ACTIVE PIEZOELECTRIC STRUCTURES FOR TIP CLEARANCE MANAGEMENT

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Background and Objectives

The presentation reviews analytical work which has been conducted in the Structural Mechanics Branch towards the development of smart casing structures with embedded piezoelectric actuators enabling active control of blade tip clearance. The regulation of clearance between the blade-tip and casing is a significant problem for advanced aero-engines. Variations of clearance may occur during a flight cycle, leading to the development of secondary flows, losses of pressure and efficiency if the clearance is too high, or to rubbing between the blades and casing if the clearance is too small. Various factors affecting tip clearance include: deformation of the blades due to changes in rotating speed; distortion of the casing from uneven pressure; thermal deformation of the blades and the casing due to temperature differentials and gradients; and vibrations of the blades, casing and rotor. Consequently, the development of active structures with embedded piezoelectric actuators seems a very promising technology for blade tip clearance management. Such structures have inherent capabilities for deformation and vibration control. Moreover, they are electromechanical systems readily providing electric input and output signals to the actuators and sensors respectively, and can provide compact designs.

Yet, the development of active propulsion structures entails many technical challenges, which should be addressed. They practically involve a new material, the so-called piezoelectric-composite laminate, which is a series of stacked and bonded composite and piezoelectric layers. We need to understand and model the behavior, capture the evolution of new phenomena and characterize the electromechanical response of these piezoelectric laminates. Modeling of realistic structural configurations is also required, which may turn to be a demanding task, as it may involve modeling of complex curvilinear structural configurations with distributed actuators and/or sensors, as well as, addressing the effects of curvature on the performance of piezoelectric actuators/sensors. Variations of temperature will affect the active piezoelectric structure in many ways, thus, the effects of thermal loading should be also addressed. The structural integrity, durability and failure mechanisms of the piezoelectric laminate should be ultimately investigated and understood. Finally, the utilization of smart structures in aero-engines will eventually mandate the solution of multi-disciplinary problems, such as, the interactions between a smart structure and the acoustic field or internal flow in the engine.

Consequently, the objectives of the current research are to develop analytical and computational capabilities for modeling active piezoelectric structures, which encompass effects and conditions which are typical for aero-propulsion applications. Moreover, to apply these models to evaluate the feasibility of active casing structures for controlling the clearance between the blade tips and casing.

Material Relations

The dual behavior of a linear piezoceramic material as an actuator and sensor is described by the two coupled constitutive equations. The first equation describes the behavior of the material as an actuator. In isothermal conditions, the right-hand term of the first constitutive equation (Fig. 4a) shows the strain components in a piezoelectric material which include the mechanical strain and the piezoelectric strain induced by an applied electric field due to the converse piezoelectric effect, respectively. In non-isothermal conditions, thermal strains are also present (Fig. 4b).

The second equation (Fig. 4a) characterizes the behavior of the piezoelectric material as a sensor of mechanical strain or temperature. The right hand side shows the components of electric displacement D (electric charge per unit area) induced by the mechanical stress due to the direct piezoelectric effect, and the electric permittivity (capacitance) of the material, respectively. Thus this equation provides the relationship between stress, temperature and electric field. In non-isothermal conditions a pyroelectric electric displacement component due to the temperature differential is also present.

Modeling of Smart Structures

Starting from the previous material relations and equilibrium equations, rigorous analytical models have been developed for piezoelectric laminates and smart structures with piezoelectric actuators and sensors. A 4-node plate- and an 8-node shell-finite element have been formulated which enable simulations of general structural geometries, laminations and placement of actuators and sensors. The finite elements can provide the static and dynamic response (displacements and electric potential at sensors) of a smart structure subject to application of mechanical loads F, thermal loads F^{th}, electric and pyroelectric charge Q^S and Q^{th} respectively, and electric potentials ϕ^A applied at the actuators (Fig. 5). More details about the mechanics and the finite elements are provided in Refs. 1-2.

Feasibility Studies

Feasibility studies have been performed, using the developed shell finite element on two candidate smart structural concepts: (1) a cylindrical titanium casing ring with curved piezoceramic (PZT-4) actuators and sensors; and (2) a curved flat untwisted Gr/Ep composite blade with symmetrically placed piezoceramic (PZT-4) actuators on the free surface.

Active Cylindrical Casing. A quarter segment of the active cylindrical casing is shown in Fig. 7. It consists of a 2 mm thick titanium layer with four curved piezoceramic actuators each 1 mm thick, and four piezoceramic sensors (0.1 mm thick) attached on the outer surface. Application of the electric voltage pattern shown in Fig.8, will result in the static ovalization of the casing shown in the same Figure and the development of the corresponding voltage pattern at the sensors. Thus the results indicate, that this active casing can self-correct ovalizations with up to 0.5 mm maximum radial deflections, which is significant for tip clearance control.

Application of uniform electric potential (Fig. 9) will force the casing to open, however, the obtained values of uniform radial displacement are low. Thus, other types of actuators or methods should be used to compensate for this type of deformation.

Active Flat Composite Blade. Another way to change the tip clearance, is to develop blades with embedded piezoelectric actuators. To investigate this possibility, a series of flat untwisted [0/45/-45/-45/45/0] Graphite/Epoxy composite blades of various curvatures, with surface attached continuous piezoceramic actuators, were modeled. The thickness of each composite ply and piezoelectric actuator were 0.12 and 0.24 mm respectively. The length of the blade remained constant at 314 mm. Electric potentials of 100 Volts of opposite polarity were applied on each actuator. Fig. 10 shows the combinations of axial in-plane (u) and lateral (w) deflections, normalized by the blade thickness h, at the tip of the blade as the curvature of the blade changes. For an uncurved blade (h/R=0), only lateral deflections can be induced by the actuators. However, as the curvature of the blade (expressed by the inverse of the radius R) is increased, two dimensional tip deflections are developed, which can take substantial values and affect the blade tip clearance. To illustrate the effect of curvature on blade tip position further, two-dimensional deformation plots of the blade are shown in Fig. 11. It is clear that curved blades with piezoelectric actuators can provide two dimensional tip positioning and are more suitable for tip clearance management.

Conclusions

Robust and generalized finite element based mechanics have been developed for active composite structures with piezoelectric actuators, which enable modeling of curvilinear geometries, actuator placement, and include the effects of thermal loads. In this manner, a computational platform is available for the analysis and design of smart casing and blade structures enabling active blade tip clearance control.

Feasibility studies have demonstrated the potential of casings with surface bonded curved piezoceramic actuators to correct tip clearance variations caused by casing ovalization. Additional investigations have shown the feasibility to manage tip clearance with two-dimensional tip positioning in curved flat blades with surface bonded piezoceramic actuators. The same studies have shown the limitation of piezoelectric structures to achieve significant extensional deformations, such as, opening of the casing or elongation of uncurved blades.

References

1. Saravanos D. A. "Coupled Mixed-Field Laminate Theory and Finite Element for Smart Piezoelectric Composite Shell Structures," AIAA J., Vol. 35, No. 8, pp. 1327-1333, 1997; (also NASA CR 198490, 1996)

2. Lee H. J. and Saravanos D. A., "Coupled Layerwise Analysis of Thermopiezoelectric Smart Composite Beams," AIAA Journal, Vol. 34, No. 6, June 1996; (Also, *NASA TM 106889*)

Questions

Q. Could you apply this technology to the leading edge of an inlet

A. Yes you could, the technology is there. It's interesting that you asked that. There's somebody here at the Lab that is working on piezoelectric de-icing techniques for leading edge deicing.

Q. You mentioned something about thermal loads. Is there an upper temperature limit that you run into?

A. Thermal loads gradually affect the properties of piezoelectric materials. At about 360 degrees C, you are losing your piezoelectric effect for this piezoceramic (PZT-4)

Q. So for right now you're saying your limit would be about 360 degrees Centigrade?

A. Absolutely. Maybe even less. For this type of material.

OUTLINE

- PIEZOELECTRIC MATERIAL GOVERNING EQUATIONS
- MECHANICS FOR PLATE LAMINATES WITH EMBEDDED PIEZOELECTRIC ACTUATORS & SENSORS
- MECHANICS FOR CURVILINEAR LAMINATES WITH EMBEDDED ACTUATORS & SENSORS
- FINITE ELEMENTS FOR SMART COMPOSITE STRUCTURES
- NUMERICAL RESULTS & EVALUATIONS

BACKGROUND

- REGULATION OF CLEARANCE BETWEEN BLADE-TIP AND CASING IS A "BARRIER" PROBLEM FOR ADVANCED AERO-ENGINES
  - Secondary Flow
  - Pressure & Efficiency loss
  - Blade-Casing Rubbing, etc...

- FACTORS AFFECTING TIP CLEARANCE:
  - Blade deformation
  - Casing distortion due to uneven pressure
  - Temperature variations & gradients
  - Blade, casing & rotor vibration, etc...

- ACTIVE COMPOSITE MATERIALS/STRUCTURES WITH EMBEDDED PIEZOELECTRIC MICRODEVICES SEEM PROMISING TECHNOLOGY
  - Accurate Deformation Control
  - Adapt Vibratory Response
  - Fast response & wide frequency bandwidth
  - Electromechanically Coupled System
  - Compact design

Fig. 1

TECHNICAL CHALLENGES & NEEDS

- NEW MATERIAL: PIEZOELECTRIC-COMPOSITE LAMINATE
  - <u>Understand</u> and <u>Model</u> behavior
  - Capture new phenomena
  - Characterization
- DEMANDING STRUCTURAL MODELLING
  - Complex (curvilinear) geometries
  - Distributed actuators & sensors
  - Curvature effects on actuators & sensors
- STATIC & DYNAMIC RESPONSE
- THERMAL EFFECTS
- DURABILITY & FAILURE MECHANISMS
- MULTIDISCIPLINARY PROBLEM
  - Acoustic Field
  - Flow

Fig. 2

OBJECTIVES

- DEVELOP ANALYTICAL & COMPUTATIONAL CAPABILITIES FOR ACTIVE PIEZOELECTRIC STRUCTURES
- ADDRESS EFFECTS & CONDITIONS UNIQUE TO AERO-PROPULSION APPLICATIONS (ie. ACTIVE TIP CLEARANCE PROBLEM)
- STUDY AND EVALUATE FEASIBILITY OF ACTIVE PIEZOELECTRIC CASING STRUCTURES FOR TIP CLEARANCE REGULATION

Fig. 3

MATERIAL RELATIONS
(ISOTHERMAL)

- CONSTITUTIVE RELATIONS

$$S_i = (C_{ij}^E)^{-1}\sigma_j + d_{im}E_m$$

$$D_k = d_{kj}\sigma_j + \varepsilon_{km}^{\sigma}E_{km}$$

where:

S_i = Engineering Strain
σ_i = Stress
E_k = $-\partial\varphi/\partial x_k$ (Electric Field)
D_k = Electric Displacement

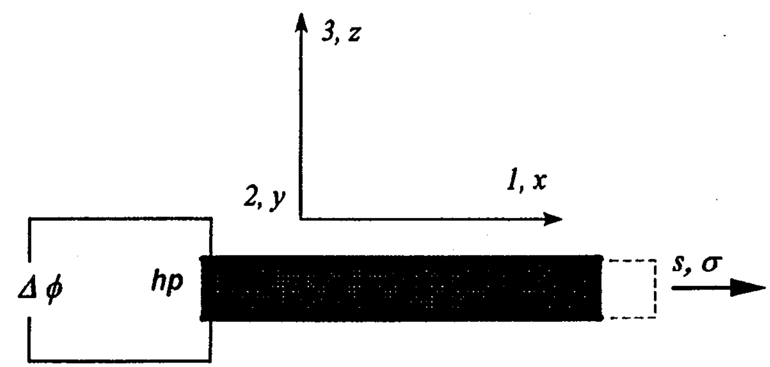


Fig. 4a

MATERIAL RELATIONS
(NON-ISOTHERMAL)

- CONSTITUTIVE RELATIONS

$$S_i = (C_{ij}^E)^{-1}\sigma_j + d_{im}E_m + \alpha_i\Theta$$

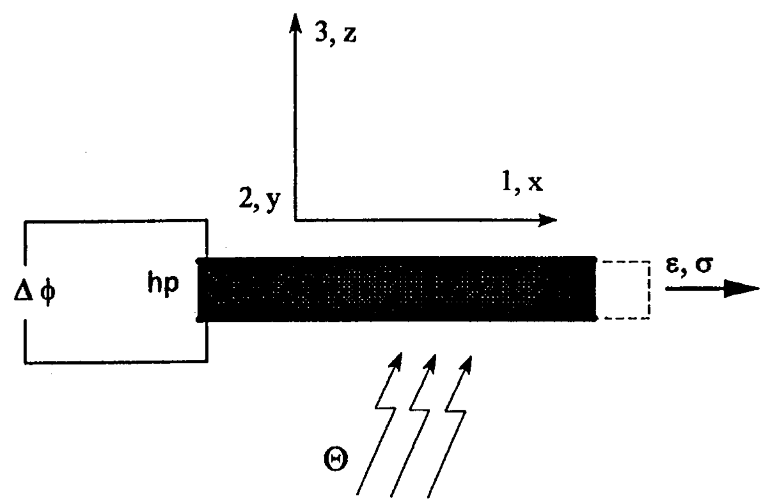
$$D_k = d_{kj}\sigma_j + \varepsilon_{km}^{\sigma}E_{km} + p_k^{\sigma}\Theta$$

where:

Θ = temperature differential

α_i = CTE

p_k = pyroelectric coefficient



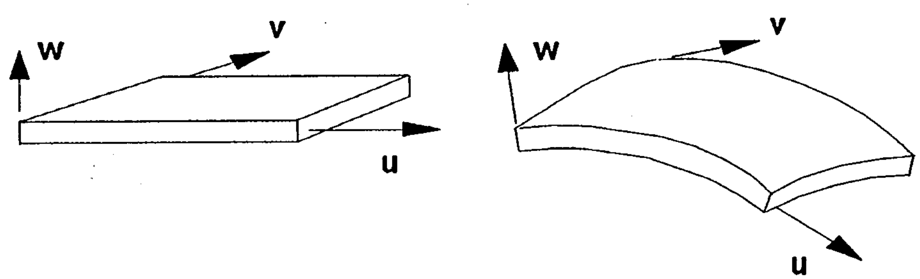
Note:
- Coupled Equations
- Localized Piezoelectric and Thermal Strains

Fig. 4b

SMART STRUCTURES

- FINITE ELEMENT BASED STRUCTURAL SOLUTIONS

(a) plate (4-nodes) (b) curvilinear shell (8-nodes)



- DISCRETE ELECTROMECHANICAL SYSTEM:

$$\begin{bmatrix}[M_{uu}] & 0\\ 0 & 0\end{bmatrix}\begin{Bmatrix}\{\ddot{u}\}\\ \{\ddot{\varphi}^S\}\end{Bmatrix}+\begin{bmatrix}[K_{uu}] & [K_{ue}^{SS}]\\ [K_{eu}^{SS}] & [K_{ee}^{SS}]\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{\varphi^S\}\end{Bmatrix}=\begin{Bmatrix}\{F(t)\}+\{F^{th}(t)\}-[K_{ue}^{SA}]\{\varphi^A\}\\ \{Q^S(t)\}+\{Q^{th}(t)\}-[K_{ee}^{SA}]\{\varphi^A\}\end{Bmatrix}$$

where:
$\{U\}$ = Structural Displacements
$\{\phi^S\}$ = Voltage Output at Sensors
$\{\phi^A\}$ = Voltage Applied at Actuators
$\{F, F^{th}\}$ = Mechanical & Thermal Loads
$\{Q^S, Q^{th}\}$ = Electric & Pyroelectric Charge

Fig. 5

FEASIBILITY STUDIES

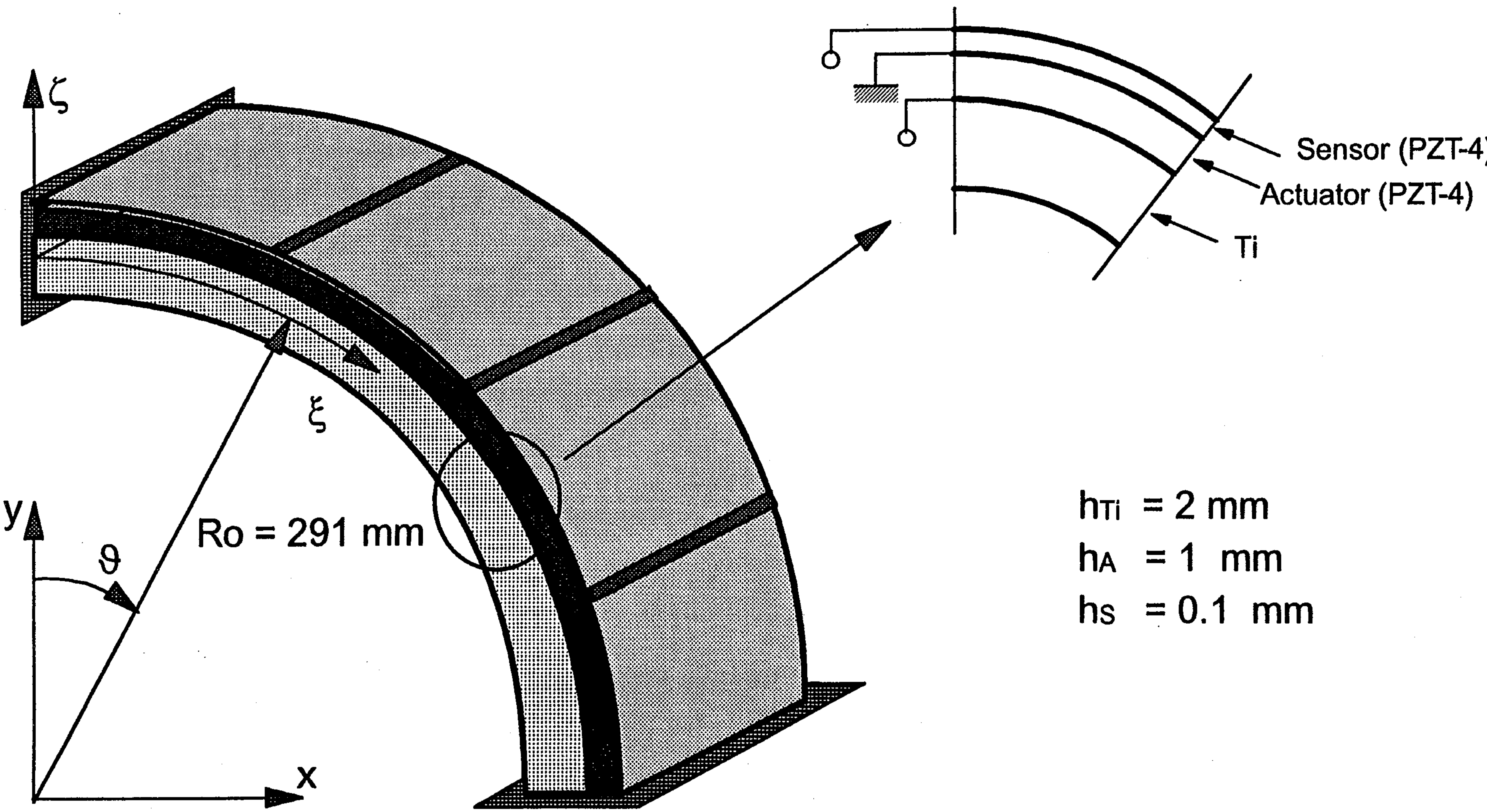
- TITANIUM CYLINDRICAL CASING WITH PIEZOCERAMIC (PZT-4) ACTUATORS
  - Opening
  - Ovalization

- CURVED FLAT COMPOSITE BLADE WITH SYMMETRIC PIEZOCERAMIC ACTUATORS
  - $[p_2/0/45/-45/-45/45/0/p_2]$
  - PZT-4 piezoceramic
  - Gr/Epoxy composite plies

Fig. 6

Cylindrical Casing

Quarter Model



h_{Ti} = 2 mm
h_A = 1 mm
h_S = 0.1 mm

Fig. 7

Active Ovalization

Ti/PZT-4 Cylindrical Casing

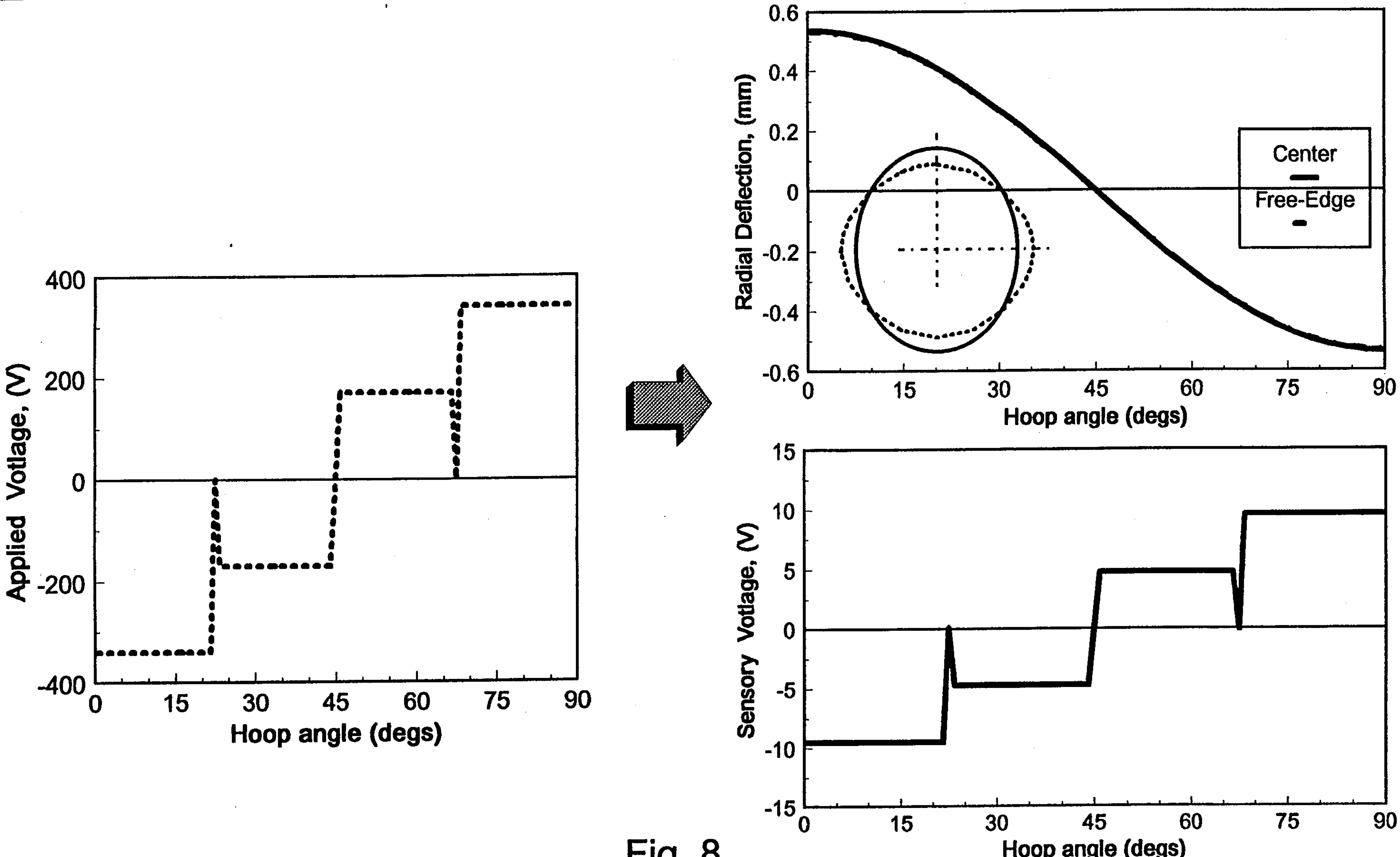


Fig. 8

Active Composite Blade

[p2/0/45/-45]s Gr/Ep & PZT-4

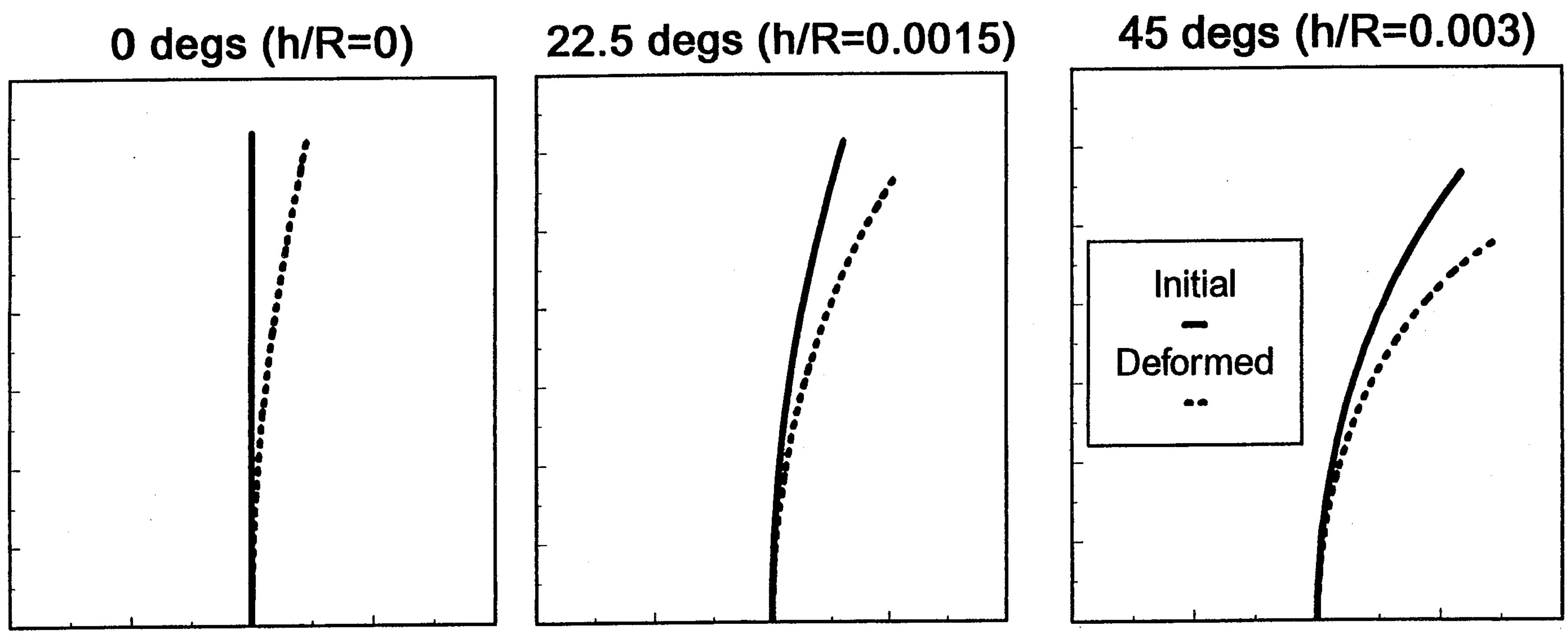


Fig. 11

CONCLUSIONS

- ROBUST & GENERALIZED MECHANICS HAVE BEEN DEVELOPED FOR SMART COMPOSITE LAMINATES & STRUCTURES WITH PIEZOELECTRIC ACTUATORS & SENSORS
  - General Piezoelectric-Composite Laminate Configurations
  - Curvilinear Geometries
  - Thermal Loads
- ANALYTICAL & COMPUTATIONAL PLATFORM FOR BLADE TIP CLEARANCE CONTROL PROBLEM
- INITIAL STUDIES HAVE DEMONSTRATED FEASIBILITY OF:
  - Static & dynamic active casing ovalization with surface bonded curved actuators
  - Static & dynamic two-dimensional tip positioning in curved blades
- LIMITATIONS OF PIEZOELECTRIC COMPOSITES TO ACHIEVE SIGNIFICANT EXTENSIONAL DEFLECTION (ie. CASING OPENING, BLADE EXTENSION)

Fig. 12