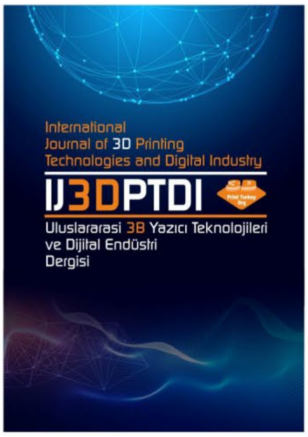

ULUSLARARASI 3B YAZICI TEKNOLOJİLERİ
VE DİJİTAL ENDÜSTRİ DERGİSİ

INTERNATIONAL JOURNAL OF 3D PRINTING TECHNOLOGIES AND DIGITAL INDUSTRY

ISSN:2602-3350 (Online)

URL: https://dergipark.org.tr/ij3dptdi

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Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): *Çaşka S., Dokuz M. E., Aydın M, İlman M. M., Yavuz Ş., "System Identification and Vibration Analysis of Rotating Beam With Lattice Structures" Int. J. of 3D Printing Tech. Dig. Ind., 7(2): 322-327, (2023).*

DOI: 10.46519/ij3dptdi.1325131

Araştırma Makale/ Research Article

Erişim Linki: (To link to this article): https://dergipark.org.tr/en/pub/ij3dptdi/archive

SYSTEM IDENTIFICATION AND VIBRATION ANALYSIS OF ROTATING BEAM WITH LATTICE STRUCTURES

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(**Received:** 10.07.23; **Revised:** 26.07.23; **Accepted:** 15.08.23)

ABSTRACT

Today, lattice-structured materials are used in many engineering applications. Research and applications including lattice structures focused on obtaining lightweight components with the optimal distribution. In literature, studies on obtaining vibration models of the beams with lattice structures are limited. In this study, vibration models of rotating beams with lattice structure were obtained by using system identification methods. Beams used in the experimental phase of this study were produced using FDM 3D printer. Three types of lattice structure such as triangular, hexagonal, and square rotated were used. Lattice-based generative design program nTopology was used for the design of the beams. The experiments were carried out using a setup that includes a servo system and a wireless accelerometer. It was proved that the obtained models successfully represent the vibration behavior of the rotating beams. The success of the vibration models of the rotating beams was compared and discussed using tables and figures.

Keywords: Rotating Beam, System Identification, Vibration Analysis, Lattice Structures, Additive Manufacturing.

1. INTRODUCTION

In recent years, one of the fastest-growing and most popular fields has been flexible and soft manipulators in the robotics field [1-2]. Especially since there is no need for rigidity, it is possible to make designs that are much lighter and have higher load-carrying capacity [3]. Due to these new designs, problems such as dynamic strength and vibration sensitivity come to the fore again. Such that there are many design developments and control systems related to vibration, which is one of the reasons that reduce the efficiency of flexible manipulators. First and foremost, accurate dynamic modeling is required to apply these solutions [4].

The purpose of vibration analysis of mechanical systems is to obtain system behaviors under different dynamic conditions [5]. In the literature, there is an interest in the analysis of the vibration characteristics of rotating flexible beams [6]. Several structural configurations such as helicopter blades, spinning spacecraft, and satellite booms can be counted in this category [7]. In recent years, there is an increase in the number of paper that includes simulation and experimental-based studies [8].

System identification is a significant process in obtaining mathematical models of dynamic systems. Identifying the system dynamics successfully provides the design of robust systems for prediction, planning, and control [9]. In control system design, one of the most important steps is to obtain an accurate system model. If the dynamic model does not represent the real behavior of the system, the controller cannot provide optimum system output [10].

Lattices can be referred to as periodic cellular structures, metamaterials, or architected materials. Lattice applications focused on obtaining lightweight components with the optimal distribution [11-12]. Additive manufacturing methods have numerous advantages over traditional subtractive manufacturing methods such as machining, and injection molding. In recent years, additively manufactured or 3D-printed lattice materials have been studied in many research [13]. For instance, in a previous study, the bioactivity and compressive strength of the specimens were examined to observe the bonding and adhesion effects of different lattice structures on bone tissue [14].

In this study, vibration models of rotating beams with lattice structures were obtained by using system identification approaches. In the previous study, the mechanical properties of the parts produced by the FDM method with various additives and various particle sizes were investigated [15]. There has not been a comprehensive study on vibration analysis of parts produced with FDM 3D printing. Three types of beams were used in the experimental phase of this study and were produced by using an FDM type 3D printer. Lattice sizes suitable for the precision of the FDM method were preferred in the design of the parts. PLA material, which is the most commonly used and optimum strength polymer, was used. The success of the obtained vibration models of the rotating beams was compared. The followings are some of the potential novelties that the study could bring to the literature:

(i) Lighter and more stable manipulators were produced thanks to the lattice designs,
(ii) manipulator vibration analyses were carried out and the modal analysis results were compared,
(iii) despite the complex form of the manipulator caused by lattice topology, very accurate models have been derived utilizing system identification methods,
(iv) these reduced-order models are also appropriate for future control applications as well, by means of their fast-computable structures.

2. MATERIAL AND METHODS

Topology computer-aided design software was used to create three specimens with varying lattice structures. In this study, strut-based triangular, hexagonal, and square lattice structures were preferred for the internal structure of the specimens. The lower and upper shells were assessed to be 2 mm thick. To connect the specimen to the experimental setup, a 30 mm long connection area was designed. The specimen dimensions were 300 mm total length, 25 mm width, and 10 mm thickness. The specimen was converted to STL file format by meshing with a minimum feature size of 0.6 mm.

The specimens were produced using the FDM (Fused Deposition Modeling) 3D printing process. STL design files were converted to g-code files using the PrusaSlicer software. The printing direction is rotated in relation to the plane with the least gravitational effect on the parts. The specimens were printed using PLA (Polylactic acid) filament with a nozzle diameter of 0.4 mm, a layer height of 0.1 mm, and a fill rate of 100%.

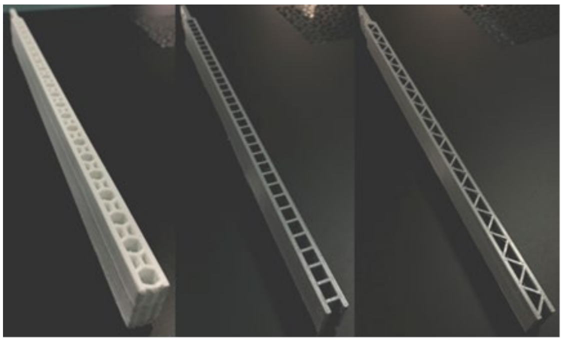

Figure 1. Lattice structured beams, (left) hexagonal form, (middle) square form, (right) triangular form

3. EXPERIMENTAL SETUP

The scheme of the experimental system used for the vibration analysis of lattice-structured beams in the study is given in Figure 2. Also, the properties of the system are given in Table 1, together with data sampling information. Accordingly, first of all, the planar uniaxial flexible manipulator moves in the XY plane (local axes are shown in Figure 2). In addition, since it is known that the manipulator will mostly try to bend under payload, the accelerations in the local Y-axis at the endpoint of the beam are measured to obtain the maximum vibration. For this, a wireless accelerometer sensor (WAS) and a wireless data acquisition system (WDA) are used. The fixed sampling frequency of the signal is set at 650 Hz. Node Commander software is used to save the data. The servo system that gives motion to the system consists of a servo driver with model MR-J2S-20A and a servo motor with model HC-KFS23B (200W), a harmonic drive gearbox with model HFUC-32-100 (with the gear ratio of 100) that does not create vibration during the transmission of motion. Motion control can be employed by transmitting the angular velocity inputs from the computer to the servo driver via the Adlink PCI-8366 motion card. The SSCNET system links the motion control card and driver in cascade form. The Adlink-ActiveX component serves to program the driver employing Visual Basic commands [16].

Table 1. The properties of the system.

Hexagonal form Manipulator Mass	60.2 g
Square Form Manipulator Mass	50.5 g
Triangular Form Manipulator Mass	49.4 g
Manipulator Lengths	372 mm
Sensor Mass	50 g
Sample Frequency	50 Hz
Sensor Distance to Endpoints	31 mm

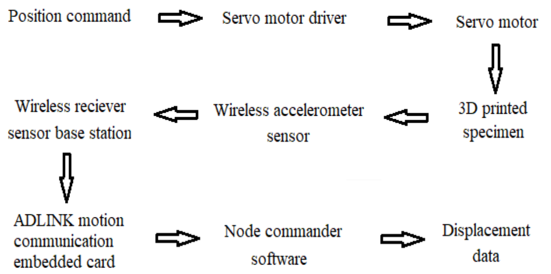

Figure 2. Scheme of the experimental setup

System identification is an approach to obtaining mathematical models of dynamic systems by using a specified input and output signal belongs the system. In control system design, one of the most important steps is building an accurate model of the system. If the obtained model does not represent the real behavior of the system, even the optimal controllers cannot provide optimum system output [17]. In this study, the System Identification Toolbox (SIT) of MATLAB was used to obtain vibration models of the beams. The system identification step in control system design is shown in Figure 3.

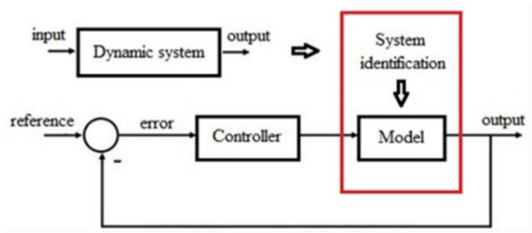

Figure 3. System identification in control system design.

SIT of MATLAB provides functions and blocks to build mathematical models of dynamic systems using measured input-output data. The toolbox helps the researchers to create and use dynamic system models. Time-domain and frequency-domain input-output data sets are used to obtain continuous-time and discrete-time transfer functions, process, and state-space models. In this study, the discrete-time transfer function, discrete-time state space model, nonlinear ARX model, and Hammerstein-Wiener model were used to obtain the dynamic models. The application interface of SIT of MATLAB is shown in Figure 4.

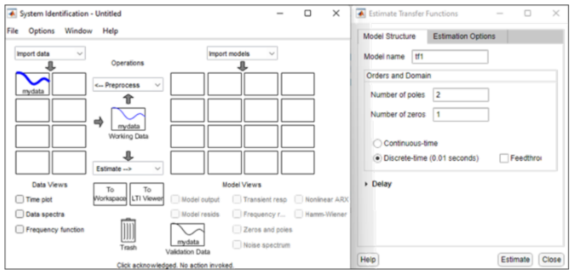

Figure 4. System identification application of MATLAB.

4. RESULTS AND DISCUSSION

In the application interface of SIT, there are some options for the models. In the discrete-time transfer function section, the model includes 4 poles and 4 zeros were selected. In the discrete-time state space model section, model form, and order were respectively selected as free and 4. In the nonlinear ARX model section, the regressor type was selected as polynomial with order 4. In the Hammerstein-Wiener model section, a number of breakpoints were selected as 10 and the search method was selected as Levenberg-Marquardt. To evaluate the success of the obtained models, the goodness of fit value that is calculated by using Normalized Root Mean Square (NRMSE) was used as statistical criteria. The goodness of fit value of the models was given in Table 2, Table 3, and Table 4.

Table 2. The goodness of fit value for the model of the Triangular Lattice beam.

Model	Goodness of fit(%)
Discrete-time transfer function	97.67
Discrete-time state space model	78.81
Nonlinear ARX model	85.06
Hammerstein-Wiener Model	97.91

Table 3. The goodness of fit value for the model of the Hexagonal Lattice beam.

Model	Goodness of fit(%)
Discrete-time transfer function	90.77
Discrete-time state space model	41.43
Nonlinear ARX model	61.49
Hammerstein-Wiener Model	94.41

Table 4. The goodness of fit value for the model of the Square Lattice beam.

Model	Goodness of fit(%)
Discrete-time transfer function	96.75
Discrete-time state space model	73.68
Nonlinear ARX model	85.38
Hammerstein-Wiener Model	96.78

The highest goodness of fit value in Table 2, Table 3, and Table 4 is the model obtained for square formed beam by using the Hammerstein-Wiener approach. Figure 5 shows the measured and model output for square formed beam.

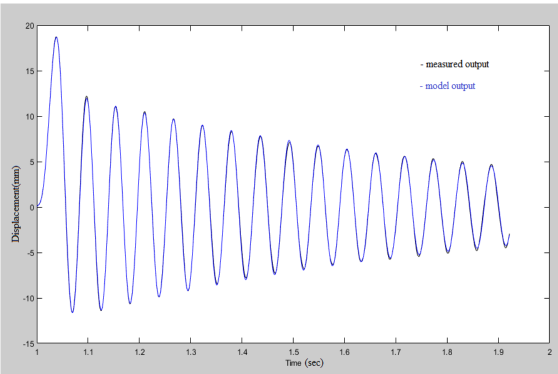

Figure 5. The success of system identification in MATLAB [18].

Tables 2, 3, and 4 show the success of different models for Triangular, Hexagonal, and Square formed beams, respectively. Accordingly, it can be said that all three different designs were modeled with approximate success. Additionally, Table 5 provides a comparison of the modal analyses for each beam.

Table 5. Natural frequencies of the beams

Specimen (Figure 1)	1. Natural Frequency [Hz]	2. Natural Frequency [Hz]
Triangular Form	17.70 ± 0.07	169.68 ± 4.33
Hexagonal Form	19.31 ± 0.08	174.06 ± 1.18
Square Form	17.59 0.25	162.01± 1.63

5. CONCLUSION

It has been seen from Table 2 that the Hammerstein-Wiener model has the highest goodness of fit value with 97.91 while the Discrete time state space model has the lowest goodness of fit value with 78.81 for Triangular formed Beam. Table 3 shows that the Hammerstein-Wiener model has the highest goodness of fit value at 94.41 while the Discrete time state space model has the lowest goodness of fit value at 41.43 for hexagonal formed beam. Table 4 shows that the Hammerstein-Wiener model has the highest goodness of fit value at 96.78 while the Discrete time state space model has the lowest goodness of fit value at 73.68 for square formed beam. Results prove that the best model type to obtain vibration models of Triangular, Hexagonal, and square formed rotating beams is the Hammerstein-Wiener model. The order of the success of model types from the worst to the best is the discrete time state space model, nonlinear ARX model, discrete-time transfer function, and Hammerstein-Wiener model. After the model evaluation, the modal analyses result of the beams are also compared. It has been seen that a beam with a hexagonal form is the most stable since it has the highest fundamental frequency. And also, the orientation (square or triangular) of the support parts seems to be ineffective against natural frequencies.

In this study, the fast fourier transform (FFT) method was used to obtain the natural frequencies of the beams [7]. In the literature, the suitability of the system identification methods for vibration analysis of the beams was discussed [18]. Since the measured output and the model output are compatible, Figure 5 proves the suitability of system identification methods for obtaining dynamic models of flexible beams. Considering previous studies, it can be said that the results of this study are compatible with the literature.

It is known that as its natural frequency decreases, the structure becomes more flexible and more susceptible to vibration. Considering Table 5, the natural frequencies of the square and triangular forms seem quite similar. It is clear that the support element arrangements (in a diagonal or horizontal configuration) have little impact on the bar's stability. On the other hand, it is noticeable that the fundamental (initial) natural frequency is higher when examining the beam that is formed in the shape of a Hexagonal. This indicates that the hexagonal-shaped beam is the most stable specimen used in the investigation.

The number of 3D-printed engineering designs with lattice structures have been increased in literature [19-20]. The contribution of this paper is to include lattice structures, additive manufacturing, and also vibration analysis.

In future studies, multi-link flexible systems can be considered a good candidate since the increase in degrees of freedom brings an increase in nonlinearity. In addition, experimental and numerical studies on the design and analysis of vibration-damping elements with various lattice structures for a real system with vibration are thought to be promising.

ACKNOWLEDGES
No funding was received to assist with the preparation of this manuscript.

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