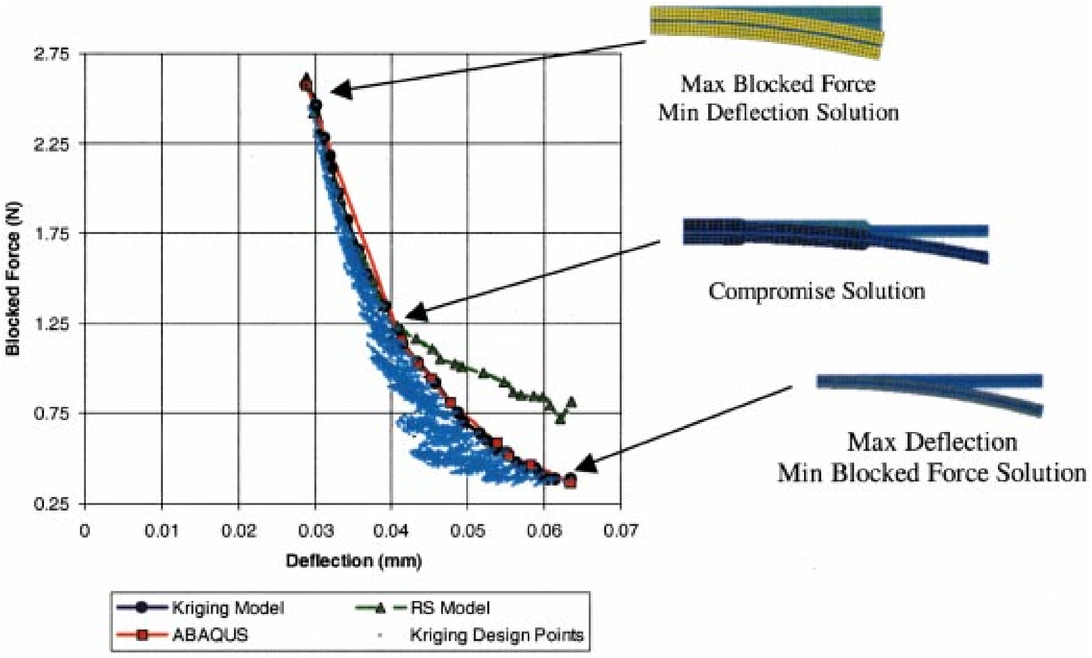

Fig. 4 Design space and Pareto frontier

It is evident from Fig. 4 that the Pareto frontier is not concave, indicating that a unique maximum combination of force and deflection does not exist. The maximum force solution is a thick bimorph actuator, where all the design variables are at their upper limits, while the maximum deflection solution is thin, where all the design variables are at their lower limits. A tapered design is selected as a compromise solution with section thicknesses of 2.5 mm, 2.0 mm, 2.0 mm, 1.0 mm, and 1.0 mm. This solution provides sufficient force performance for the intended MIS application. The kriging models predict $F_{blocked}=1.21$ N and $\delta_{free}=0.0411$ mm, which compare well with values obtained from ABAQUS (1.16 N and 0.0413 mm, respectively).

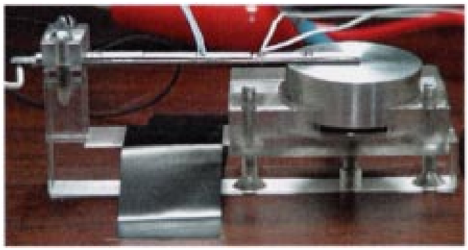

Fig. 5 Experimental setup

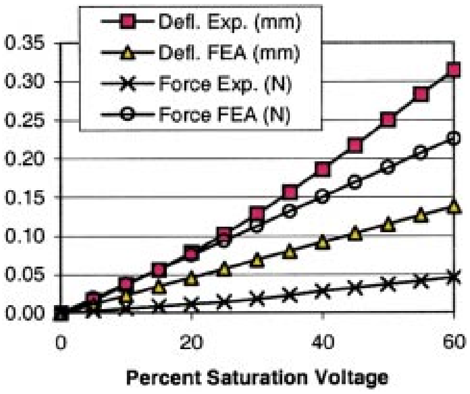

Fig. 6 Experimental data and FEA prediction

5 Experimental Results

A scaled prototype of the compromise design was constructed and tested in the laboratory. The free deflection was measured using a laser vibrometer, and the blocked force was measured using a 500 g load cell. The experimental setup is pictured in Fig. 5, and the data is shown in Fig. 6. The ABAQUS model under-predicts the free deflection and over-predicts the blocked force significantly at high voltage levels. This difference between the experimental data and the FEA predictions is attributed to the presence of the epoxy bonding layer, which is not accounted for in the finite element model.

6 Closing Remarks

A variable thickness PZT bimorph actuator design is proposed, where the PZT material is discretized into five segments along the length. It is desired to maximize both the tip deflection and blocked force of the actuator for application to minimally invasive surgical procedures. A metamodel-based approach is employed in this work to rapidly explore the design space and identify candidate designs along the Pareto frontier. The kriging models predict tip deflection and blocked force more accurately, particularly for the designs with high deflection and low blocked force. The plot of the Pareto frontier reveals that a unique maximum does not exist for this problem, but a compromise design is selected that provides sufficient force. A prototype of the compromise design was constructed, and experimental testing reveals that the bonding layer may significantly affect the performance of the bimorph actuator.

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