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FEM Analysis of an Amplified Bidirectional Piezoelectric Actuator for Shape Control of Thermally Distorted Structures

by

Christian van der Horst, *B.Eng. (Electrical),*
School of Computer Science, Engineering and Mathematics,
Faculty of Science and Engineering

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Abstract

Increasingly, engineers are pushing the boundaries of aerospace vehicles to fly at hypersonic speeds of Mach 10. However, flying at these speeds introduces aerothermoelastic problems, since the skin of the hypersonic vehicle is subjected to friction with the hypersonic airstream. As a result, the skin demonstrates deformation as well as melting of the leading edges of the vehicle.

A significant amount of research has been conducted to control this deformation by employing an actuator that is bonded on, or within, the structure. The actuator usually consists of a smart material that is able to change one or more of its properties under the influence of an external stimulus, e.g. electric field, stress or temperature. One of the challenges that arises, is that, under the influence of high temperature, the performance and properties of the smart materials change. Furthermore, the actuator must typically be able to generate sufficient force and displacement in order to compensate for the thermally induced deformation. The generated force and displacement depends on the amount of external stimulus applied to the smart material, as well as the magnitude of actuator authority that the smart material can produce. However, when shape control is applied to aerospace structures, such as a hypersonic vehicle, the possibility to generate a large amount of external stimulus is not always guaranteed. The deformation that occurs when a structure is subjected to thermal loading is bidirectional, forcing the structure to exhibit a displacement orthogonal to the original shape. The challenge arises that most smart materials used for shape control exhibit unidirectional or semi-bidirectional displacements and, therefore, only compensate for shape distortions in one direction. In order to achieve shape compensation of thermally exposed structures, there is a need for a bidirectional actuator that is able to generate large strains and forces to counteract the thermal stress. In this research, two amplified bidirectional actuators are proposed, namely: the Amplified Dual-Stack Actuator (ADSA) and the Amplified Bidirectional Actuator (ABA). The actuators can be mounted to one side of a structure and are able to compensate for the deformation generated by the thermally induced loading. The actuators are self-preloading, which eliminates the need of a preload spring to protect the actuators against tensile stresses. Moreover, the actuators are able to operate under a relatively small external stimulus.

Both actuators consist of a bidirectional actuator that employs two piezoelectric ring-stack elements. The piezoelectric stacks are operated in opposing fashion, i.e. when the first stack contracts, the second extends and vice versa. The displacements generated by the bidirectional actuator are amplified using a diamond-shaped amplifying compliant structure. To identify the actuation performance and thoroughly study the behaviour of the actuators, theoretical calculations and finite element simulations are conducted. A benchmark finite element model is built containing a beam structure that is subjected to thermal loading by two film heaters and is actively compensated using two piezoelectric patches, which are mounted either side of the structure. The compensation performance of the proposed amplified actuators is then identified by mounting the actuators to an identical beam structure as used in the benchmark model.

A comparison of the compensation performance of the ADSA and the ABA against that of the benchmark model, demonstrates that both actuators are able to compensate for shape deformations of the beam structure. The main advantage of the proposed actuators is their ability to generate equal bidirectional displacements to control the shape of a structure, when mounted to only one side of the structure. Furthermore, the actuators are actuated by applying a relatively low electrical field and obtain self-preloading capabilities.

This study servers as a foundation to examine the potential of using amplified bidirectional actuators to control the shape of a hypersonic vehicle, and demonstrates that the proposed actuators show promise to be used for control of bidirectional shape deformations.

List of Abbreviations

1-D	One-Dimensional
2-D	Two-Dimensional
3-D	Three-Dimensional
ABA	Amplified Bidirectional Actuator
AC	Alternating Current
ADSA	Amplified Dual-Stack Actuator
APC	American Piezo Ceramics
APDL	ANSYS Parametric Design Language
BMT	Barium Magnesium Tantalate
BST	Barium Strontium Titanate
BT	Bismuth Titanate
DC	Direct Current
DOF	Degrees Of Freedom
FEM	Finite Element Method
FSDT	First-order Shear Deformation Theory
LiNbO3	Lithium Niobate
MFC	Macro-Fibre Composite
MIMO	Multiple Input Multiple Output
MPC	Multi Point Constraint
NiTiCu	Nickel-Titanium-Copper
Nitinol	Nickel-Titanium Naval Ordnance Laboratory
PID	Proportional Integral Derivative
PVDF	Polyvinylidene Fluoride
PZT	Lead Zirconate Titanate
SMA	Shape Memory Alloy
UX	Displacement in X-direction
UY	Displacement in Y-direction
UZ	Displacement in Z-direction

Certification

I certify that this thesis does not incorporate, without acknowledgement, any material previously submitted for a degree or diploma in any university; and that, to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where due reference is made in the text.

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I dedicate this thesis in honour of my beloved grandfather

Leonardus Hubertus Oijen