ENERGY HARVESTING FROM VARIABLE STIFFNESS PIEZOLAMINATED PANELS IN HYGROTHERMAL ENVIRONMENT

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by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

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- Dedicated to my beloved parents-

- Smt Seema Shukla and Shri Krishna Murari Shukla

- and my wife-

- Priya

CERTIFICATE

This is to certify that the thesis entitled **"Energy harvesting from variable stiffness piezolaminated panels in hygrothermal environment"** being submitted by **Mr. Rishabh Shukla** to the Indian Institute of Technology Delhi for the award of degree of **Doctor of Philosophy** in Applied Mechanics is a record of original, bonafide record of research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or in full, to any other university or institute for the award of any degree or diploma.

Date: 10^{th} July, 2025

Place: New Delhi

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Rishabh Shukla

Abstract

As the world is advancing through environment-friendly solutions to all the big problems, need for the technology to address the concern is the priority for researchers, scientists etc., working in different areas. One such technology that has been in focus for the past few decades is energy harvesting from ambient or structural vibration. The technology requires the use of smart materials like piezoelectric to convert mechanical stimuli into electrical output. The electrical output can be voltage, power etc. As the vibrations are always present in mechanical, civil or aerospace structures, the technology utilizes these vibrations to power different sensors and micro electromechanical devices thus reducing the cost of installation and maintenance of a large number of batteries. These mechanical-to-electrical signals can also be used for monitoring the condition of machines and structures. As the technology was well established during previous decades, researchers are now more focused on the parameters and the causes which affect the performance of energy harvesting. These parameters either affect the stiffness or inertia of the structure. It is not possible to develop prototypes for every geometrical or material modification to analyze the energy harvesting characteristics, the task of numerical modelling of these harvesters becomes very important. This the-

sis presents the numerical modelling of a piezolaminated composite energy harvester. The use of curvilinear fiber composite has been greatly explored by researchers in the efficient design of the composite structures and tailoring the characteristics of the structure for different applications like aerospace, marine etc. The use of curvilinear fiber in piezolaminated composite energy harvester is explored in this thesis work and it has been found that the curvilinear fiber possesses the potential to tailor make the energy harvesting characteristics of the bimorph variable stiffness laminated composite (VSCL) energy harvesters. The variation in the angle of fiber path throughout the panel makes it a continuously varying stiffness structure. This varying stiffness tailors the resonance or tuning frequency and power harvesting characteristics. Thus fiber path variation brings a unique method of tailoring the characteristics without the addition of any inertia or mechanism attachment. Due to this, composite structures are widely used in weight-sensitive applications like aerospace, marine structures etc. The analysis is performed in the frequency domain, as it is the steady-state response which is the closed-to-reality measure of power output from structures subjected to periodic ambient vibration. The characteristics that have been reported are voltage Frequency response function (FRF), Power FRF, and Motion FRF for fundamental resonance conditions. The effect of fiber path in laminate and aspect ratio of the plate on these characteristics are also studied. The composite structures and energy harvester can be made to operate in environmental conditions which are different from the normal ambient conditions. In such a situation, elevated moisture and temperature conditions can affect the performance of piezolaminated composite structure. It has been observed in the study that, due to exposure to elevated temperature and moisture conditions, the stiffness of the composite structure decreases. Thus it affects the resonance frequency and harvesting characteristics like Voltage, Power and Motion FRFs. A detailed study has been presented in the thesis. The results are shown for both plate and shell panels subjected to elevated hygrothermal conditions. The variation of these FRFs with external resistance when the structure is excited at short and open circuit conditions is also studied. One more issue that has been widely reported in laminated composite structures is the presence of delamination in the interface of laminae. Delamination affects the vibration response of the structure. In the present work, the effect of delamination size and location on the energy harvesting characteristics is investigated. The study also reveals the importance of using curvilinear fiber for the improved performance of a delaminated energy harvester. The location of delamination also affects the response of the energy harvester significantly. These responses can be used to detect the presence of delamination in the structure thus allowing preventive measures before the catastrophic failure of the structure.

There is a growing trend of utilizing the properties of the meta structures like auxetic honeycomb structures for better durability of structure as well as the desired vibration response. The research in this field can be categorized as a modification of structure for tailored responses. In the current study, the energy harvester is modelled with an auxetic honeycomb as a core covered with the VSCL facesheets. The VSCL facesheets provide additional scope to further tailor the energy harvester characteristics for better performance. The effect of unit cell geometry of auxetic honeycomb core combined with the fiber path of VSCL facesheets is investigated. Throughout the work, the finite element method based on the first-order shear deformation theory (FSDT) is used to model the harvester. The theory is computationally efficient with fair accuracy for the

सारांश

यह शोध–कार्य दुनिया में पर्यावरण–अनुकूल समाधानों के प्रति बढ़ती प्रवृत्ति के बीच उभरती एक उन्नत तकनीक पर केंद्रित है—वाइब्रेशन से ऊर्जा प्राप्त करना। यह तकनीक पीजोइलेक्ट्रिक जैसे स्मार्ट मैटेरियल्स का उपयोग करती है, जो यांत्रिक उत्तेजना को विद्युत ऊर्जा में बदलते हैं। चूंकि यांत्रिक, सिविल या एयरोस्पेस संरचनाओं में कंपन हमेशा मौजूद होते हैं, यह तकनीक इन कंपन को विभिन्न सेंसर्स और माइक्रो–इलेक्ट्रोमैकेनिकल उपकरणों को ऊर्जा प्रदान करने के लिए उपयोग करती है, जिससे बैटरियों की आवश्यकता और रखरखाव की लागत में कमी आती है। यह विद्युत ऊर्जा—जैसे वोल्टेज या पावर—संरचनाओं की निगरानी में भी उपयोगी होती है। चूंकि प्रौद्योगिकी पहले से ही विकसित हो चुकी है, अब शोधकर्ताओं का ध्यान उन मापदंडों की ओर अधिक है जो इसकी प्रदर्शन क्षमता को प्रभावित करते हैं, जैसे संरचना की कठोरता या जड़ता। विभिन्न ज्यामितीय या सामग्री आधारित संशोधनों के लिए प्रोटोटाइप बनाना हमेशा संभव नहीं होता, इसलिए इन हार्वेस्टर्स का संख्यात्मक मॉडलिंग आवश्यक हो जाता है। इस शोध में एक पीजोलैमिनेटेड कंपोज़िट एनर्जी हार्वेस्टर का मॉडलिंग प्रस्तुत किया गया है। वक्राकार फाइबर कंपोज़िट का उपयोग संरचनाओं के गुणों को विशेष अनुप्रयोगों जैसे एयरोस्पेस या नौसेना के अनुसार अनुकूलित करने के लिए पहले ही काफी अध्ययन किया जा चुका है। इस शोध में पाया गया कि वक्राकार फाइबर पाथ के कारण कठोरता में सतत परिवर्तन आता है, जिससे रेज़ोनेंस फ्रीक्वेंसी और ऊर्जा प्राप्ति क्षमता को बदला जा सकता है, बिना किसी अतिरिक्त यांत्रिक प्रणाली या भार के। यह विश्लेषण फ्रीक्वेंसी डोमेन में किया गया है क्योंकि यह कंपन के स्थिर अवस्था की प्रतिक्रिया को दर्शाता है, जो शक्ति आउटपुट का यथार्थ प्रतिनिधित्व करता है। रिपोर्ट किए गए गुणों में

वोल्टेज एफ आर एफ, पावर एफ आर एफ, और मोशन एफ आर एफ शामिल हैं। फाइबर पाथ और प्लेट के आयाम अनुपात के प्रभाव का भी विश्लेषण किया गया है। इसके अलावा, जब यह संरचनाएं उच्च तापमान और आर्द्रता वाली परिस्थितियों में कार्य करती हैं, तो उनकी कठोरता में कमी आती है, जिससे उनकी ऊर्जा प्राप्ति क्षमताएं प्रभावित होती हैं। यह शोध प्लेट और शेल पैनलों के लिए ऐसे हाइग्रोथर्मल स्थितियों के प्रभाव को दर्शाता है। शॉर्ट और ओपन सर्किट परिस्थितियों में बाह्य प्रतिरोध के साथ एफ आर एफ के परिवर्तन का भी अध्ययन किया गया है। अंततः, शोध में लैमिनेटेड कंपोज़िट संरचनाओं में डिलैमिनेशन की समस्या पर भी ध्यान दिया गया है। डिलैमिनेशन की स्थिति और आकार वाइब्रेशन प्रतिक्रिया को प्रभावित करता है, जिससे ऊर्जा हार्वेस्टर की कार्यक्षमता बदलती है। वक्राकार फाइबर का उपयोग डिलैमिनेशन वाले हार्वेस्टर की प्रदर्शन क्षमता में सुधार करता है। इन प्रतिक्रियाओं का उपयोग संरचना में डिलैमिनेशन की पहचान के लिए किया जा सकता है जिससे संभावित विफलताओं को पहले ही रोका जा सके। स्ट्रक्चर की बेहतर टिकाऊ क्षमता और इच्छित कंपन प्रतिक्रिया प्राप्त करने के लिए मेटा–संरचनाओं, जैसे ऑक्सेटिक हनीकॉम्ब संरचनाओं के गुणों का उपयोग करने की प्रवृत्ति बढ़ती जा रही है। इस क्षेत्र में अनुसंधान को संरचना में संशोधन के रूप में वर्गीकृत किया जा सकता है ताकि उत्तरदायित्वों को अनुकूलित किया जा सके। वर्तमान अध्ययन में, ऊर्जा हार्वेस्टर को ऑक्सेटिक हनीकॉम्ब कोर के साथ मॉडल किया गया है, जिसे वी एस सी एल फेसशीट्स से ढका गया है। वी एस सी एल फेसशीट्स ऊर्जा हार्वेस्टर की विशेषताओं को बेहतर प्रदर्शन के लिए अनुकूलित करने के अतिरिक्त अवसर प्रदान करती हैं। इस कार्य में, ऑक्सेटिक हनीकॉम्ब कोर की यूनिट सेल ज्यामिति और वी एस सी एल फेसशीट्स के फाइबर पाथ के संयुक्त प्रभाव का अध्ययन किया गया है। पूरे अध्ययन में, फर्स्ट आर्डर शीयर डिफॉर्मेशन थ्योरी (एफ एस डी टी) पर आधारित फाइनाइट एलिमेंट विधि का उपयोग करके हार्वेस्टर का मॉडलिंग किया गया है। यह थ्योरी कंप्यूटेशनली कुशल होती है और पतली एवं मध्यम मोटाई की प्लेट और शेल पैनल संरचनाओं के कंपन प्रतिक्रियाओं के लिए उचित सटीकता प्रदान करती है।

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