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During the past year, research efforts were focused on developing analytical formulations and global optimization methods for design of compliant structures for prescribed shape change under distributed pressure loads. The method employs a new Fourier Transform based objective function to capture the desired shape change under the action of applied (actuator) forces and external distributed loads (air loads).

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FINAL REPORT

SYNTHESIS OF COMPLIANT STRUCTURES FOR ADAPTIVE SHAPE CHANGE WITH DISTRIBUTED PRESSURE LOADS

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ABSTRACT

The objective of this research is to develop mathematical formulations to perform systematic design (synthesis) of compliant structures for prescribed shape change under distributed pressure (air) loads.

During the past three years, the PIs developed a scientific basis for synthesizing compliant mechanisms for static and kinetostatic problems based on linear as well as non-linear elastic deformation assumptions and concentrated loads. Formulations for dynamic analysis of compliant structures were also developed

During the past year, research efforts were focused on developing analytical formulations and global optimization methods for design of compliant structures for prescribed shape change under distributed pressure loads. The method employs a new Fourier Transfom based objective function to capture the desired shape change under the action of applied (actuator) forces and external distributed loads (air loads).

1.0 Objectives

Development of synthesis formulations to perform systematic synthesis of compliant structures for a prescribed shape change with distributed air loads.

2.0 Status of Effort

During the past three years, the PIs developed a scientific basis for synthesizing compliant mechanisms for static and kinetostatic problems under linear as well as non-linear elastic deformation assumptions and concentrated loads. Having solved the synthesis task, we developed formulations for dynamic analysis of compliant structures.

In the past two years, our research effort focused on developing analytical formulations for synthesis of complint structures under deformation-dependent pressure loads (air loads). Our major accomplishment during the past two years is the development of global optimization methods for topology synthesis of compliant mechanisms for adaptive structures application. This method employs a new Fourier descriptors based objective function to capture the desired shape change under the action of applied (actuator) forces and external distributed loads (air loads).

3. 0 Summary of Accomplishments

3.1 Previous work on Basic Research

The PIs, S. Kota, and N. Kikuchi have developed and tested the fundamental formulations for the design of compliant mechanisms including the following tasks:

- (1996-1998) Given a set of functional requirements; that is forces and desired displacements, determine an optimized topology (configuration) of a complaint mechanism.
- (1996-1998) Given the initial and final shape of a flexible body, determine the optimal topology of a complaint mechanism that can produce the desired shape change using a single actuator - external loading was not taken in to account in this preliminary investigation.
- (1997-1999) Given the topology of a compliant mechanism, determine the optimum size and shape of all members of the mechanism such that energy efficiency is maximized.
- (1999-2000) Dynamic analysis of compliant mechanisms and determination of sensitivity coefficients.
- (1999-2001) Topology, Size and Shape Optimization of Compliant Structures that undergo large deformation using Non-Linear Models.
- (2000-2002) Global Optimization of Compliant Adaptive structures under distributed external (air) loads.

3.2 Publications

The results from the work supported by the AFOSR contract are published in the following journal articles

- Kerr-Jia Lu, S. Kota, Compliant Mechanism Synthesis for Shape Change Applications – Preliminary Results, Proc. of the 2002 SPIE Modeling, Signal Processing, and Control Conference, San Diego, March 2002, pp. 161-172.

3.3 Technology Transition

1. Under a contract with WPAFB, the PI S. Kota has designed, fabricated and tested a 3-foot wing section of NACA63418 profile embedded with compliant mechanisms. A low-speed wind tunnel test revealed significant improvement in lift coefficient as the leading camber is changed. A Phase 2 SBIR contract is in progress in collaboration with Lockheed Martin Tactical Systems.

2. A STTR contract with AFOSR is underway to develop high-frequency vortex generator for active flow control. The device utilizes a compliant stroke amplification mechanism in conjunction with a piezo actuator. The project is in collaboration with Lockheed Martin Tactical Aircraft Systems.

3.5 Benefits to AFSOR

- Lays a scientific foundation for designing multifunctional structures with embedded actuation for applications to aerospace adaptive structures such as camber changing leading edge and trailing edge control surfaces.

4.0 Personnel Supported

Sridhar Kota, PI/PD Professor of Mechanical Engineering, University of Michigan, Ann Arbor

Doctoral Students: Kerr-Jia Lu, Mechanical Engineering, University of Michigan, Ann Arbor.

5.0 Synthesis of Complaint Mechanisms for Shape Morphing applications

5.1 Methodology Overview

A brief overview of our synthesis strategy is described in this section. It is assumed that (1) the initial and target curve shapes (before and after the shape morphing) are specified a priori, (2) the compliant mechanism has only a single external input actuator at a prescribed location, and (3) the shape-morphing object (say a wing leading edge, or an antenna reflector surface) is integrally connected to the compliant mechanism. Figure 1 is a simple illustration of how a compliant mechanism can transfer energy from an actuator to morph a surface contour.

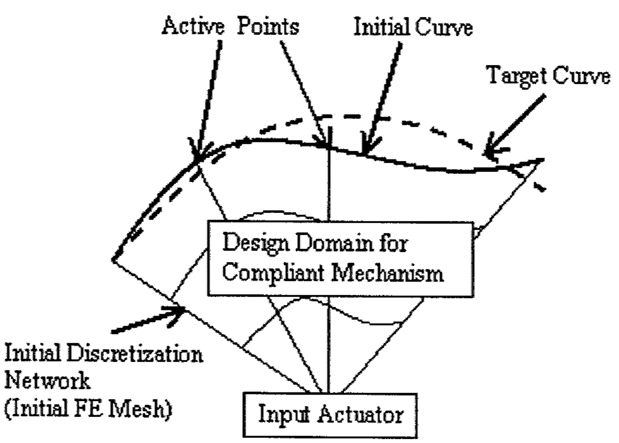

Figure 1: An illustration for a shape change compliant mechanism.

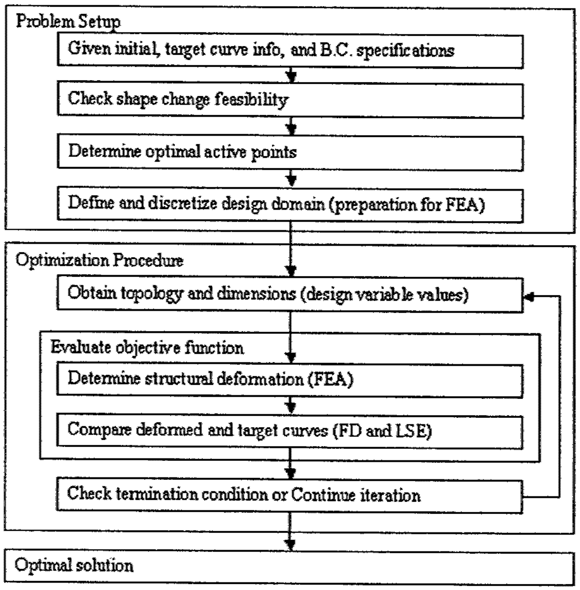

Figure 2: Flowchart for the compliant mechanism synthesis approach.

The flowchart in Figure 2 gives an overview of our synthesis approach. With the problem specifications given, a feasibility check is performed before the synthesis procedure starts to ensure that the desired shape change is attainable. To begin the synthesis procedure, a design domain, which is an area or volume within which the compliant mechanism must fit, is first defined, and a preferred actuator location, and boundary conditions are specified. The design domain is then discretized into an initial grid, where grid nodes are connected with beam elements to form an initial finite element (FE) mesh. When the external actuator is activated, the compliant mechanism undergoes elastic deformation and the shape change boundary changes from its initial shape to a deformed shape, which, ideally, will be the desired target shape after the compliant mechanism is optimized. This structural deformation is calculated using Finite Element Analysis (FEA). To evaluate the effectiveness of the shape change, the deformed and target curves are compared using Least Square Errors (LSE) and a modified Fourier Transformation (FT). The FEA and curve comparison steps are embedded in the optimization procedure, which minimizes the deviation between the deformed and target curves. Due to the discrete nature of topology variables, a genetic algorithm (GA) is adopted to simultaneously determine the optimal topology and dimensions of the compliant mechanism. The optimization problem formulation will be described in more detail following the flowchart.

5.2 Objective Function

After the structural deformation of the compliant mechanism is determined using FEA, the deformed curve is compared to the target curve to evaluate the effectiveness of the shape change. Two curve comparison formulations are investigated in measuring the shape difference between the deformed and target curves. One way to measure the 'deviation' between the two curves is to use the average Euclidian distance between the two curves at the sampling points shown in Figure 3. This is termed as the Least Square Error (LSE) as defined in Equation 1.

$$deviation_{LSE} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_{DEF,i} - x_{TAR,i})^2 + (y_{DEF,i} - y_{TAR,i})^2}\ , \qquad \text{Equation 1}$$

where $(x_{DEF,i}, y_{DEF,i})$ and $(x_{TAR,i}, y_{TAR,i})$ are the coordinates of the sampling points on the deformed and target curve respectively.

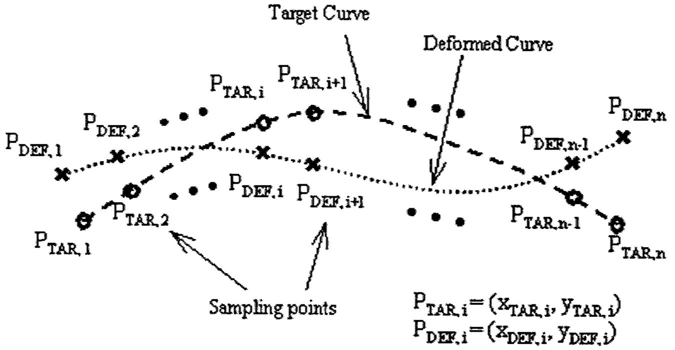

Figure 3: Sampling points on the deformed and target curves.

The second curve comparison scheme uses a modified Fourier Transformation (FT) method that considers both deformed and target curves a period of oscillating signals. Their harmonic amplitudes, AmpDEF and AmpTAR, can be calculated using FT. The shape deviation can then be defined as the sum of amplitude differences at corresponding frequencies, as shown in Equation 2.

$$deviation_{FT} = \sum_{k=1}^{nAmp} | AmpTAR_k - AmpDEF_k |, \qquad \text{Equation 2}$$

where $AmpTAR_k$ and $AmpDEF_k$ is the k^{th} harmonic amplitude for the target and deformed curves relatively, and nAmp is number of amplitudes.

Since the LSE focus on the 'location' differences at the sampling points on the curves, it only provides location and orientation difference of the curves, not the 'shape' deviation. On the other hand, the modified FT measures shape differences between the curves, but it fail to recognize the difference in location and orientation. As seen in Equation 3, in order to capture all aspects of the curves, LSE and FT are combined to form the total deviation of the deformed and target curves. This is also the objective function for this optimization procedure.

$$deviation_{total} = deviation_{LSE} \times deviation_{FT}\ , \qquad \text{Equation 3}$$

5.3 Optimization Model

Objective Function

$$\min(deviation_{total}) = \min(deviation_{LSE} \times deviation_{FT})$$

$$= \min\left(\frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_{DEF,i} - x_{TAR,i})^2 + (y_{DEF,i} - y_{TAR,i})^2} \times \sum_{k=1}^{nAmp}| AmpTAR_k - AmpDEF_k |\right)$$

Constraints

$g1: h_{\min} < h_i \le h_{\max}$

$g2: \sigma_i \le \sigma_{allow}$ for i $\in$ all beam elements

$g3: h_i = hTop_i \times hDim_i$

Due to the binary values in the design variables, a discrete optimization method is implemented to handle these discrete variables. Genetic Algorithm (GA) is one such method, which, as opposed to the gradient-based continuous optimization methods, does not require the sensitivity information of the objective function.

6.0 Design Examples – Adaptive Antenna

6.1 Adaptive Antenna Example

Recent studies [5-7] have shown that antenna reflector adaptation can potentially enhance system performance and increase flexibility, such as changing the signal pattern or coverage area. An examples related to antenna reflector shape change is shown here to demonstrate the feasibility of this compliant mechanism synthesis approach. The problem specification is shown in Figure 4, where the initial parabolic curve is required to be changed into a circular curve. No external loads are presented in this example. The design domain is defined by the initial curve profile and the actuator location. The optimized compliant mechanism in its initial and deformed configurations is shown in Figure 5. As can be seen, the desired shape change is achieved with an input displacement of 5mm in the y-direction.

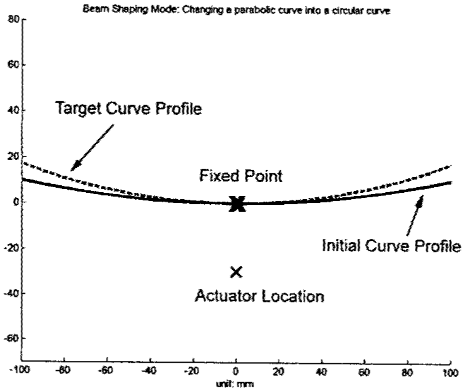

Figure 4: An antenna reflector that changes from a parabolic shape into a circular

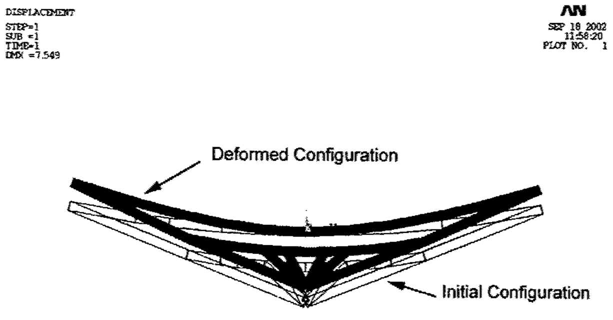

Figure 5: The initial and deformed shapes of the optimized compliant mechanism that changes a

shape.

parabolic boundary into a circular curve.

6.2 Adaptive Wing Surface Example

A closed curve with an external load acting against the desired shape change is considered here as an example to demonstrate the design procedure. As shown in **Error! Reference source not found.**, the curve resembles the leading edge of an airplane wing and the external loads can be considered as the air loads acting on the wing surface. The optimal topology and dimensions of the compliant mechanism is simultaneously determined using the optimization procedure in the synthesis approach presented in this research. The resulting compliant mechanism configuration and its deformed shape are shown in **Error! Reference source not found.**. Note that the result in **Error! Reference source not found.** is obtained from an optimization problem with a different objective function formulation. The deformed and target curves are described using Fourier Descriptors (FDs) with the target curve as the reference shape. Details regarding FDs and the optimization problem formulation for this example can be found in another paper [8].

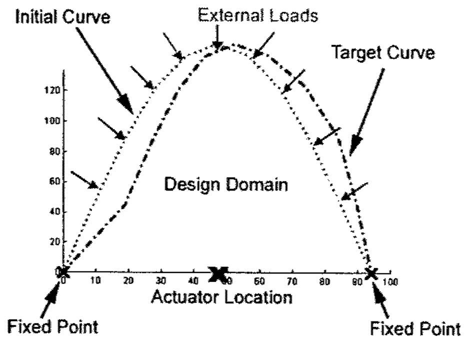

Figure 6: An example of aircraft leading edge shape change with external loads.

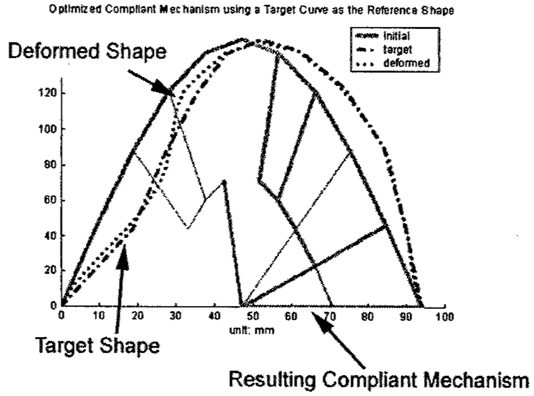

Figure 7: The optimized compliant mechanism for the leading edge example.

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