

Modeling and Design of MEMS Devices

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Indian Institute of Technology Delhi
September, 2022

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Modeling and Design of MEMS Devices

by

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Submitted

in fulfilment of the requirements of the
degree of

Doctor of Philosophy

to the



**Indian Institute of Technology Delhi
September, 2022**

To Nabi Sir

Certificate

This is to certify that the thesis entitled “**Modeling and Design of MEMS Devices**”, submitted by **Ananya Roy** to the Indian Institute of Technology Delhi, for the award of the degree of Doctor in Philosophy in Electrical Engineering, is a record of the original, bonafide research work carried out by her under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

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, to the best of my knowledge.

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Acknowledgements

I would like to express my heartfelt gratitude to Dr. S. Janardhanan, my research supervisor. Without his assistance and wise counsel, this work would not have been feasible.

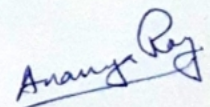
I would like to express my heartfelt and appreciation to my research supervisor Late Dr. Mashuq-un Nabi. The work presented in this thesis would not have been possible without his persistent support, direction, and patience.

I would also like to give special thanks to my student research committee members for their support and valuable comments: Prof. I. N. Kar, Prof. Anima Nagar and Prof. N. Senroy. I will always be indebted to the other faculty and staff members of Electrical Engineering Department of IIT Delhi for their assistance and support.

I could not have accomplished this work without help of several individuals. Especially my lab mates and friends.

Last, but certainly not least, I would want to express my gratitude to my family: my mother, father, and sister, for their unwavering support, encouragement, and presence throughout my difficult period.

Finally, I want to express my gratitude to the almighty God for his blessings, which enabled me to complete my thesis.



Ananya Roy

Abstract

Microelectromechanical systems (MEMS) have been popular in recent decades, with large systems being converted into small chips and portable devices. Due to their compact size, low cost, and other advantages, these devices find applications in a wide variety of fields, including aeronautics, biological science, telecommunications, automobile industry, etc. Here in this thesis, the two most used MEMS devices (MEMS thermoelectric energy harvester and electrothermal microgripper) are modeled. Like most MEMS devices, thermoelectric energy harvester and electrothermal microgripper are modeled as distributed parameter systems with partial differential equations. The finite element method converts these partial differential equations into a large number of ordinary differential equations making the entire procedure computationally expensive. Model order reduction (MOR) reduces the computational complexity of such systems. It produces lower order approximations of such large scale systems, preserving the characteristics of the large scale system.

To come up with an adequate design, a complete understanding of the relationship between the structure, materials, and performance of the device is required. If this parameter dependence can be retained within the reduced models, the large-scale system does not have to be synthesized and reduced repeatedly for each parameter value. This idea gives rise to parametric model order reduction (pMOR).

It has been observed that when geometric parameters are changed, the finite

element meshes, the size of the models or the dimension of system matrices change invariably. Popular pMOR methods become inapplicable in such cases. This thesis proposes a new finite element compatible matrix interpolation for pMOR for handling such problems. It is applied to the thermoelectric generator system and microgripper system. This method is also applied to the microgripper system considering multiple parameters.

While designing, most design methodologies obtain the optimum value of the parameter by comparing the data obtained through testing or device responses without considering optimality. An efficient design of the microgripper is achieved here. The Sine Cosine Algorithm, a population-based optimization algorithm, is employed to obtain a desirable solution for optimizing the design parameters of the microgripper. Following that, an averaging process is carried out to propose an efficient design procedure.

Not only design parameters but also the generated heat of the device has an impact on the performance. The electrical conductivity of gold changes nonlinearly as the produced heat of the system changes, making the electrothermal model of the microgripper system nonlinear. Again, as the produced heat changes, the SU-8 polymer's elastic properties vary nonlinearly, and as a result, the thermo-mechanical system becomes nonlinear. Nonlinear model order reduction methods such as POD-DEIM and POD methods are applied to reduce the computational complexity of the system.

Keywords: Micro-Electro-Mechanical Systems (MEMS), Thermoelectric Generator (TEG), Electrothermal Microgripper, Finite-Element Method (FEM), Parametric Model Order Reduction (pMOR), Sine Cosine Optimization (SCA), Nonlinear Model Order Reduction

सारांश

माइक्रोइलेक्ट्रोमैकेनिकल सिस्टम (एमईएमएस) हाल के दशकों में लोकप्रिय रहे हैं, बड़े सिस्टम को छोटे चिप्स और पोर्टबल डिवाइस में परिवर्तित किया जा रहा है। अपने कॉम्पैक्ट आकार, कम लागत और अन्य लाभों के कारण, ये उपकरण वैमानिकी, जैविक विज्ञान, दूरसंचार, ऑटोमोबाइल उद्योग, आदि सहित विभिन्न प्रकार के क्षेत्रों में आवेदन पाते हैं। यहां इस थीसिस में, दो सबसे अधिक इस्तेमाल किए जाने वाले एमईएमएस डिवाइस (एमईएमएस थर्मोइलेक्ट्रिक एनर्जी हार्वेस्टर और इलेक्ट्रोथर्मल माइक्रोग्रिपर) को मॉडल किया गया है। अधिकांश एमईएमएस उपकरणों की तरह, थर्मोइलेक्ट्रिक एनर्जी हार्वेस्टर और इलेक्ट्रोथर्मल माइक्रोग्रिपर को आंशिक अंतर समीकरणों के साथ वितरित पैरामीटर सिस्टम के रूप में तैयार किया गया है। परिमित तत्व विधि इन आंशिक अंतर समीकरणों को बड़ी संख्या में साधारण अंतर समीकरणों में परिवर्तित करती है जिससे पूरी प्रक्रिया कम्प्यूटेशनल रूप से महंगी हो जाती है। मॉडल ऑर्डर रिडक्शन (MOR) ऐसी प्रणालियों की कम्प्यूटेशनल जटिलता को कम करता है। यह बड़े पैमाने की प्रणाली की विशेषताओं को संरक्षित करते हुए, इस तरह के बड़े पैमाने के सिस्टम के निचले क्रम के अनुमानों का उत्पादन करता है।

एक पर्याप्त डिजाइन के साथ आने के लिए, डिवाइस की संरचना, सामग्री और प्रदर्शन के बीच संबंधों की पूरी समझ की आवश्यकता होती है। यदि इस पैरामीटर निर्भरता को कम किए गए मॉडल के भीतर बनाए रखा जा सकता है, तो बड़े पैमाने पर सिस्टम को प्रत्येक पैरामीटर मान के लिए बार-बार संश्लेषित और कम करने की आवश्यकता नहीं होती है। यह विचार पैरामीट्रिक मॉडल ऑर्डर रिडक्शन (pMOR) को जन्म देता है।

यह देखा गया है कि जब ज्यामितीय मापदंडों को बदल दिया जाता है, तो परिमित तत्व मेश, मॉडल का आकार या सिस्टम मैट्रिक्स का आयाम हमेशा बदलता रहता है। ऐसे मामलों में लोकप्रिय पीएमओआर विधियां अनुपयोगी हो जाती हैं। यह थीसिस ऐसी समस्याओं से निपटने के लिए pMOR के लिए एक नए परिमित तत्व संगत मैट्रिक्स इंटरपोलेशन का प्रस्ताव करता है। यह थर्मोइलेक्ट्रिक जनरेटर सिस्टम और माइक्रोग्रिपर सिस्टम पर लागू होता है। यह विधि कई मापदंडों पर विचार करते हुए माइक्रोग्रिपर सिस्टम पर भी लागू होती है।

डिजाइन करते समय, अधिकांश डिजाइन पद्धतियां इष्टतमता पर विचार किए बिना परीक्षण या डिवाइस प्रतिक्रियाओं के माध्यम से प्राप्त डेटा की तुलना करके पैरामीटर का इष्टतम मूल्य प्राप्त करती हैं। माइक्रोग्रिपर का एक कुशल डिजाइन यहां हासिल किया गया है। साइन कोसाइन एल्गोरिथम, एक जनसंख्या-आधारित अनुकूलन एल्गोरिथम, माइक्रोग्रिपर के डिजाइन मापदंडों को अनुकूलित करने के लिए एक वांछनीय समाधान प्राप्त करने के लिए नियोजित है। उसके बाद, एक कुशल डिजाइन प्रक्रिया का प्रस्ताव करने के लिए एक औसत प्रक्रिया की जाती है।

न केवल डिजाइन पैरामीटर बल्कि डिवाइस की उत्पन्न गर्मी भी प्रदर्शन पर प्रभाव डालती है। सोने की विद्युत चालकता गैर-रैखिक रूप से बदलती है क्योंकि सिस्टम की उत्पादित गर्मी में परिवर्तन होता है, जिससे माइक्रोग्रिपर सिस्टम का इलेक्ट्रोथर्मल मॉडल नॉनलाइनियर हो जाता है। फिर से, जैसे ही उत्पादित गर्मी में परिवर्तन होता है, एसयू-8 बहुलक के लोचदार गुण गैर-रैखिक रूप से भिन्न होते हैं, और परिणामस्वरूप, थर्मो-मैकेनिकल सिस्टम नॉनलाइनियर हो जाता है। सिस्टम की कम्प्यूटेशनल जटिलता को कम करने के लिए नॉनलाइनियर मॉडल ऑर्डर रिडक्शन मेथड्स जैसे POD-DEIM और POD मेथड्स को लागू किया जाता है।

महत्वपूर्ण शब्द: माइक्रो-इलेक्ट्रो-मैकेनिकल सिस्टम्स (एमईएमएस), थर्मोइलेक्ट्रिक जेनरेटर (टीईजी), इलेक्ट्रोथर्मल माइक्रोग्रिपर, परिमित-एलिमेंट मेथड (एफईएम), पैरामीट्रिक मॉडल ऑर्डर रिडक्शन (पीएमओआर), साइन कोसाइन ऑप्टिमाइजेशन (एससीए), नॉनलाइनियर मॉडल ऑर्डर रिडक्शन

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List of Abbreviations

MEMS Micro-Electro-Mechanical Systems

DLPs Digital Light Projectors

BioMEMS Biomedical Micro-Electro-Mechanical Systems

TEG Thermoelectric generator

PDEs Partial Differential Equations

FEM Finite Element Method

MOR Model Order Reduction

pMOR Parametric Model Order Reduction

MI Matrix Interpolation

FEMI Finite Element compatible Matrix Interpolation

SCA Sine Cosine Algorithm

POD Proper Orthogonal Decomposition

DEIM Discrete Empirical Interpolation Method

ROM Reduced Order Model

FOM Full Order Model

ODEs Ordinary Differential Equations

SOAR Second Order Arnoldi Reduction

EAs Evolutionary Algorithms

CTE Coefficient of Thermal Expansion