AC 2009-1885: INTRODUCING "MEMS" TO UNDERGRADUATE ME STUDENTS

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Introduction

In the past ten years, both industry and research groups have made significant advances in Micro Electro Mechanical Systems (MEMS). These highly promising models and systems have potential for applications in many areas including Mechanical, Electrical and Medical industries. Although MEMS has been introduced for over a decade, many engineering students are unaware of its existence and its associated possibilities in the research, development, and application areas. This paper provides two practical and interesting examples of applications of MEMS. The first one discusses the “Design of a Two-Stage Accelerometer for Automobile Airbags” and the second focuses on the “Design of a Micro-Actuator” that triggers/closes a MEMS Circuit when a change in temperature of **ΔT** occurs. These projects have been designed for sophomore level students. Pedagogical measures have been taken for their realistic effectiveness (nation-wide). Therefore, the framework of the projects has been set at a level that sophomores may succeed in understanding them and developing interest in MEMS. Their imagination will also be challenged. A higher level of details is provided for the first project to serve as a sample of the depth and breadth of information that may be added and transmitted to the students.

Project #1: Design of a Two-Stage Accelerometer for Automobile Airbags

Performance requirements

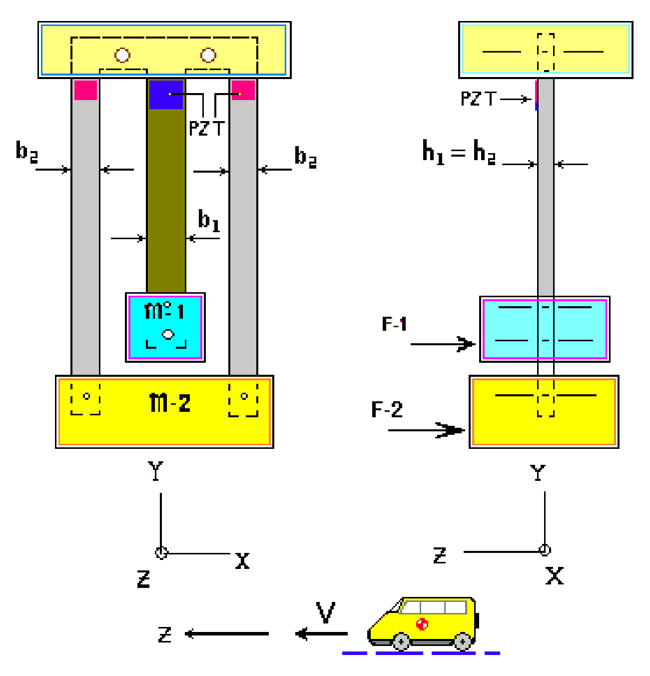
An accelerometer that would deploy a Two-Stage Airbag System with the first stage deployed at a G-Force of ≥ 7*g with a Voltage Range of $6 \le V \le 9$ volts and the second stage deployed at a G-Force of ≥ 12*g with a Voltage Range of $9 \le V \le 12$ volts. The spatial constraints limit the space to a rectangular prism with the dimensions of 3.0 mm deep, 4.50 mm wide and 6.0 mm long.

Design Characteristics

Figure MP-1 illustrates a proposed design for the Two-Stage accelerometer. In this figure, the middle cantilever beam supports a mass (***m – 1***) and the two outside cantilevers form a unified beam by (together) supporting a second mass (***m – 2***). A single sheet of material is utilized to form the two beams (in the shape of an “m”). This arrangement reduces the space required for inclusion of the two independently activated units.

General Description of the System

With reference to the attached coordinate system (in the figure), the vehicle is moving in the Z-direction with a velocity of “V”. In case of a Head-on collision, the masses ***m – 1*** and ***m- 2*** will respectively exert forces equal to $F_1 = m_1 . a_1$ and $F_2 = m_2 . a_2$ on their associated beams. These forces will generate new levels of stress and strain on the beams. Piezoelectric sensors are implanted at the roots of the beams. Since these sensors are an integral part of the beams, they would experience the same levels of stress / strain. At a certain level of deformation, they will generate the necessary level of voltage to activate the switch(es) for deploying the airbag(s).



$m-1$ = Hanging (proof) mass #1

$m-2$ = Hanging (proof) mass #2

PZT = Piezoelectric Sensors

b_1 = width of beam #1

h_1 = depth of beam #1

$b_2 + b_2 = 2\,b_2$ = width of beam #2

h_2 = depth of beam #2

$F_1 = 7.\,g$ = force assigned to beam #1

$F_2 = 12.\,g$ = force assigned to beam #2

$V \leftarrow$ = Velocity and direction (of the movement) of the vehicle

Figure 1 The Proposed Two-Stage Accelerometer

Material of the beams is chosen to be Silicon. This is a typical material of choice for such MEMS applications. Peterson [1] and Madou [2] report the material properties of silicon as listed below:

Table 1 Material Properties of Silicon

E = Young's Modulus of Elasticity	190 GPa
S_U = Ultimate Fracture Strength	7000 MPa
ν = μ = Poisson's Ratio	0.17
ρ = Mass Density	2.30 grams/cm^3
α = Coefficient of Thermal Expansion	2.33 x 10^{-6}/ºC

The Modeling of the Load System

The First Order Model of the Beam and Loading may be characterized by cantilever beams experiencing axial loads (due to the weight of the hanging masses) and the laterally applied forces of $\sum F_i = \sum m_i \,.\, a_i$ (due to the force of the collision). Application of these forces will induce the following types of stresses on the beam(s):

$$\sigma_{\text{Total}} = \sigma_1 + \sigma_2$$

Where:

$$\sigma_1 = \text{Axial Stress} = P/A = mg / A$$

$$\sigma_2 = \text{Flexural / Bending Stress} = M.C / I = F.L.C / I$$

Where:

m = the hanging (proof) mass g = gravitational acceleration A = cross sectional area of the beam M = moment = F. L F = the applied lateral force	L = moment arm / effective length of the beam $I = I_{ZZ}$ = (Second / Area) Moment of Inertia of the Beam { For a rectangular section, $I = (1/12)\, b.\, h^3$ } C = Distance from the Neutral axis to the top /bottom fibers { For a rectangular section, $C = h / 2$ }

Piezoelectric Crystals *VS* Strain Gauges

Piezoelectric Crystals are known to generate voltage due to the application of conventional mechanical forces. Conversely, they would experience deformation if a voltage is applied to them. Similar to alloys of Aluminum and Steel, many natural and synthesized versions of such crystals exist. For our purposes, their behavior may be described as analogous to those of strain gauges. We recall that strain gauges are implanted at critical locations of structural / machine members to collect information about the strain levels induced by the application of externally applied loads. Information on strains will then be used to obtain the existing levels of stress by the use of:

$$\boldsymbol{\sigma = E . \varepsilon}$$

Where: { σ = Stress, E = Young's Modulus of Elasticity, and ε = Strain }.

We limit our choice of crystals to Lead (Pb) Zirconate Titanate (***PZT***). Askeland [3] and Kasop [4] provide valuable information about the unique characteristics of Piezoelectric Crystals. They describe the correlation of the mechanical and electrical effects by the following set of relationships:

Table 2 Correlation of the Mechanical and Electrical effects of Lead Zirconate Titanate (PZT)

///////////////////////	Where:	
$v = \sigma . f$	v = generated Electric field (volts/m) σ = Stress (Pa) ε = Strain (m / m)	d = Piezoelectric Coefficient { for PZT, this value is = 480×10^{-12} m/v } E = Young's Modulus of Elasticity f = a constant = $1/ (E.d)$
$v = \varepsilon/d$		
$E= 1/ (d . f)$		
$f = 1 / (E . d)$		

Analytical Design

We begin by deciding on the actual strength of the chosen material. The fracture strength of silicon is listed by several sources such as [1] and [2] as 7000 MPa [about 20-30 times the strength of many steels]. This extremely high failure stress is contradicted by experience with anisotropically etched diaphragms where failures stresses are estimated to be in the order of 300 MPa [5]. Results of tests provided by Sooriakumar [6] shows that in case of anisotropically etched specimens, the stress concentration factors may rise up to 33 at the sharp corners. Isotropic etching reduces this concentration factor and increases the load carrying capacity. To stay on the safe side, we choose to set the ultimate strength of the material at 300 MPa.

The spatial constraints are both a blessing and a disguise. They limit our freedom of choice on one end but they also set a starting platform for selection of some dimensions. Assuming that the choice of the material will remain unchanged, our problem may be viewed as an iterative process of assigning (manufacturable) values to the parameters $\boldsymbol{m_i}$, $\boldsymbol{L_i}$, $\boldsymbol{b_i}$, $\boldsymbol{h_i}$, and $\boldsymbol{E_i}$.

We will use the same section for the two beams. After several iterations, we arrive at our first promising model that seems to address the Performance Requirements (with the following dimensions and justifications).

Table 3 Material properties and Dimensions of the Components in Iteration #3

Beam # 1	**Beam # 2**
$b_1 =$ 0.100 mm	$b_2 = b_1 =$ 0.100 mm
$h_1 =$ 0.300 mm	$h_2 = h_1 =$ 0.300 mm
$L_1 =$ 2.00 mm	$L_2 =$ 2.50 mm
$m_1 =$ 1.50 grams	$m_2 =$ 2.00 grams
$a_1 = 7 \times g = 7 \times (9.81\ m/s^2)$	$a_2 = 12 \times g = 12 \times (9.81\ m/s^2)$
$E_1 =$ 190 GPa	$E_2 = E_1 =$ 190 GPa
$d_1 =$ Piezoelectric Coefficient $= 480 \times 10^{-12}$ m/v	$d_2 = d_1 =$ Piezoelectric Coefficient $= 480 \times 10^{-12}$ m/v
$\ell_1 =$ Length of the PZT film = 5 μ m	$\ell_2 =$ Length of the PZT film = 5 μ m

Table 4 Analytical Justification of the Proposed Design in Iteration #3

Stage # 1	**Stage # 2**
$A_1 = 3.000 \times 10^{-8}\ m^2$	$A_2 = 2\ A_1 = 6.000 \times 10^{-8}\ m^2$
$\sigma_{\mathbf{Axial}} = P_1 / A_1 = m_1 g / A_1 =$ 0.491 MPa	$\sigma_{\mathbf{Axial}} = P_2 / A_2 = m_2 g / A_2 =$ 0.327 MPa
$I_1 = 1/12\ (b_1 . h_1^3) = 225.0 \times 10^{-18}\ m^4$	$I_2 = 2\ I_1 = 450.0 \times 10^{-18}\ m^4$
$F_1 = m_1 . a_1 = 103.0 \times 10^{-3}$ N	$F_2 = m_2 . a_2 = 235.5 \times 10^{-3}$ N
$M_1 = F_1 . L_1 = 206.0 \times 10^{-6}$ N. m	$M_2 = F_2 . L_2 = 588.6 \times 10^{-6}$ N. m
$C_1 = h_1 / 2 = 150.0 \times 10^{-6}$ m	$C_2 = C_1 = 150.0 \times 10^{-6}$ m
$\sigma_{\mathbf{Bending}} = M_1 . C_1 / I_1 = F_1 . L_1 . C_1 / I_1 =$ 137.3 MPa	$\sigma_{\mathbf{Bending}} = M_2 . C_2 / I_2 = F_2 . L_2 . C_2 / I_2 =$ 196.2 MPa
$\sigma_{\mathbf{Total\text{-}Beam\ \#1}} = \sigma_{\mathbf{TB\#1}} = \sigma_{\mathbf{A}} + \sigma_{\mathbf{B}} =$ 137.8 MPa	$\sigma_{\mathbf{Total\text{-}Beam\ \#2}} = \sigma_{\mathbf{TB\#2}} = \sigma_{\mathbf{A}} + \sigma_{\mathbf{B}} =$ 196.6 MPa
Factor of Safety = F.S. = 300 / 137.8 = 2.177 > 2	Factor of Safety = F.S. = 300 / 196.6 = 1.526 < 2
$\sigma_{\mathbf{TB\#1}} = E_1 . \varepsilon_1 \rightarrow \varepsilon_1 = \sigma_{\mathbf{TB\#1}} / E_1$ $\varepsilon_1 = 725.3 \times 10^{-6}$ (m / m)	$\sigma_{\mathbf{TB\#2}} = E_2 . \varepsilon_2 \rightarrow \varepsilon_2 = \sigma_{\mathbf{TB\#2}} / E_2$ $\varepsilon_2 = 1.035 \times 10^{-3}$ (m / m)
$\Delta L_1 = 1.451 \times 10^{-6}$m $L_{1(Final)} = 2.0015 \times 10^{-3}$m	$\Delta L_2 = 2.587 \times 10^{-6}$m $L_{2(Final)} = 2.5026 \times 10^{-3}$m
$v_1 = \varepsilon_1 / d_1 = 1.511 \times 10^6$ v/m	$v_2 = \varepsilon_2 / d_2 = 2.156 \times 10^6$ v/m
$\boldsymbol{V_1} = v_1 . \boldsymbol{\ell}_1 =$ 7.555 volts 6 < 7.555 < 9	$\boldsymbol{V_2} = v_2 . \boldsymbol{\ell}_2 =$ 10.78 volts 9 < 10.78 < 12

The factor of safety for the second stage is less than 2. This may pose some reliability issues for such a sensitive operation. We may choose to increase the moment of inertia of beam #2 and start another iteration for this stage.

Additional Considerations, Questions and Observations

Although, the targeted audience for this project is the sophomores, they should be alerted to the following additional concerns and observations.

1. It should be obvious that additional beams and masses may be integrated with the system to further graduate the stages of deployment of the Air Bag System.

2. To avoid failure due to Resonance, the natural frequency of each subsystem must be determined and checked against the inherent frequencies of the vehicle when in use. Such frequencies may range from that of the engine, traveled roads, speakers, etc. Assuming that the choice of the material will remain unchanged, the above consideration may play an important role in further adjustment / calibration of the values of mass (m), length (L), and the moment of inertia (I).

3. The effects of the (small) weight of the beam must be taken into account in a Second Order Analysis / Design.

4. The applied force of the collision may be considered an Impact Force (Impulse force). If so, the model for analysis (and design) will take a completely different turn. Of course, the deformations (strains) with the current model will be achieved within the model of Impact Loading. However, in an Impulsive Mode, the deformations will exceed those predicted by the current model (for a fraction of time). This may affect the value of the voltage generated and as a result, the switches must be Robustly designed to handle the side issues raised by this phenomenon. [i.e.: would F_1 activate the circuit of beam #2? Would the voltage caused by F_1 exceed the prescribed range of the voltage for stage #1?]

5. The long-term hanging of the mass over the beam may introduce Creep Effects. This effect may lead to the replacement of the beams with plates where the ***b / L*** ratio is significantly larger.

6. Depending on the line of action / the angle of the impact force, the right/ left side of the mass(es) may absorb the energy more than the other side. This may cause appreciable levels of angular deformations and twist of the mass(es) and their associated beams. Torsional stress and torsional vibration analyses should be conducted to insure the full reliability of the overall system.

7. How would the proof masses be attached to the beams?

8. What sort of micromachining process would be required for creation of the components?

9. How would the electrical network(s) of the PZTs be accomplished?

10. It goes without saying that there is no substitute for a comprehensive testing of the ACTUAL system. However, to control cost, such tests should be performed after the potential system has been realistically simulated through reliable software and theoretically validated.

Software Applications

Working Model (software) may be used to model the system and observe (and analyze) the dynamic behavior of the system in an animated mode. Other Professional engineering tools such as CoventorWare™ may also be used to perform the actual design and further analyses.

An Alternative Design and a Mini-Project

Consider the possibility of using a single prismatic beam / plate and a single mass attached to the free end. The stress / strain at the mid-span would be (about) half as much the stress / strain at the support. We may take advantage of this distribution / ratio and implant two films of PZT at these desired locations to induce the desired range of voltages. Alternatively, we may install three or four films of PZT at desired lengths to increase the number of stages of deployment. The newly generated concern is that of whether the wires coming from each of the PZTs will not rupture before they activate the system.

Project

Considering the above alternative approach, design a Two-Stage Accelerometer that satisfies the original performance requirements. Although you do not possess the full know-how for the use of plates instead of beams, consider the break-even ratio of a beam turning into a plate and perform your Analytical Design using Beam Equations. Conduct research to obtain this break-even ratio. Use SI units and prepare a highly professional report.

The recommended project may be assigned in the following courses:

#	Course	Year	Semester
1	Mechanics of Materials	Sophomore	2nd.
2	Mechanical Design Analysis	Junior	1st.

Upon a comprehensive discussion and coverage of the issues involved in the above project (in the earlier years), the following open-ended project may be assigned in more advanced courses.

Potential (Follow up) Project

Recommended for Assignment in the following undergraduate courses:

#	Course	Year	Semester
1	Introductory MEMs	Junior/Senior	1st. / 2nd.
2	Control Systems	Senior	1st. / 2nd.
3	Mechatronics	Senior	1st. / 2nd.
4	Vibrations	Senior	1st. / 2nd.
5	Computer Aided Design	Senior	1st. / 2nd.
6	Advanced Strength / Mechanics of Materials	Senior	1st. / 2nd.
7	(Modeling) in Advanced Engineering Mathematics	Senior	1st. / 2nd.

Design, Analysis, Manufacturing and Assembly issues for a Two-Stage Accelerometer System for Automobile Airbags has been presented in the above project. A more elegant and comprehensive design however, would address and incorporate the following issues:

1. Is there a passenger in the seat?
2. Is the Seat Belt on?
3. What is the (approximate) weight of the occupant?
4. What should be the volume and the rate of the inflation of the Air Bag based on the magnitude of the G-force applied to the specific occupant?
5. Is it possible to control the shape of (each of) the inflated bag(s) to comply with the line of action of the collision force and in turn with the (reaction) line of the movement of the occupant(s)?

A feed-back control system may be designed to incorporate the above factors. This system would then be able to control the (combination) of the valve opening and the rate of flow of the fluid into the bag (for maximum protection and minimum injury from the Air Bag System itself). Complex geometry and possibly multi-layer bags must be designed to achieve the goal mentioned in issue #5. This level of treatment may be challenged at a culminating Senior Design Project for one or two students.

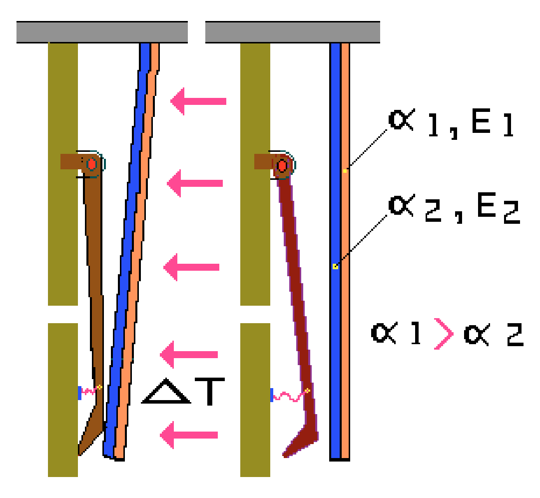
Project #2: Design of a Micro-Actuator

This project is recommended for undergraduate Strength of Material/Mechanics of Materials and Mechanical Design Analysis courses. It explores the design of a Micro-Actuator that triggers/closes a MEMS Circuit when a change in temperature of $\Delta T = +8^\circ C$ occurs. The Gap (G) for closing/triggering the circuit may be set between $90\ \mu m \leq G \leq 110\ \mu m$. The system must have a Life Cycle of 100,000 (Triggers).

Bimetallic strips may be constructed by bonding two different materials ($E_1 \neq E_2$) possessing two totally distinct "Coefficients of Thermal Expansion ($\alpha_2 \neq \alpha_1$)." When the composite experiences a change in temperature, the strip will deform from its original configuration. This change in geometry has found interesting applications for design of Micro-Actuators. Figure 2 illustrates such an arrangement. Bi-layer strips of this kind are commonly used in Micro-actuators such as micro-tweezers by thermal means. The fact that the two strips have distinct thermal expansion coefficients can make the strip curve either upward or downward when it is subjected to temperature rise or drop. This actuated curvature can result in either opening or closing an electric circuit [7].

The following properties of the system must be at hand in order to successfully perform the design. Several sources including Hsu [8] and Boley and Weiner [9] have provided the expressions for the "Interface Force" and the associated "Curvature of the Strip." These equations may be used to obtain the deformation / movement of the composite.

The Interface Force $= F = [b \cdot h \cdot E_1 \cdot E_2 \cdot (\alpha_2 - \alpha_1) \cdot (\Delta T)] / [8 (E_1 + E_2)]$
The Radius of Curvature $= \rho = 2h / [3 (\alpha_2 - \alpha_1)]$
{ Where: **b** and **h** *are properties of the composite's section.* }



α_1 = Coefficient of Thermal Expansion of Material #1

E_1 = Modulus of Elasticity of Material #1

α_2 = Coefficient of Thermal Expansion of Material #2

E_2 = Modulus of Elasticity of Material #2

Δ T = Temperature Change (↑ or ↓)

Figure 2 The use of a bi-layer strip for closing an electric circuit.

The model of the bilayer strip may be easily created in the Pro-Engineer and then transported into ANSYS. For every iteration, new dimensions would be introduced in the solid model at Pro-E and again transported into ANSYS where new material properties (***E & α***) and desired values of (***ΔT***)'s inserted. The animation mode in ANSYS would display the behavior of the composite.

The second recommended project may be assigned in the following courses:

#	Course	Year	Semester
1	Mechanics of Materials	Sophomore	2nd.
2	Mechanical Design Analysis	Junior	1st.
3	Heat Transfer	Senior	1st.

Summary and Conclusions

Advances in design and applications of Micro Electro Mechanical Systems (MEMS) make them an interesting area of exploration in graduate studies of engineering students. Although MEMS has been introduced for over a decade, many engineering students are unaware of its true potential. Two practical examples for applications of MEMS are offered to expose the sophomores in Mechanical Engineering to MEMS. The first one discusses the "Design of a Two-Stage Accelerometer for Automobile Airbags" and the second focuses on the "Design of a Micro-Actuator" that triggers/closes a MEMS Circuit when a change in temperature of **ΔT** occurs. Pedagogical measures have been taken for their realistic effectiveness and the framework of the projects has been set at a level that sophomores may succeed. A sample of the depth and breadth of information that may be added and transmitted to the students is provided in the first project. It is hoped that this approach will create a functional link for generating the initial interest and better understanding of MEMS.

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