Southwest Center for Microsystems Education (SCME)
University of New Mexico

MEMS Fabrication Topic

MEMS Cantilevers Learning Module – Book 2

This booklet contains two (2) Sharable Content Object (SCOs):
Dynamic Cantilever Activity
Terminology and Research Activity

Target audiences: High School, Community College.

Support for this work was provided by the National Science Foundation's Advanced Technological Education (ATE) Program through Grants #DUE 0830384 and 0902411.

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MEMS Applications Topic

Dynamic Cantilever Activity: Resonant Frequency vs. Mass

Shareable Content Object (SCO)

This SCO is part of the Learning Module
MEMS Cantilevers

Target audiences: High School, Community College.

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Dynamic Cantilever Activity: Resonant Frequency vs. Mass

Participant Guide

Description and Estimated Time to Complete

This activity provides a procedure that will allow you to further explore the motion of a cantilever under a varying mass and to determine the relationship that expresses the resonance frequency of a cantilever as a function of mass. This activity simulates the dynamic mode of operation for microcantilevers used in MEMS sensors.

Estimated Time to Complete
Allow approximately 1.5 hours to complete this activity in class. The report will take an additional 2-6 hours depending on your experience and existing knowledge of cantilever operation.

Introduction

In many MEMS applications, a change in the resonant frequency of a cantilever structure indicates a change in the cantilever system mass. The system includes the cantilever structure itself plus any mass added to the structure. For example, in a chemical sensor array (CSA) that contains an array of microcantilevers, target molecules bind with the surface probe molecules of the oscillating cantilevers. This causes a change in the mass of each cantilever system and in turn, their natural frequency of oscillation. These frequencies are monitored and any changes are converted to electrical outputs which represent the amount of accumulated mass on the cantilevers' surfaces.

In this activity, you will simulate a single cantilever of a CSA by adding mass and observing the change in the system's natural frequency.

Activity Objectives and Outcomes

Activity Objectives
- Determine the relationship between the resonant frequency of a cantilever system to added mass.
- Explain the similarities between the physical characteristics of the macrocantilever model and the microcantilever-based chemical sensor array.

Activity Outcomes
Through experimentation, data collection and analysis, you will explore the relationship between mass and its affect on the resonant frequency of a cantilever. At the end of this activity you should be able to answer the following questions:
- How is the natural resonant frequency of a mechanical system affected by the addition of mass?
- How do you determine the frequency of a system from digital video data?
- How do you determine if the Frequency vs. Mass Added relationship is linear or non-linear?

Attitude & Behavior

In this activity, consistency, repeatability, and attention to detail are needed to ensure the most accurate and repeatable outcome.

Team

This activity should be performed in teams of 2 to 3 participants to ensure the best outcome. The multiple tasks for some of the procedure steps require more than one set of eyes and one set of hands; therefore each team should assign a specific task to each individual on the team. These tasks can be rotated at various points in the activity so that all participants experience each part of the experiment.

Materials

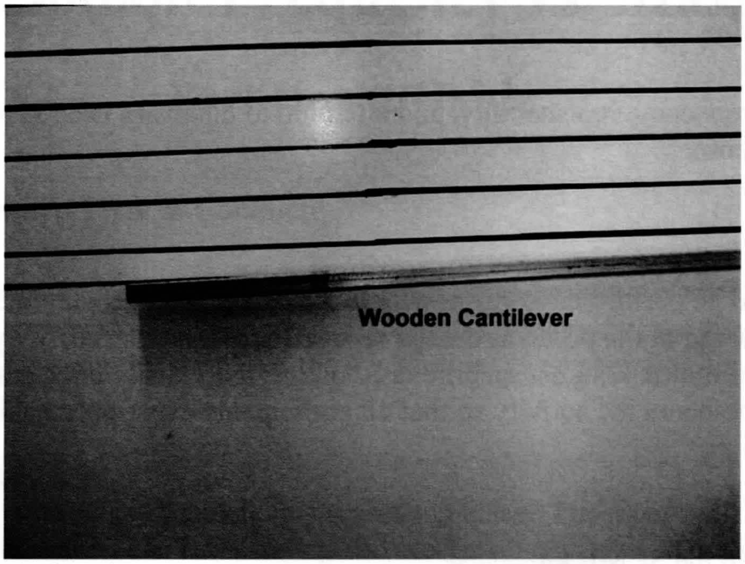
Supplies provided in the SCME kit

- Several sticks of different lengths, widths, thicknesses, and/or materials.
- Clamps (Large enough to clamp the stick to a table)
- Binder clips (unit masses – do not need to weigh as they are all the same and considered *unit masses,* analogous to individual molecules or particles adhering to a micro cantilever sensor).

Supplies provided by the instructor and/or participants

- Digital Camera with video capability – 30 frames/sec is best
- Camera tripod
- Computer with spreadsheet software, Apple QuickTime software, and the software needed to transfer the video files from the camera.
- A sturdy table to clamp the sticks (cantilevers) to.

Preparation/setup



Cantilever in front of white board with reference lines. This activity can be done with any type of individual planks or sticks. The equations apply to any cantilever structure that has a rectangular cross section of thickness, t, width, w and length, l.

This activity can be performed in any classroom with a sturdy flat table and a computer with the required software (see materials). To make recording the data easier, place a background within the field of view that can be used as a reference. Such a device could be a file cabinet, clock, set of window panes, or white board with a few horizontal lines (see picture above). Points on the reference device allow you to better identify the specific points of an oscillation within a video frame.

Before getting started, review the Documentation Supplement at the end of this activity.

Documentation

Write a formal lab report for this activity. Report should include the following components:

- Title
- Author(s)
- Objectives / Abstract
- Introduction (Background and Pre-Lab Questions)
- Materials / Equipment
- Setup Description (Sketch or pictures of the experimental setup)
- Pre-Activity questions / answers
- Procedure: Each procedure step with outcomes where applicable
- Summary of observations and results
- Video to support outcomes
- Data, graphs, tables to support outcomes
- Analysis / Discussion
- Conclusions
- Post-Activity questions / answers
- References (when applicable)

A Formal Lab Report Sample is provided at the end of this activity.

Pre-Activity Questions

1. What is frequency?

2. What is the natural resonant frequency of a system?

3. What do you expect to happen to the natural frequency of the cantilever system as you add mass to it? (Hint: Think of a child vs. an adult on a diving board)

4. Will the natural frequency of the cantilever oscillation increase or decrease with added mass?

5. With your digital camera set for video, how many frames per second does it run?

Procedure: Dynamic Cantilever - Resonant Frequency vs. Mass

The activity allows you to discover a functional relationship through experimentation, data collection and analysis.

Description

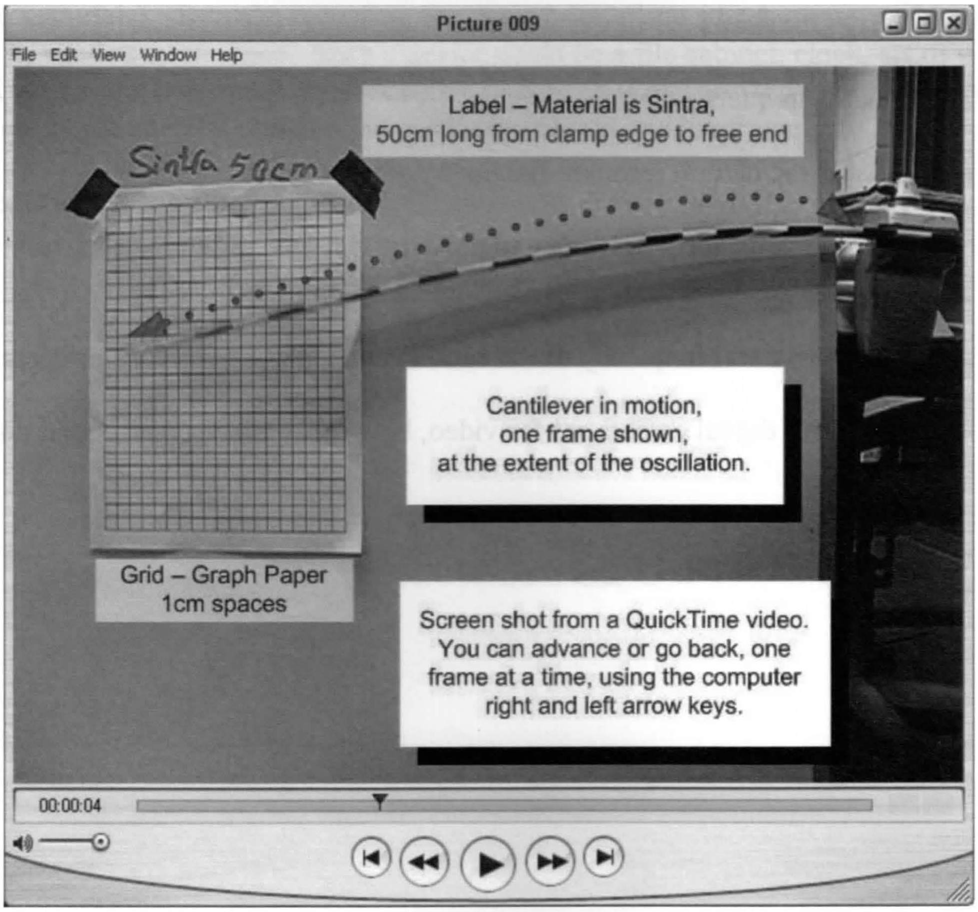
This procedure will use cantilever sticks, clamp(s), binder clips, and a video camera to determine the effect that mass has on the resonant frequency of a cantilever.

Use the Document Supplement and Lab Report sample provided at the end of this activity to help you gather and analyze the outcomes of each step of this procedure.

1. Set up cantilever

Description Place a sturdy table in front of a background within the field of view that can be used as a reference, something with a grid or lines. You can print out graph paper of any specific grid spacing at Incompetech or create your own.

Using the clamp, secure one end of the cantilever stick to the table to make your cantilever system. The length of the meter stick should extend in front of and across your reference device. See figure below.



2. Set up camera

Description Secure the camera in a position that will allow it to record the movement of the cantilever with the reference device as background. A tripod is extremely useful for this task.

3. Record cantilever specifications

Description Record the cantilever's specifications:

- Length between the clamp (fixed) and free end.
- Thickness
- Width
- Type of material

4. System Calibration

Description

- Place the camera on the tripod.
- Put a clock with a second hand in the field of view. (A digital clock that shows seconds could also be used).
- Record (video) the clock for 5 seconds.
- Download the video from the camera to the computer.
- View the video in a viewer (QuickTime, free viewer download) that allows you to step through the video frame by frame.
- Count the number of frames over a five-second interval, second hand iterations. Start counting when the second hand just starts to move (or in the case of a digital camera, as the second number display just starts to change to the next second).

5. Create a data table

Description Create a table using a spreadsheet such as Microsoft Excel in which to record your data. The table should be set up to record frequency as a function of mass added. See example below for a camera having 30 frames per second.

Camera Frames/Second = 30 frames/second, length = 50cm, thickness = 3mm, width = 5cm, material: Sintra			
# clips added	# Oscillations	# Frames	Frequency = Osc/Sec = Hz
Example	5	38	6.33
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Table 1: Frequency as a Function of Mass

6. Record cantilever oscillations with no mass

Description

- Ready the camera to record the first oscillation.
- Start recording.
- Set the cantilever in motion by pushing down (apply force) on the open end of the cantilever, then releasing. This is similar to plucking a guitar string.
- Record for several oscillations – at least 5 complete oscillations should be recorded.

NOTE: This step gives you the data needed to determine the natural resonant frequency for the cantilever before mass is added.

7. Record cantilever oscillations with added mass

Description

- Add a binder clip to the free (suspended) end of the cantilever.
- Start video record.
- Set the cantilever in motion as before.
- Stop the video
- Transfer the video to the computer

Note: Add the masses at the end of the cantilever only, do not spread out the masses over the entire length of the cantilever.

8. Determine the natural resonant frequency of the cantilever system

Description
- View the video segments.
- Note the number of complete oscillations, number of frames associated with this number.
- Calculate the frequency in Hz.

$$f = \frac{(\#oscillations) * (frames/second)}{(\#frames)}$$

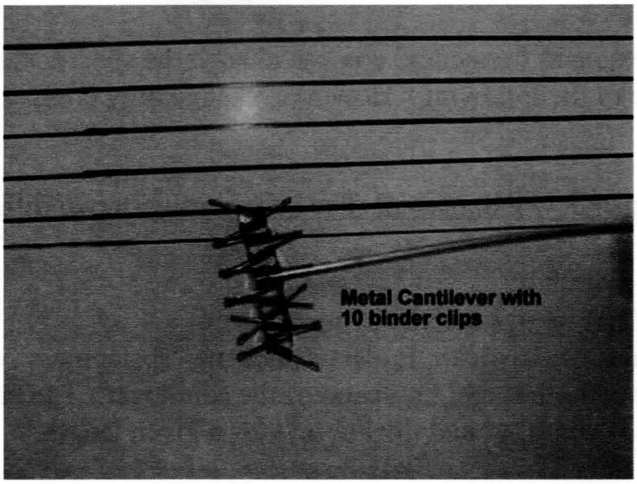
NOTE: If you were unable to get consistent values, evaluate your setup and procedure. Make any necessary adjustments and repeat steps 6 and 7.

9. Record your data

Description Record the raw data for each mass added. (Number of frames per oscillations – you can count the number of frames for several oscillations to get a more accurate value).

10. Repeat steps 7 – 9

Description Repeat steps 7 – 9 for up to 10 binder clips or as many as you can put on the meter stick. Attach all the clips as close as you can to the first one. *(See picture below)*



11. Plot your data

Description When all the data has been collected, plot a line graph that shows the frequency vs. mass added to the cantilever. If you are using Excel, the Chart Wizard makes this step easy. See the documentation supplement at the end of this unit for an example.

12. Complete the documentation requirements

Description Write a formal lab report for this activity. Report should include the following:

- Title
- Author(s)
- Objectives / Abstract
- Introduction (Background and Pre-Lab Questions)
- Materials / Equipment
- Setup Description (Sketch or pictures of the experimental setup)
- Pre-Activity questions / answers
- Procedure: Each procedure step with outcomes where applicable
- Summary of observations and results
- Video to support outcomes
- Data, graphs, tables to support outcomes
- Analysis / Discussion
- Conclusions
- Post-Activity questions / answers
- References (when applicable)

13. Answer all of the Post-Activity Questions and turn in with the report.

Activity Variations – May be required by the instructor in addition to the Frequency Vs Mass added component of this lab.

To further explore the effect that mass has on resonant frequency, you can change the specifications of the cantilever. Repeat this activity for one or more of the following. However, change only ONE specification for each activity.

<u>Use a cantilever stick of a different material – metal, wood, plastic. The kit comes with two different materials.</u>

- Complete this activity with 2 or 3 different materials.
- Discuss the effect that "cantilever material" has on this activity's outcomes.

Note: the material property call Young's Modulus of Elasticity, E, determines the "springiness" of the material. The spring constant, k, is determined by both E and the shape of the cantilever. The equations listed here assumes a rectangular cross section of width, w, and thickness, t for a given length, l.

<u>Frequency vs. length</u>

- Complete this activity with 5 to 10 different lengths of cantilevers.
- Put the data in a table and graph accordingly.
- Discuss the effect that "cantilever length" has on the natural frequency of the system.
- How does this compare to the mathematical model? Can you plot the theory with the measured data on the same graph?
- Plot Frequency vs. Length for at least one cantilever.
- As time permits, acquire data for a cantilever of different thickness, how does the curve change?
- What about a cantilever of different widths? Materials?

Frequency vs. Thickness

- Glue two sticks together to double the thickness, or use a stick of double thickness and having the same width and length. You only want to change one variable at a time. Changing thickness and length or width at the same time will confound your results. Note: Doubling the thickness also doubles the mass! What change in frequency do you expect to see as you double the thickness?
- What about tripling the thickness? How does the frequency change?
- Create a table and graph showing your results.
- Discuss the effect that "cantilever thickness" has on the resonant natural frequency of the system. How does this compare to theory (equation)? Try to plot the predicted results with the actual data.

Post-Activity Questions

1. Does the graph of frequency vs. mass added represent a linear relationship (is it a straight or curved line)? What do you predict from the equation?

2. Is the frequency decreasing or increasing with added mass? Why?

3. Based on the graph of your actual data, how would you state the relationship between frequency and mass added? In other words, is it an inverse relationship? Inverse squared? Inverse square root? Squared? Direct proportion?

4. Your frequency vs. mass added graph (number of clips) can be used to determine the mass of an unknown sample. Say you add several coins to the end of the cantilever and determine the frequency of the system. How would you determine the mass of the coins in "clip units" from the graph?

5. Study the MEMS Cantilever unit on Chemical Sensor Arrays (CSA) *(if you haven't already)*. Write a short discussion on how this activity simulates a dynamic mode CSA. Discuss how you could "tune" your sensor for a given situation. For example, if you wanted to make the cantilever work in a lower frequency range, how would you change its design?

   Ideas for discussion:
   a. How could you tell how much additional mass has been added to the cantilever based on the observed frequency shift? (Take a look at your curve. Imagine you are reading a shift in the output of a CSA, how would you determine the amount of material adhered to the cantilever?)
   b. How would you adjust the cantilever length and/or thickness to make the resonance match an off the shelf electronics package? This is critical in design since designing a new electronics package in addition to a cantilever device becomes more costly.

6. What effect does the cantilever's material have on its frequency? (Prove your answer using the E (Young's Modulus) for at least 3 different materials). Note: E is usually given in units of GPa, or Giga Pascal's – this is a pressure and stress unit, force/area. Definition of a Pascal:

7.

$$1Pa = \frac{1kg}{m * s^2} = 1\ N/m^2$$

For most materials, E is given in GPa or kN/mm^2

E = 9.6GPa for Sintra, a type of PVC Foam. This was determined assuming a $1.4g/cm^3$ density, 3mm thickness, 50cm length, 5cm width and measuring a 2.5Hz resonant frequency for this cantilever at this length.

   a. What would happen to the frequency if the cantilever was made of Aluminum, having an E=69GPa and density $\rho = 2.7g/cm^3$?
   b. What about steel which has an E = 200 GPa and density $\rho = 7.9g/cm^3$?
   c. And one of the stiffest materials, diamond, E=1220 GPa and density $\rho = 3.5g/cm^3$?

8. Based on the following equation, what variables affect a cantilever's frequency?
    a. Does density?
    b. Length?
    c. Width?
    d. Thickness?
    e. Young's Modulus of Elasticity?

$$\omega_0 = 2\pi f_0 = \sqrt{\frac{k}{m}}$$

where

$$k = \frac{Et^3w}{4l^3}$$

Note: Omega (ω) is in radians per second and frequency is in cycles or oscillations per second. There are 2π radians in one cycle.

Summary

This activity simulates the output of a cantilever in a dynamic mode Chemical Sensor Array. The binder clips represented unit masses such as molecules, viruses, DNA snippets, proteins, and antibodies that attach to the surface of the cantilevers. As these molecules attach to each of the cantilevers' surfaces, the cantilevers' effective mass changes resulting in a change in resonant frequency. The change in resonant frequency indicates a change in the concentration of target material in the sample being evaluated or the amount of time the cantilevers were exposed to the sample environment.

Dynamic Cantilever Activity – Documentation Supplement

As part of the Dynamic Cantilever Activity: Resonant Frequency Vs. Mass, this supplement will assist you in

1) gathering the correct data for your laboratory report (documentation), and
2) clarifying what is to be included in your lab report (documentation template provided).

Before starting on this Lab, you should answer the Pre-Activity Questions.

To obtain accurate data, you will be acquiring data through the use of a video camera or a digital camera with video capabilities. You will capture video for each experiment, and then review it frame by frame to determine the resonant frequency of the dynamic cantilever system. It is highly recommended that you go through the steps of data acquisition and analysis at least once before acquiring all the video and then trying to analyze it.

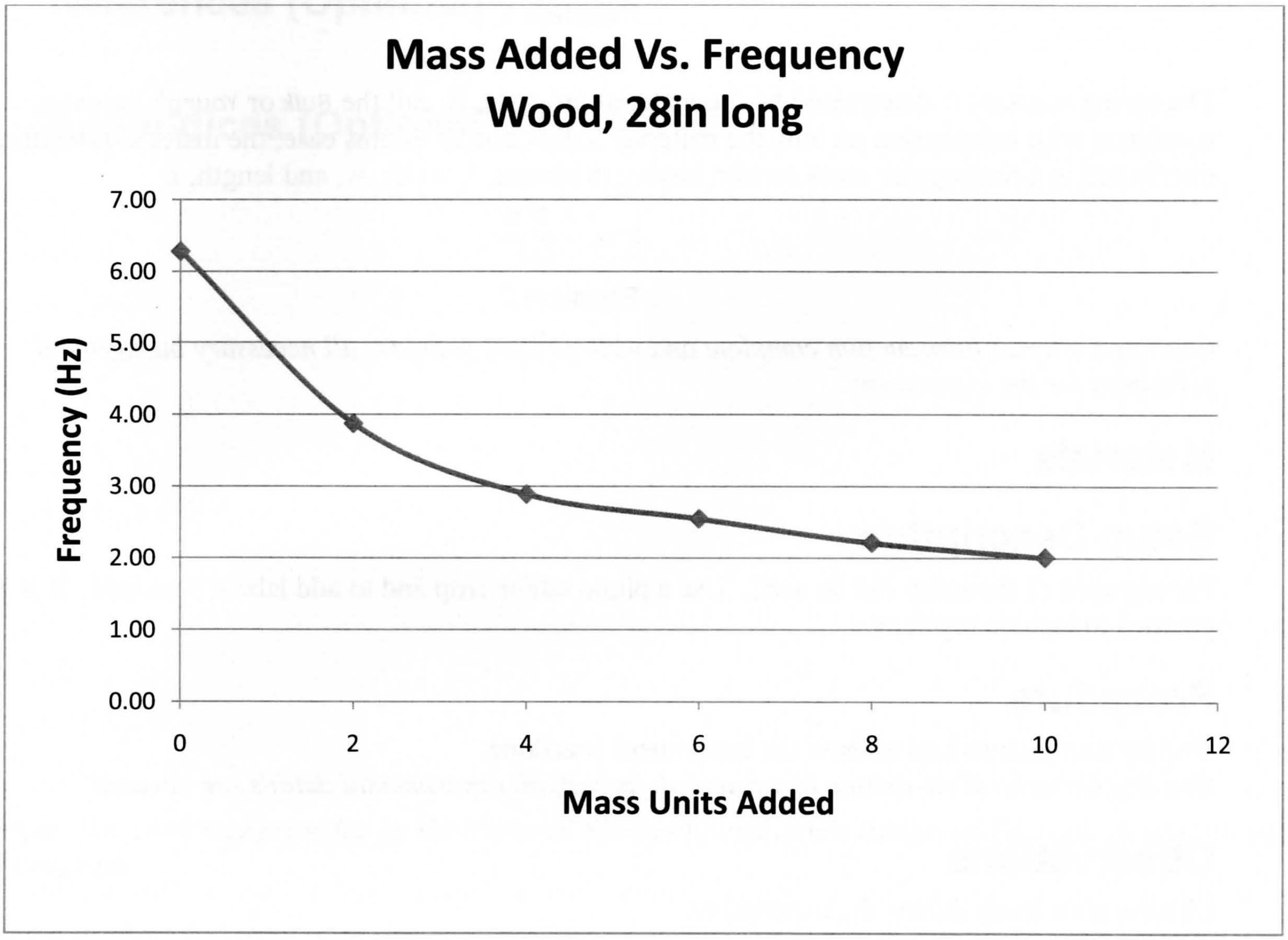
Follow the steps in the Procedure section of this activity.

To determine frequency, you need to combine the number of oscillations observed, the number of frames counted for those number of oscillations and knowledge of the frame rate of your camera. The frame rate can be easily found by capturing several seconds of a watch and counting the number of frames for a given number of seconds, and then calculating frames/second.

Below are examples of chart and data tables that illustrate the outcomes of a similar experiment.

Experimental Run Number:	2
Material:	Wood
Length:	28in
Thickness:	t
Width:	w
Camera Frames / Sec:	30

Wood Video File	# Clips Added	Number of Oscillations	Number of Frames	Wood Frequency (Hz)
1588	0	9	43	6.28
1598	2	8	62	3.87
1599	4	5	52	2.88
1600	6	5	59	2.54
1601	8	5	68	2.21
1602	10	5	75	2.00



Title

Authors

Grading Criteria: All sections in order, well-formatted, very readable. All grammar/spelling correct and very well-written

Objectives or Abstract

Grading Criteria: Abstract contains reference to all major aspects of carrying out the experiment and the results, well-written. Should not be more than 250 words.

Introduction (Background and Pre-Lab Questions)

Here you can include some of the background related to this experiment including theory and equations.
Frequency is related to the spring constant of the system, k, and the system's mass:

$$\omega = 2\pi f = \sqrt{\frac{k}{M}}$$

Equation 1

The spring constant is determined by the material property, E, call the *Bulk* or *Young's Modulus*, combined with information on how the material is distributed. In this case, the material is uniformly distributed in a rectangular cross section having thickness, t, width, w, and length, l.

$$k = \frac{E\,t^3 w}{4l^3}$$

Equation 2

Grading Criteria: Introduction complete and well-written; provides all necessary background principles for the experiment

Materials

Setup Description

Photographs of the setup can be used. Use a photo editor crop and to add labels if needed. It is good practice to include captions.

Procedure

Step by step instructions on how the experiment was done.
Grading Criteria: Well-written in paragraph format, all experimental details are covered

Observations

Observations made during the experiment.

Data Tables, Graphs

Collection of tables and graphs. Label all tables and make sure the reader knows what each represents. Graph axes must be labeled clearly, units included and graphs containing multiple data sets must include clear legends. Graphs should have captions summarizing what is being shown. Graphs and Tables need to have Figure and Table numbers so that the author(s) can reference the graphs in the text.

Grading Criteria: All figures, graphs, tables are correctly drawn, are numbered and contain titles/captions.

Analysis/Discussion

This is where the author(s) summarize the graphs and tables in text. "From figures xx and yy we see that as the cantilever has mass added to it, the resonance frequency of the system decreases in a non-linear manner as is expected from Equation 1 above."

Grading Criteria: All important trends and data comparisons have been interpreted correctly and discussed, good understanding of results is conveyed

Conclusion

Grading Criteria: All important conclusions have been clearly made, student shows good understanding

References (Optional)

Appendices (Optional)

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MEMS Fabrication Topic

MEMS Cantilevers Terminology and Research Activity

Shareable Content Object (SCO)

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MEMS Cantilevers

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MEMS Cantilevers Terminology and Research Activity

MEMS Cantilevers Learning Module
Participant Guide

Description and Estimated Time to Complete

In this activity you demonstrate your understanding of MEMS Cantilevers terminology and how MEMS cantilevers work in a real application. This activity consists of two parts:

- A **crossword puzzle** that tests your knowledge of the terminology and acronyms associated with MEMS Cantilevers, and
- **Post-activity questions** that ask you to demonstrate a better understanding of MEMS cantilevers and their applications.

If you have not reviewed the reading materials in the MEMS Cantilevers Learning Module, you should do so before completing this activity.

Estimated Time to Complete
Allow at least 1 to 1.5 hours to complete this activity.

Introduction

A cantilever is a type beam which is supported and constrained at only one end. Based on this description the wings of most aircrafts, balconies of buildings and certain types bridges are cantilevers. Free standing radio towers, anchored to the ground, suspended upwards without cables are also cantilevers. Of course the most familiar cantilever is a diving board.

Cantilevers come in all sizes. The previous examples range in length from a few meters to hundreds of meters. In contrast, MEMS cantilevers can be as thin as a few nanometers with lengths that range from a few microns to several hundred microns. MEMS cantilevers are used in micro transducers, sensors, switches, actuators, resonators, and probes. As transducers, microcantilevers are operated in the static and the dynamic modes.

The microcantilever is one of the cornerstone components of microsystems. It is used in a wide variety of applications including micro-chemical sensor arrays, atomic force microscopes, microswitches, needles and atomic force probes.

Activity Objective

Activity Objectives

- Identify the correct terms used for several definitions or statements related to MEMS cantilevers.
- Research and discuss the operation of a specific MEMS application that incorporates a microcantilever or microcantilever array.

Resources

SCME's MEMS Cantilevers Learning Module.

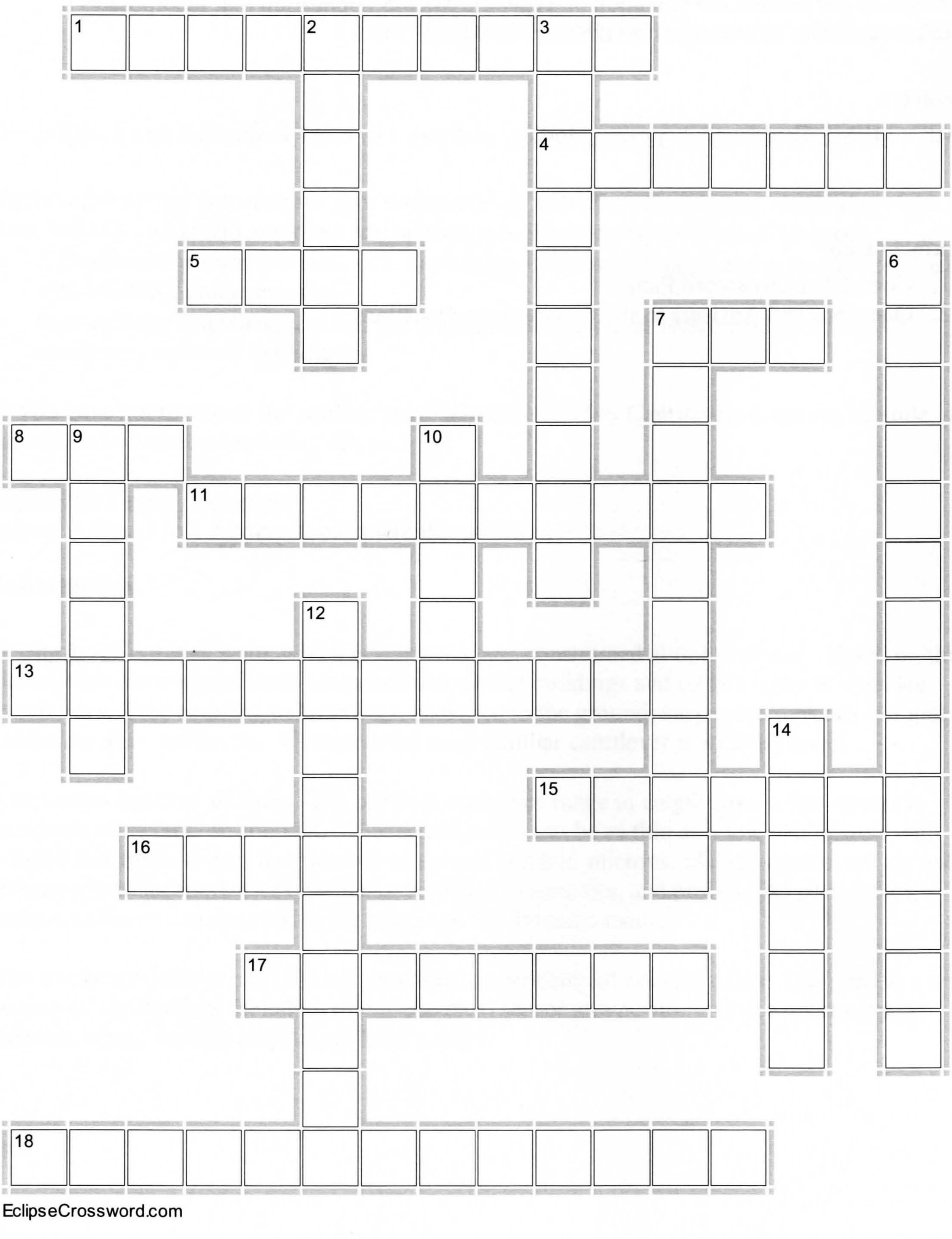
Documentation

1. Completed Crossword Puzzle
2. Questions and Answers to the Post-Activity Questions

Activity: MEMS Cantilevers Terminology

Procedure:

Complete the crossword puzzle using the clues on the following page.



Across

1. A system which transforms one form of energy (mechanical) to another (electrical) or vice versa, is called a __________
4. A substance or chemical constituent that is undergoing analysis or being measured.
5. One one-thousands of a micron (micrometer) is a ______ meter
7. Abbreviation for the type of microscope which can measure down to the atomic forces.
8. Chemical Sensor Array - abbr.
11. The incorporation of a substance in one state into another of a different state (e.g., gas molecules entering into a liquid, or liquid into a solid).
13. A cantilever based sensor system used in static mode measures the bend or flex by detecting a change in the angular ________________ of a light beam, for example.
15. Microsystems applications in the biological and medical fields are also referred to as _________
16. Cantilever are used in RF application. The "R" stands for _________
17. The frequency at which an object vibrates naturally is also called the _________ frequency. It is the frequency at which a system oscillates when struck.
18. The type of actuation used in many MEMS devices, including the cantilever. Hint: Of or related to electric charges at rest or static charges

Down

2. For an object that obeys Hooke's Law, the _____________ constant is defined as the force needed to stretch a structure per unit extension (N/m)
3. Young's modulus of _____________
6. When stress is applied to these materials, the resistance changes. This is called a ___________ material or effect.
7. ___________ is the adhesion of molecules to a surface.
9. A cantilever can vibrate or just bend. When we measure the change in the frequency, we are using the cantilever system in dynamic mode. When we measure the amount that a cantilever bends, we are measuring the change in _________ mode.
10. Cantilever __________ coating on which the target molecules or particles stick.
12. A suspended beam fixed at one end.
14. A device or system which measures an environmental factor such as pressure, pH, amount of a certain gas in the air, microphone, chem lab on a chip, etc.

Post-Activity Questions

1. List at least three MEMS applications of microcantilevers.
1. Briefly describe the two methods of transduction measurement used in static mode microcantilevers (how is the bend measured?)
2. Research a specific MEMS that incorporates a microcantilever component which is used as a transducer or sensor. Describe the application, function, and limitations of this device. Your write-up should include, but is not limited to the following criteria.
    a. Application – What does it do, what is it use for, and who uses it?
    b. Operation – Physical description (i.e., size, components) and how does it work?
    c. Limitations and Versatility – What is its specificity (if any)? How versatile is it? (i.e., Is it adaptable for fields other than the one described?) What are its limitations (e.g., sample size, sample type)?

Summary

MEMS cantilevers are used for a wide variety of applications. The specific application defines the best geometric shape of the cantilever, and the material from which it should be made. These two parameters define the structure's stiffness characteristics (spring constant). The MEMS cantilever is a cornerstone component used in a wide variety of microsystems including micro-chemical sensor arrays, atomic force microscopes, microswitches, and neural probes.

Several of these MEMS applications operate the cantilever in either a static or a dynamic mode of operation.

- The static mode is when the cantilever is in a static state (stationary). Any displacement of the cantilever due to a load or intrinsic stress generated on or within the cantilever is measured.
- The dynamic mode is when the cantilever is externally actuated causing the cantilever to oscillate at its natural resonant frequency. Any change in the load or mass of the cantilever results in a change in this frequency. The change in frequency is measured and can be related back to the change in load.

Several factors are considered when determining the mode of operation. Such factors can include the operational environment (e.g., ambient pressure, liquid samples), cost, size, and logic interface.

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