OP-06

3D プリンティング材料のための構成モデルの音響キャリブレーション法

Acoustic Calibration Method of Constitutive Model for 3D Printing Materials

钟 圣泽, プンポンサノン パリンヤ, 岩井 大輔, 佐藤 宏介
Shengze ZHONG, Parinya PUNPONGSANON, Daisuke IWAI, Kosuke SATO

大阪大学基礎工学研究科
Graduate School of Engineering Science, Osaka University
(zhong@sens.sys.es.osaka-u.ac.jp, {parinya, daisuke.iwai, sato}@sys,es.osaka-u.ac.jp)

【要約】

アディティブマニュファクチャリングでは、材料の機械的特性が構造の設計と最適化に重要な役割を果たします。本研究では、モーダルサウンドによって材料構成モデルを取得するための音響校正方法を提案します。アディティブマニュファクチャリングにおける材料構成モデルの役割を紹介し、関係を分析します。材料構成モデルとモーダルサウンドを融合させ、モーダルサウンドにより材料構成モデルを回帰させる最適化手法を提案します。この手法は、複雑な機器を使用せずに材料特性の迅速な評価を実現し、製品の最終設計品質を向上させるのに役立ちます.

キーワード：3D プリンティング，構成モデル，モーダルサウンド

【Abstract】

In additive manufacturing, the mechanical properties of materials play a vital role in designing and optimizing structures. We propose an acoustic calibration method for obtaining the material constitutive model by modal sound. It introduces the role of the material constitutive model in additive manufacturing, analyzes the relationship between the material constitutive model and modal sound, and proposes an optimization method of regressing the material constitutive model through modal sound. This method is helpful to realize the rapid evaluation of material properties without using complex instruments to improve the final design quality of products.

Keywords:3D printing, constitutive model, modal sound

1. Introduction

The development of additive manufacturing technology has triggered personal manufacturing and led to rapid prototyping and structural optimization design. Through 3D printing, individual users can enrich their living space with personalized structures; companies can achieve rapid design iterations to considerably shorten the product design cycle. With the continuous evolution of 3D printing structures from ornaments to functional parts, users have put forward higher requirements for structures' mechanical performance, such as load-bearing and vibration.

Introducing material constitutive models in the design process meets these growing demands. The material constitutive model describes the material's mechanical response under load by numerically correlating stress and strain. This relationship is of great significance for the design of parts with mechanical performance requirements. After obtaining the material constitutive model, users can choose materials that are more in line with product characteristics, or they can significantly improve the performance of materials by optimizing the structure design without increasing the consumption of printed materials [1], like the MBB beam (i.e., a supported

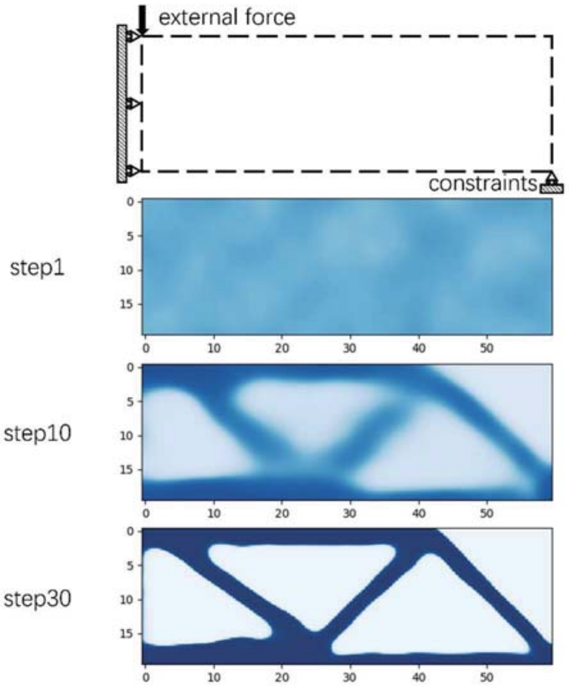

Figure 1. Optimization of 2D MBB beam. With the material constitutive model, the structure is generated with stronger

loading performance and lower weight after iterations.

beam which removes material to perform weight reduction while maintaining low compliance) [2] as shown in Figure 1.

Previously, it was difficult to obtain the constitutive model of 3D printing materials. Most 3D printed material documents do not contain the corresponding constitutive model, and the traditional constitutive model calibration method requires complex experimental equipment and operations, such as using amplified audio and laser to force and record the material's vibration [3] or use fixtures and machine tools to conduct groups of material deformation experiments [4]. In order to enable individual users to measure material properties easily, this research proposes a user-friendly acoustic calibration method that regresses the constitutive model of the material based on the modal sound of the 3D printed sample.

2. Acoustic Calibration Method

In this section, we first introduced the application of the constitutive model in structural design, followed by the calculation of modal sound through the constitutive model. Finally, we proposed the method of using modal sound to regress the material constitutive model.

The material constitutive model describes the relationship between stress and strain. In practice, the constitutive model $\mathbf{c}$ is a 6×6 matrix of material constants [5], which includes normal and shear stress-strain relationships $\sigma = c\varepsilon$, as shown in equation 2.1.

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} c_{11} & \cdots & c_{16} \\ \vdots & \ddots & \vdots \\ c_{61} & \cdots & c_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{Bmatrix} \tag{2.1}$$

When there is a precise demand for the force feedback of the structure, we need a more accurate constitutive model to complete the optimal design. For example, when designing the supporting flange of a shelf, we need a constitutive model to ensure that the structure looks elegant while having sufficient load-bearing capacity. Besides, when the structure is embedded in a more complex system, the constitutive model can be used to calculates and adjusts the natural frequency of the structure to avoid resonance. For example, in vehicle design, there are requirements of high NVH performance (noise, voice harshness), and structures' frequency design is of great importance.

In order to observe such stress-strain relationship to calibrate the material constitutive model, the conventional method deforms the material to observe the stress-strain relationship. However, the individual user does not have such experimental equipment. Therefore, we consider using modal analysis (to be more specific, modal sound) to observe loaded material's stress and strain relationship.

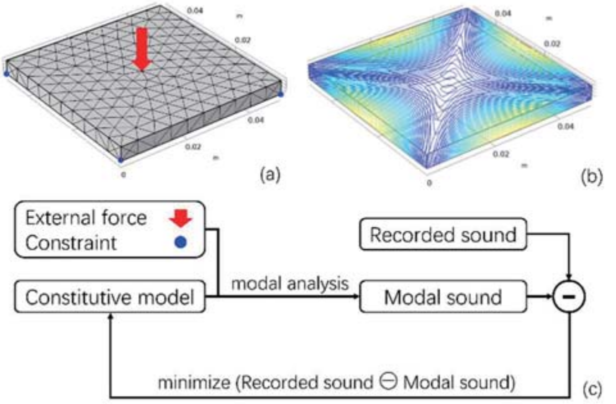

Figure 2. The proposed acoustic calibration scheme of the material constitutive model. (a) The 3D printed structure for calibration. The red arrow is the external force, and the blue dots are constraints. (b) The vibrated structure under a particular mode. (c) The constitutive model calibration process, which aims to minimize the difference between simulated and recorded sound.

Modal analysis is widely applied for measuring structural vibration in aerospace, vehicles, ships, and electrical appliances. Engineers often conduct finite element analysis according to the structure's CAD model and material parameters to obtain the computational modal. They then use the exciter to knock the vibration sensor attached to the structure's surface to obtain the experimental modal. The experimentally measured modal is also helpful to calibrate the material parameters. However, it is essential for individual users who cannot access industrial equipment to measure structural vibration more straightforwardly. Therefore, we propose a method to measure vibration using sound, which only needs a microphone.

The modal sound is closely related to the constitutive model of the material. Derivation from the constitutive model to modal sound can be divided into two parts. The first part is the vibration process. That is, the object produces modal vibration under external force. For linear systems, this vibration can be decoupled into N orthogonal single-degree-of-freedom vibration, corresponding to the N modes of the system. The second part is the acoustic transfer process, that is, the vibration of the object surface excites the surrounding air to produce a sound pressure change, and such sound pressure change will eventually radiate to our ears or the microphone and become the sound we perceive. During this process, the material constitutive model determines the vibration frequency of each mode, thereby determining the final tone of the sound. The force, constraints of the structure, and the acoustic transfer process can be understood numerically as a filter for each modal frequency, which determines the amplitude of each sound frequency. In the experimental scenario of this article, amplitude change caused by acoustic transfer is tinier, so it is not considered in the modal sound simulation process.

Through finite element analysis, we can establish the relationship between the constitutive model and the vibration. Using the constitutive model $\mathbf{c}$ and the structure shape, the element stiffness matrix $\mathbf{k_e}$ can be assembled, as shown in equation 2.2.

$$\mathbf{k_e} = \int \mathbf{B^T c B}\, dV = \mathrm{V_e}[\mathbf{B^T c B}] \tag{2.2}$$

Here $\mathbf{k_e}$ is the element stiffness matrix, $\mathbf{c}$ is the constitutive model. $\mathrm{V_e}$ is the element volume, and $\mathbf{B}$ is the strain matrix. These parameters depend on the finite element method. With $\mathbf{k_e}$, we can assemble the structure stiffness matrix $\mathbf{K}$. The mass matrix $\mathbf{M}$ is generated in a similar way with material density and the structure shape.

Therefore, solving the structure modal vibration becomes a generalized eigenvalues problem, which is

$$\mathbf{K}\mathrm{U} = \mathbf{M}\mathrm{US} \tag{2.3}$$

The solution consists of eigenvalue $\omega = \sqrt{S}/2\pi$ and eigenvector U. Eigenvalue ω is used to calculate the frequency of each mode, and eigenvector U represents the displacement of each node of the finite element under free vibration. Combined with the known external force and constraint, we can finally calculate the modal vibration of the structure as the weighted sum of each modal frequency and amplitude product [6].

Therefore, we associate the material constitutive model with modal sound. For ease of understanding, we can regard the modal sound as the dependent variable y; structure shape, external force and constraint as independent variable x. The constitutive model participates in the connection between the independent variable x and the dependent variable y as $y = \mathrm{f}(\mathbf{c}, x)$. With groups of paired (x, y), we can optimize the best constitutive model to minimize the difference between the simulated and real modal sound. The whole calibration process is illustrated in Figure 2.

We use a conventional microphone to record the modal sound of sample parts printed with nylon material using the Fused Deposition Modeling (FDM) 3D printer (Ultimaker3). We initialize the material with orthotropic conditions based on Young's modulus and Poisson ratio. During the experiment, we obtain multiple groups of data with different shapes and knocking positions. Specifically, we apply modal frequency with the highest amplitude difference as features to regress and estimate results. The experimental results are shown in Figure 3, where red lines show the feature frequency computed from the uncalibrated constitutive model, and blue lines show the feature frequency with the calibrated constitutive model, demonstrating a higher frequency than experimental results. It shows that calibrated constitutive model fits better to the ground-truth experimental results.

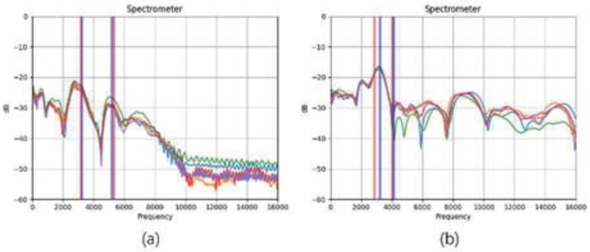

Figure 3. Modal sound of two FDM 3d printed parts with different thickness, where (a) 6mm, (b) 4mm. Each part is knocked 5 times in case of operation error. Red and vertical lines demonstrate feature modal frequencies before and after constitutive model calibration.

3. Conclusion

The acoustic calibration of the material constitutive model proposed in this paper provides a convenient and low-cost method to figure out 3D printing material mechanical property for individual users and studios. This constitutive model will allow user for better material selection, optimized structure design, and improve mechanical performance.

参考文献

1. Bendsoe, Martin Philip, and Ole Sigmund. Topology optimization: theory, methods, and applications. Springer Science & Business Media, 2013.
2. Sigmund, Ole. A 99 line topology optimization code written in Matlab, Structural and multidisciplinary optimization, Vol 21, 2, pp. 120–127, 2001.
3. Joël Cugnoni, Thomas Gmür, Alain Schorderet. Inverse method based on modal analysis for characterizing the constitutive properties of thick composite plates, Computers & Structures, Vol 85, 17–18, pp. 1310–1320, 2007.
4. Yap, Yee Ling, et al. A non–destructive experimental–cum–numerical methodology for the characterization of 3D–printed materials—polycarbonate–acrylonitrile butadiene styrene (PC–ABS), Mechanics of Materials, Vol. 132 pp. 121–133, 2019.
5. Liu, Gui–Rong, and Siu Sin Quek. The finite element method: a practical course. Butterworth–Heinemann, 2013.
6. Changxi Zheng and Doug L. James. Toward high–quality modal contact sound. ACM Trans. Graph. 30, 4, Article 38, 2011.