FINAL SCRIPT: APPROVED FOR FILMING

Submission ID #: 68141
Scriptwriter Name: Sulakshana Karkala
Project Page Link: https://review.jove.com/account/file-uploader?src=20783053

Title: Investigating the Potential of Singly Curved Thin Piezoelectric Transducers for Energy Harvesting and Structural Health Monitoring

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Author Questionnaire

1. **Microscopy**: Does your protocol require the use of a dissecting or stereomicroscope for performing a complex dissection, microinjection technique, or something similar? **No**

2. **Software:** Does the part of your protocol being filmed include step-by-step descriptions of software usage? **No**

3. **Filming location:** Will the filming need to take place in multiple locations? **Yes, 12 km apart**

    Videographer: please note that
    Locations are

    1. CSIR-CRRI 1.1, 1.3, 1.4, 1.6,

    2. IIT Delhi.1.2, 1.5, 1.7, Entire protocol (Section 2)

Current Protocol Length
Number of Steps: 14
Number of Shots: 28

Introduction

Videographer: Obtain headshots for all authors available at the filming location.

1.1. **Aleena V Krishnanunni:** The main scope of our research is to comprehensively evaluate our newly invented sensor: concrete vibration energy harvester (CVEH) as compared to the existing sensor: concrete vibration sensor (CVS) for energy harvesting and Structural Health Monitoring.

1.1.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B.roll:3.1*

Videographer's Note: C0011 is the test shot; C0012 is the final take

What are the most recent developments in your field of research?

1.2. **Suresh Bhalla:** Recent advances include low-cost innovatively designed sensors like CVS, CVEH and trapezoidal variant that can replace expensive accelerometers for full 3D modal analysis and integrated seamlessly with AI-ML, and UAV technologies.

1.2.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B.roll:2.2*

Videographer's Note: C0020 is the standing final take, C0025 is the sitting final take

What technologies are currently used to advance research in your field?

1.3. **Naveet Kaur:** In our view, the futuristic sensing technologies are AI-ML integrated with piezoelectric sensors, fibre optics and vision-based sensing. Sensor fusion and Internet of Things holds a great promise for future.

1.3.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.

Videographer's Note: C0006 is the final take

What are the current experimental challenges?

1.4. **Aleena V Krishnanunni:** The main challenge is the development of stand-alone PEH powered autonomous miniature cloud centric data acquisition systems qualifying IoT sensing in true sense .

1.4.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.

Videographer's Note: C0015 is the final take

What significant findings have you established in your field?

1.5. **Suresh Bhalla:** Our new invention CVEH, endowed with a novel topology-based design, backed by principles of mechanics, dramatically boosts energy harvesting several folds and also excels in SHM , based whether on global or local vibrations.

1.5.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.
Videographer's Note: C0029 is the final take

Videographer: Obtain headshots for all authors available at the filming location.

Testimonial Questions (OPTIONAL):

Videographer:

- ***Please ensure that all testimonial shots are captured in a wide-angle format, while also maintaining sufficient headspace, given that the final videos will be rendered in a 1:1 aspect ratio.***
- ***Also, kindly note that testimonial statements will be presented live by the authors, offering their spontaneous perspectives.***

How do you think publishing with JoVE will enhance the visibility and impact of your research?

1.6. **Naveet Kaur , Senior Scientist, CSIR-Central Road Research Institute (CRRI), New Delhi, India** (authors will present their testimonial statements live): When I first came to know about this journal, I was delighted to know that something like this journal also exists. We strongly believe that the our work published in this journal will have much more outreach among our peers and will surely pave way for new collaborations in future.

1.6.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.
Videographer's Note: C0010 is the final take

Can you share a specific success story or benefit you've experienced—or expect to experience—after using or publishing with JoVE? (This could include increased collaborations, citations, funding opportunities, streamlined lab procedures, reduced training time, cost savings in the lab, or improved lab productivity.)NK

1.7. **Suresh Bhalla, Professor (Higher Administrative Grade), Indian Institute of Technology (IIT) Delhi, India**: (authors will present their testimonial statements live): Visual form always offers quicker understanding. Hence, we expect more derivative research stemming out.

1.7.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.
Videographer's Note: C0030 is the final take

Protocol

2. Energy Harvesting and Storage Using Piezoelectric Transducers

Demonstrator: Aleena V Krishnanunni

~~2.1. To begin, use M5628-P2*(M-Five-Six-two-Eight-P-Two)* variant of the piezoelectric material, placing it in straight and curved configurations to cast the CVS *(C-V-S)* and the CVEH *(C-V-E-H)* sensors **[1-TXT].**~~

~~2.1.1. WIDE: Talent holding the two sensors and symbolically showing the configuration of the piezoelectric material in each sensor. **TXT: CVS: Concrete Vibration Sensor; CVEH: Concrete Vibration Energy Harvester**~~

~~2.2. Then cast a reinforced concrete beam using M30 grade concrete **[1-TXT]**. During casting, tie the concrete vibration energy harvester and the concrete vibration sensor to the top layer compression reinforcement of the beam, ensuring that their top surfaces align with that of the beam **[2]**.~~

~~2.2.1. Talent casting a reinforced concrete beam using M30 grade concrete.**TXT: Dimensions: 1500 mm [L] × 300 mm [B] × 100 mm [D]**~~
~~**NOTE: Deleted by authors**~~

~~2.2.2. Talent symbolically showing configuration.~~

NOTE: Shots were not filmed due to a patent issue. Authors also left note saying shots could be deleted

2.3. To begin, confirm that the electrical connections of the piezoelectric transducers remain protected throughout the casting process. Then, position the reinforced concrete beam in a supported setup with an effective span of 1100 millimeters for experimental testing **[1]**.

2.3.1. Shot of the experimental setup

Videographer's Note: C0057 is the final take; C0058 is the tight close of the beam

2.4. Next, position a shaker at one third length of the beam **[1]**.

2.4.1. Talent positioning the shaker at one third length of the beam
Videographer's Note: Use C0033

2.5. Now connect the concrete vibration sensor and concrete vibration energy harvester outputs to two channels of an oscilloscope **[1]**. Fix an accelerometer with a sensitivity of 100 millivolts per g at the mid-span of the beam **[2].** Then connect it to an ICP *(I-C-P)* amplifier **[3]**.

2.5.1. Talent connects CVS and CVEH to 2 channels of a oscilloscope.

2.5.2. Talent installing the accelerometer at mid-span of the beam.

2.5.3. Talent connecting the accelerometer to an ICP amplifier.
Videographer's Note: C0035 is the final take for 2.5.1-2.5.3

2.6. Excite the reinforced concrete beam using the shaker in sweep mode and conduct the frequency domain analysis of the responses from the concrete vibration sensor, concrete vibration energy harvester and accelerometer **[1-TXT].**

Added shot: Shot of the desktop showing the frequency domain analysis
Videographer's Note: C0053 is the final take

2.6.1. Shot of the experimental setup. **TXT: Excite beam between 25 Hz to 85 Hz; Step Interval: 15 Hz; Keep shifting shaker position to L/2 and L/6**
Videographer's Note: C0037 is the final take

2.7. Next, position an eccentric rotary-type shaker at a quarter of the beam length from the nearest support **[1]**. Connect and set up a speed controller to regulate the shaker **[2]**.

2.7.1. Talent positioning the shaker at one-fourth the beam's length from the nearest support.
Videographer's Note: C0054 and C0055 is the final take; C0056 is wide shot of shaker at mid level

2.7.2. Talent connecting and setting the speed controller.
Videographer's Note: C0037 is the final take

2.8. To analyze the power generated by piezo transducers, first prepare a power measurement circuit by connecting two resistors, R_1 *(R-one)* and R_2 *(R-Two)*, in series across the piezo sensors **[1-TXT]**. Connect a oscilloscope across R_1 to monitor the output voltage V2 *(V-two)* **[2]**. Voltage readings are displayed in the oscilloscope **[3]**.

2.8.1. Talent assembling the power measurement circuit with labeled R1 and R2 resistors.**TXT: R_1 = 335 kΩ and R_2 = 340 kΩ**
Videographer's Note: C00040, 41 and 43 are the final take

AND

Added shot : Close up shot of the circuit

2.8.2. Talent connecting a oscilloscope across R1.

2.8.3. Shot of an oscilloscope connected displaying live voltage readings.

2.9. Start the shaker to induce vibrations in the reinforced concrete beam and adjust the

acceleration using the speed controller **[1]**. Using the oscilloscope record the output voltage V_2 from each sensor **[2-TXT]**. Then calculate the power generated by each sensor at the different acceleration levels **[3]**.
Videographer's Note: Same as above as stated by authors

2.9.1. Talent turning on the shaker and gradually increasing the speed.

2.9.2. Shot of the oscilloscope capturing voltage output for each sensor.**TXT: Repeat vibration test for 2 or more shaker accelerations**

2.9.3. TEXT ON PLAIN BACKGROUND:

$$P = i^2(R_1 + R_2)$$

(3)

$$i = V_2 / R_1$$

Where i is the current flowing through the circuit.

2.10. To assess the power storage potential of the piezo transducers, setup the experimental apparatus without the power measurement circuit **[1].** Replace it with a simple full-bridge rectifier circuit **[2]**.

2.10.1. Shot of prepared experimental setup.

2.10.2. Talent disconnecting the resistor network and attaching a rectifier module to the sensors.
AUTHOR'S NOTE: Move shot 2.10.2 above 2.10.1
Videographer's Note: C0044: Divided in two parts. Part A - Talent disconnecting the resistor network; C0045: part b - attaching a rectifer module to sensors

Added shot: close-up shot of the capacitor
Videographer's Note: Use C0047
Video editor: please add the label " Capacitor for charger"

2.11. Start the shaker and induce vibrations in the reinforced concrete beam **[1].** Adjust the acceleration of the shaker using the speed controller **[2]**.
Videographer's Note: C0052 : final take

2.11.1. Shot of the shaker being started and the RC beam undergoing vibrations.

2.11.2. Talent adjusting speed of the shaker with the speed controller.
Added shot: C0051 : Tight shot of Bat circuit

2.12. Using the oscilloscope, measure and record the output voltage V_c *(V-C)* from the rectifier circuit for both sensors **[1]**. Calculate the total energy stored and the average power stored in the capacitor for both sensors using the given equations **[2]**.

2.12.1. Shot of oscilloscope measuring rectified voltage from both sensors.

Videographer's Note: C0050 :Final take

2.12.2. TEXT ON PLAIN BACKGROUND:

$$E_T = \frac{1}{2} C V_c^2$$

$$P_{avg} = \frac{E_T}{T_c}$$

Where *C* is the capacitance (1000 μF), and T_c is the total charging time of the capacitors

2.13. For structural health monitoring, connect an LCR meter to the desktop for the measurement of electrical admittance signature **[1].** Place a digital thermometer to ensure that a uniform room temperature is maintained throughout the experiment **[2]**.
Videographer's Note: C0065 :Final take

2.13.1. Talent connecting the LCR meter with the sensors.

2.13.2. Talent placing the digital thermometer.

2.14. Excite the sensors by applying a harmonic electric potential across them at high frequencies in sweep mode with the LCR meter **[1]**. Then induce damage in the beam by drilling holes one by one **[2].**

2.14.1. Shot of the desktop showing the readings.
Videographer's Note: C0060 :Case-1: Final take, C0062: Case 2- Final take
AND
TEXT ON PLAIN BACKGROUND:
Use two frequency ranges:
Case 1: Coarser frequency range of 1 kHz to 1000 kHz with a step interval of 1 kHz
Case 2: Finer frequency range of 100 kHz to 300 kHz with a step interval of 100 Hz

Video Editor: Please play both shots side by side

2.14.2. Shot of a hole being drilled into the beam.
Videographer's Note: C0066 :Final take

Results

3. Results

3.1. In the frequency domain, the peak frequency was identified at approximately 55 Hertz for both transducers and the accelerometer **[1]**, confirming the natural frequency of the beam **[2]**.

3.1.1. LAB MEDIA: Figure 6C. *Video editor: Highlight the peak of both the red dashed and black curves around 55*

3.1.2. LAB MEDIA: Figure 6D. *Video editor: Emphasize the single large peak in the orange plot around 55 on the frequency axis.*

3.2. In sinusoidal excitation, CVEH generated a consistently higher voltage than CVS over the same time interval **[1-TXT]**. Across various excitation frequencies and shaker positions, CVEH consistently produced a higher open circuit voltage than CVS, particularly at one-third and halfway positions from the beam support **[2]**.

3.2.1. LAB MEDIA: Figure 7A. *Video editor: Highlight the red dashed waveform (Curved)* **TXT: CVEH: Concrete Vibration Energy Harvester; CVS: Concrete Vibration Sensor**

3.2.2. LAB MEDIA: Figure 7B. *Video editor: Emphasize the bars corresponding to shaker at L/3 and L/2*

3.3. The power generated by CVEH increased substantially with acceleration, with power ratios rising from 8.36 at 15.19 meters per second squared **[1]**, to 13.01 at 21.68 meters per second squared **[2]**.

3.3.1. LAB MEDIA: Figure 8A. *Video editor: Highlight the red waveform (CVEH)*

3.3.2. LAB MEDIA: Figure 8C. *Video editor: Highlight the red waveform (CVEH)*

3.4. At a mid-point acceleration of 4.89 meters per second squared, CVEH charged the capacitor in 236 seconds **[1]**, compared to 335 seconds by CVS **[2]**.

3.4.1. LAB MEDIA: Figure 9A. *Video editor: Highlight the point on the red curve (CVEH) reaching the dashed line at 236 s.*

3.4.2. LAB MEDIA: Figure 9A. *Video editor: Highlight the black curve (CVS) reaching 1.6 volts later at a time close to 335 seconds.*

3.5. At a higher acceleration of 8.84 meters per second squared, CVEH stored 8.65 microwatts of power **[1]**, approximately 1.68 times that of CVS at 5.14 microwatts **[2]**.

3.5.1. LAB MEDIA: Figure 9C. *Video editor: Highlight the taller striped bar labeled 8.6 under "Curved" for 8.84 m/s².*

3.5.2. LAB MEDIA: Figure 9C. *Video editor: Highlight the shorter solid brown bar labeled 5.1 under "Straight" for 8.84 m/s².*

3.6. For structural health monitoring, deviation from baseline admittance signatures was more pronounced in the CVEH **[1]** than in the CVS, especially after successive damage stages **[2]**.

3.6.1. LAB MEDIA: Figure 10A. *Video editor: Emphasize the dashed curves for "1st damage" , "2nd damage" and "3rd damage"*

3.6.2. LAB MEDIA: Figure 10C. Video editor: Emphasize the dashed curves for "1st damage" , "2nd damage" and "3rd damage"

3.7. The root mean square deviation values between healthy and damaged stages were consistently higher in the CVEH than in the CVS for both conductance **[1]** and susceptance **[2]**.

3.7.1. LAB MEDIA: Figure 12A. *Video editor: Highlight the first three brown bars under "Curved" for 1st, 2nd, and 3rd damage stages showing values of 57, 77, and 34.*

3.7.2. LAB MEDIA: Figure 12B. *Video editor: Highlight the corresponding bars under "Curved" showing RMSD values of 67, 91, and 40.*

Pronunciation Guide:

1. Piezoelectric
Pronunciation link:
https://www.merriam-webster.com/dictionary/piezoelectric
IPA: /ˌpaɪ.əˌzoʊ.ɪˈlɛk.trɪk/
Phonetic Spelling: pie-ə-zo-i-lek-trik

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2. Transducer(s)
Pronunciation link:
https://www.merriam-webster.com/dictionary/transducer
IPA: /trænsˈduː.sɚ/
Phonetic Spelling: trans-DOO-ser

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3. Harvester
Pronunciation link:
https://www.merriam-webster.com/dictionary/harvester
IPA: /ˈhɑːr.və.stɚ/
Phonetic Spelling: HAR-vuh-ster

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4. Accelerometer
Pronunciation link:
https://www.merriam-webster.com/dictionary/accelerometer
IPA: /əkˌsɛl.əˈrɑː.mə.tɚ/
Phonetic Spelling: ak-sel-uh-ROM-uh-ter

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5. Admittance
Pronunciation link:
https://www.merriam-webster.com/dictionary/admittance
IPA: /ədˈmɪt.əns/
Phonetic Spelling: ad-MIT-uhns

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6. Susceptance
Pronunciation link:
https://www.merriam-webster.com/dictionary/susceptance
IPA: /səˈsɛp.təns/
Phonetic Spelling: suh-SEP-tuhns

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7. Topology
Pronunciation link:
https://www.merriam-webster.com/dictionary/topology
IPA: /təˈpɑː.lə.dʒi/
Phonetic Spelling: tuh-POL-uh-jee