THEORETICAL AND EXPERIMENTAL STUDIES ON SOUND ABSORBING PROPERTIES OF GREEN POROUS MATERIALS

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by

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Submitted

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Dedicated to

the memory of my father Late Mr. H. K. Thakur,

and

to the struggles of my mother Mrs. S. K. Thakur.

Certificate

This is to certify that the thesis entitled "**Theoretical and experimental studies on sound absorbing properties of green porous materials**" being submitted by **Mr. Manish Raj** (2016ITZ8319) to the Indian Institute of Technology Delhi, New Delhi, India, for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our supervision. The candidate has fulfilled the requirements for the submission of this research work for his thesis. In our opinion, this thesis has attained the standard needed for the award of a Ph.D. degree of this institute. The results contained in this thesis have not been submitted, in a part or in full, to any other university or institute for the award of any degree or diploma.

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Place: IIT Delhi, New Delhi, India

Acknowledgments

I still remember the night I arrived in New Delhi to join IIT Delhi as a Ph.D. candidate. While waiting for the dawn at New Delhi Railway station, I read these lines somewhere:

विदेशेषु धनं विद्या व्यसनेषु धनं मतिः। परलोके धनं धर्मः शीलं सर्वत्र वै धनम्॥

(Knowledge is wealth in a foreign land. Intelligence is wealth in tough times. Righteousness is wealth in other world. Verily, Good Character is wealth everywhere and at all the times! – Rig Veda)

These lines touched me, and I have always tried to implement these in my life to become a better version of myself**.** My first thanks go to the Almighty that I have come up to submit my thesis. The recent times have been a testing one, and I show my total devotion toward the Almighty for showing me the path at testing times.

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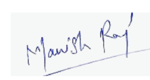
कर्मण्येवाधिकारस्ते मा फलेषु कदाचन । मा कर्मफलहेतुर्भुर्मा ते संगोऽस्त्वकर्मणि ॥

(You have a right to perform your prescribed duty, but you are not entitled to the fruits of action. Never consider yourself to be the cause of the results of your activities, and never be attached to not doing your duty. - Bhagavad Gita, Chapter II, Verse 47)



(MANISH RAJ)

Abstract

Typical sound-absorbing materials happen to be of synthetic origin, have a high carbon footprint, and harm human health. This motivates to look toward nature and propose some 'green' materials to implement for noise control applications, which happens to be the core of this study.

The study starts with discussing methodology to develop experimental facilities relevant to sound absorbers. The density of sound absorbers is linked to their porosity, and in the current study, it is measured by developing a density gradient column. Experimental facilities are developed to measure the sound absorption coefficients and airflow resistivity and validated with the results of standard experimental facilities. Thereafter, two new natural materials from agro-forestry sources, nettle fibers, and areca nut leaf sheath fibers, are thoroughly studied for their acoustical properties. Theoretical simulations are performed to predict their sound absorption coefficients. The error between the measured and predicted sound absorption coefficients is minimized by performing inverse acoustical characterization. The effectiveness of inverse acoustical characterization is improved by performing the simulations at different frequency resolutions. A comparison of sound absorption coefficients of these materials is also performed with commercial synthetic materials. Later on, an attempt is made towards using green recycled materials as potential sound absorbers, and for that, two materials, denim shoddy and waste jute fibers, are identified. The sound absorption coefficients of these materials are measured by conducting a full factorial design of experiments, and

the measured results are compared with simulated ones. Further, the performance of these materials is compared with commercial glasswool with same process parameters. A theoretical equation is developed to estimate the noise reduction coefficient of these materials and is experimentally validated. The study then progresses towards reporting an alternate methodology to determine the random incidence sound absorption coefficients. The steps consist of setting up and solving the modified Helmholtz equation in the pressure acoustics and the poroacoustic domain. The solutions in the form of oblique incident sound absorption coefficients are obtained by the finite element method.

The developed measurement facilities were found to produce results closer to the commercial measurement facilities. The comparison of results obtained show that the performance of denim shoddy fibers was found to be the best as compared to other green materials studied, followed by waste jute fibers and nettle fibers. The areca nut leaf sheath fibers were ranked fourth among the studied materials. When compared to commercial glasswool, the studied materials show sufficient potential to be competitive for acoustic purposes. The simulated random incident sound absorption coefficient for all these materials provided a better visualization of their sound absorption coefficients in realistic conditions.

सार

विशिष्ट ध्वनि-अवशोषित सामग्री सिंथेटिक मूल की होती है, जिसमें उच्च कार्बन पदचिह्न होते हैं, और मानव स्वास्थ्य को नुकसान पहुंचाते हैं। यह परिसीमन हमें प्रकृति की ओर देखने के लिए प्रेरित करता है और शोर नियंत्रण अनुप्रयोगों के लिए लागू करने के लिए कुछ 'हरित' सामग्री का प्रस्ताव करता है, जो इस अध्ययन का मूल है।

यह अध्ययन ध्वनि अवशोषक के लिए प्रासंगिक प्रयोगात्मक सुविधाओं को विकसित करने के लिए कार्यप्रणाली पर चर्चा के साथ शुरू होता है। ध्वनि अवशोषक का घनत्व उनके सरंध्रता से जुड़ा होता है, और वर्तमान अध्ययन में, इसे घनत्व ढाल स्तंभ विकसित करके मापा जाता है। प्रायोगिक सुविधाओं को ध्वनि अवशोषण गुणांक और वायु प्रवाह प्रतिरोधकता को मापने के लिए विकसित किया गया है और मानक प्रयोगात्मक सुविधाओं के परिणामों के साथ मान्य किया गया है। इसके बाद, कृषि-वानिकी स्रोतों से दो नई प्राकृतिक सामग्री, नेट्ले फाइबर, और ऐरेका नट लीफ शीत फाइबर, उनके ध्वनिक गुणों के लिए पूरी तरह से अध्ययन किया गया है। सैद्धांतिक सिमुलेशन उनके ध्वनि अवशोषण गुणांक की भविष्यवाणी करने के लिए किए गए हैं। मापा और अनुमानित ध्वनि अवशोषण गुणांक के बीच त्रुटि को उलटा ध्वनिक लक्षण वर्णन करके कम किया गया है। व्युत्क्रम ध्वनिक लक्षण वर्णन की प्रभावशीलता में विभिन्न आवृत्ति संकल्पों पर सिमुलेशन प्रदर्शन करके सुधार किया गया है। इन सामग्रियों के ध्वनि अवशोषण गुणांक की तुलना वाणिज्यिक सिंथेटिक सामग्री के साथ भी की गयी है। बाद में, संभावित ध्वनि अवशोषक के रूप में हरित पुनर्नवीनीकरण सामग्री का उपयोग करने की दिशा में प्रयास किया गया है, और उसके लिए, दो सामग्री, डेनिम शोडय और अपशिष्ट जूट फाइबर की पहचान की जाती है। इन सामग्रियों के ध्वनि अवशोषण गुणांक को प्रयोगों के एक पूर्ण तथ्यात्मक डिजाइन का संचालन करके मापा गया है, और मापा परिणामों की तुलना नकली लोगों से की गयी है। इसके अलावा, इन सामग्रियों के प्रदर्शन की तुलना समान प्रक्रिया मापदंडों वाले वाणिज्यिक कांच के ऊन

से की गयी है। इन सामग्रियों के शोर में कमी गुणांक का अनुमान लगाने के लिए एक सैद्धांतिक समीकरण विकसित किया गया है और प्रयोगात्मक रूप से मान्य किया गया है। अध्ययन तब यादृच्छिक घटना ध्वनि अवशोषण गुणांक निर्धारित करने के लिए एक वैकल्पिक पद्धति की रिपोर्ट करने की दिशा में आगे बढ़ता है। चरणों में दबाव ध्वनिकी और पोरोअकॉस्टिक डोमेन में संशोधित हेल्महोल्ट्ज़ समीकरण को स्थापित करना और हल करना शामिल है। परोक्ष घटना ध्वनि अवशोषण गुणांक के रूप में समाधान परिमित तत्व विधि द्वारा प्राप्त किए गए हैं।

विकसित माप सुविधाओं को वाणिज्यिक माप सुविधाओं के करीब परिणाम देने के लिए पाया गया। प्राप्त परिणामों की तुलना से पता चलता है कि डेनिम शोडय फाइबर का प्रदर्शन अन्य हरित सामग्री की तुलना में सबसे अच्छा पाया गया, इसके बाद अपशिष्ट जूट फाइबर और बिछुआ फाइबर का स्थान है। अध्ययन सामग्री में ऐरेका नट लीफ शीत फाइबर के रेशों को चौथा स्थान दिया गया। वाणिज्यिक कांच के ऊन की तुलना में, अध्ययन की गई सामग्री ध्वनिक उद्देश्यों के लिए प्रतिस्पर्धी होने की पर्याप्त क्षमता दिखाती है। इन सभी सामग्रियों के लिए सिमुलेटेड यादृच्छिक घटना ध्वनि अवशोषण गुणांक ने यथार्थवादी परिस्थितियों में उनके ध्वनि अवशोषण गुणांक का बेहतर दृश्य प्रदान किया।

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Nomenclature

P_b	upstream pressure	P_a	downstream pressure
m_a	mass of air	m_s	mass of fiber skeleton
Δp	pressure difference	Q_v	volume flow rate of air
ϕ	porosity of the sample	α_∞	tortuosity
ρ	density	h_1, h_2, h_3, h_4	position of calibrated floats
$F_1, F_2, F_3, F_4, F_5, F_6$	calibrated float numbers	n	number of samples
V	volume	a	flow cross section area
σ	airflow resistivity	f_l	lower working frequency limit
R_a	average roughness	Rq	Root-mean-squared roughness
L	distance between speaker and first microphone	RMSE(ε)	root-mean-squared error
D	diameter of the tube	H^I	calibration transfer function of the tubes in standard configuration
c	speed of sound	H^{II}	calibration factor in swapped configuration
f_u	upper working frequency limit	H_c	calibration factor