Machine tool multibody dynamic model updating using vision-based modal analysis

Vishal Singh, Mohit Law*

Indian Institute of Technology Kanpur, Kanpur, India

Presented in International Conference on Precision, Micro, Meso and Nano Engineering (COPEN - 12: 2022)
December 8th - 10th, 2022 IIT Kanpur, India

KEYWORDS

Machine Tools,
Model Updating,
Vision-Based Modal Analysis,
Dynamics,
Joints,
Frequency Response Function,
Digital Twin.

ABSTRACT

Machine tool dynamic behaviour is influenced by the structural properties of its subsystems assembled at interfaces as well as by the interface characteristics. Interfaces are commonly modelled as spring-damper connections, parameters of which are usually updated by minimizing the difference between model-predicted and measured dynamics characterized by frequency response functions. This model updating approach requires global mode shapes to be measured by roving the hammer and/or the sensor such as to localize the joint parameters to be updated. Such measurements are time consuming and fraught with errors. As a new, alternative, and simpler way to update joint parameters of a machine tool multibody dynamic model, this paper reports on the use of full-field vision-based modal analysis methods. Mode shapes thus identified agree with those estimated with the traditional experimental modal analysis procedures. The updated machine tool multibody dynamic model is a step towards realizing an accurate digital twin.

1. Introduction

Accurate machine tool models are digital twins of a real machine tool. As such, model predicted dynamic behaviour can inform how to guide cutting parameter selection and control the real machine through dynamical and mechatronic simulations. The model can also guide design changes. However, since machine tools are complex assemblies of several substructural elements connected at interfaces, developing accurate models is not trivial.

Modelling approaches include those in which substructural elements are flexible bodies in flexible contact with each other (Bianchi et al., 1996), or those in which substructural elements are flexible bodies in rigid contact with each other (Law et al., 2013a; Law et al., 2013b; Law et al., 2013c; Law & Ihlenfeldt, 2014). Sometimes, substructural elements are modelled as rigid bodies in flexible contact with each other (Huynh & Altintas, 2020). Of these, the flexible bodies in flexible contact modelling approach are thought to be more appropriate and rigorous than the other approaches. However, modelling substructural elements as being flexible requires the use of finite element (FE) methods. And since model orders can become very large with FE, the approach that approximates substructural elements as rigid bodies that are in flexible contact with each other are preferred for their simplicity and because analysis with them is computationally efficient.

All models are inaccurate due to the difficulty in correctly modelling interfaces. These are commonly modelled as spring-damper connections, parameters of which are usually updated by minimizing the difference between model-predicted and measured dynamics characterized by frequency response functions (FRFs) (Huynh & Altintas, 2020). Model updating is often guided by a global mode shape analysis of the machine from measurements. Mode shape analysis is usually done with the roving hammer or the sensor. Such measurements are time consuming, expensive, and fraught with errors.

Since global mode shape analysis is necessary to localize which interface parameters are to be updated, this paper proposes a new, alternative, and simpler way to update joint parameters of a machine tool multibody dynamic model

*Corresponding author E-mail: mlaw@iitk.ac.in

https://doi.org/10.58368/MTT.22.2.2023.23-28

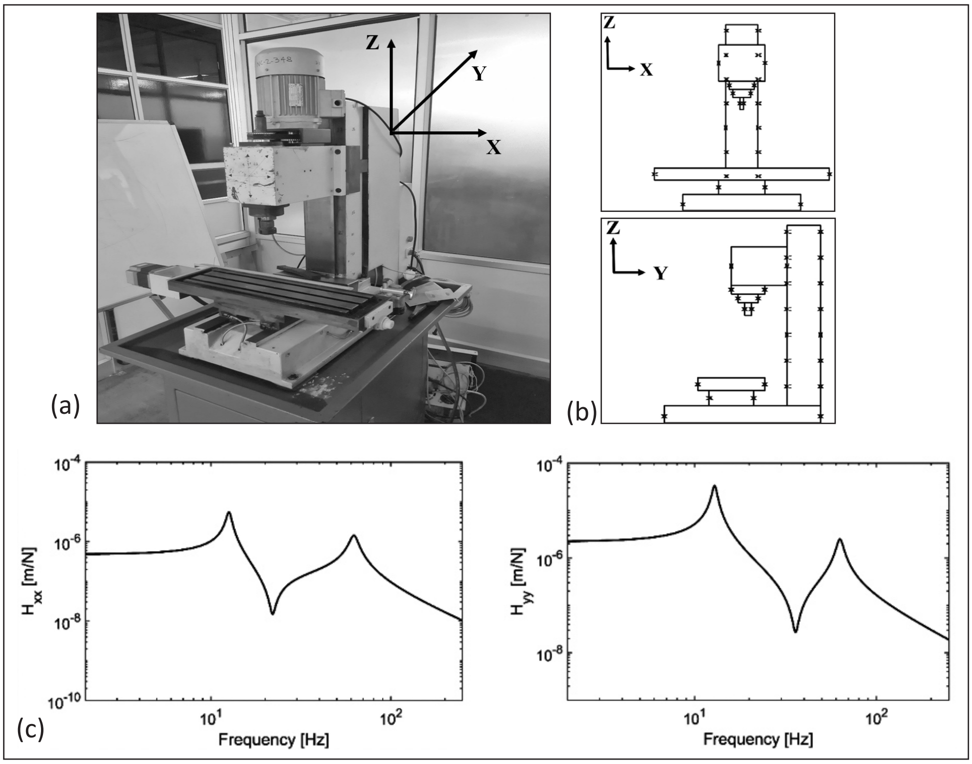

Fig. 1. (a) Machine being measured. (b) Measurement grid in two planes. (c) Direct FRFs in the X and Y directions.

based on the use of full-field vision-based modal analysis methods. The main idea is that mode shapes are to be identified using image processing schemes applied to a video recording of the vibrating machine of interest. This avoids the need for roving hammer/sensor type measurements and the associated pitfalls with those methods.

Vision-based methods are non-contact and do not require sophisticated acquisition hardware.And since every pixel is a virtual sensor, the method facilitates full-field shape analysis. Methods have hence found use in modal analysis of machine tool systems (Law et al., 2020; Gupta et al., 2022; Gupta & Law, 2021; Law et al., 2022; Lambora et al., 2022; Nuhman et al., 2022). Despite their advantages, their use has not been extended yet to update machine tool models. This paper aims to remedy that, and demonstrating as much is our modest contribution to the state-of-the-art. We update interface characteristics of a machine tool multibody dynamic model using vision-based methods for a representative small-sized 3-axis milling machine.

The remainder of the paper is organized as follows. Section 2 paper discusses traditional and vision-based modal analysis of the machine. Measured results guide development of a multibody dynamic model of the machine discussed in Section 3. We use MATLAB's Simscape™ environment to develop the model. Section 4 discusses parameter updating and compares the original, measured, and updated response of the machine to show that the updated model agrees with measured behaviour thus validating the procedure. Main conclusions follow.

2. Modal Analysis

Methods to measure the dynamics of this machine are discussed in this section. All measurements were made for when the machine was turned 'off'. At first, we discuss results obtained from a traditional experimental modal analysis (EMA) of the machine. Followed by which we discuss the proposed vision-based modal analysis.

2.1. Traditional experimental modal analysis

The machine shown in Fig. 1(a) has a classical C-frame type construction. Two axes in-plane motion are possible due to movement of table on the cross-slide, and the cross-slide on the base, respectively. The spindle housing moves on the column for the third axis motion. The machine has a combination of box and dovetail-type guideway.

To identify the natural frequencies, damping ratios and the modes shapes, the machine was excited at the spatial locations shown in Fig. 1(b) using an instrumented modal hammer. The response was measured using a tri-axial accelerometer. The spatial grid was chosen such that the global mode shapes of the structural elements could be identified. We roved the accelerometer location and kept the excitation location fixed to be at the spindle nose. We measured a total of 27 different locations. We used MALTF (CUTPRO V11.2 (2016) ©MAL Inc) to acquire data with a NI9234 data acquisition card with a NI9171 chassis. Sampling rates for these experiments were set to be 25.6 kHz with a frequency resolution of 1 Hz.

Measurements were processed in MATLAB to estimate modal parameters and shapes for the dominant modes in the XZ and in the YZ planes. Direct fitted FRFs at the spindle nose are shown in Fig. 1(c), and shapes in Fig. 2. There are two dominant modes in each of directions. Of these, the shape for the low frequency ~13 Hz mode shown in Fig. 2 suggests that this is a global rocking mode that is likely influenced by the joint characteristics between the base and the foundation. The higher frequency mode shape of the ~64 Hz mode seen in Fig. 2 shows the spindle housing moving together with the column, suggesting that the motion for this mode is likely influenced by the interface characteristics between these two substructural elements.

2.2. Vision-based modal analysis

To visualize mode shapes from a video recording of the machine tool, we recorded the response of the machine to an impulse-like input using a Samsung S20 smartphone camera. The setup to do so is shown in Fig. 2(a). This is a far field experiment such that the full-field response is visible. Since we use only one camera, we can estimate only in-plane motion of the machine. For the setup shown in Fig. 2(a), we estimate motion in the XZ plane. We conduct separate experiments with a different setup to similarly measure motion in the YZ plane. In both experiments, to reduce the influence of background noise, we use a white background. The distance from the camera to the machine was maintained to be 80 cm for both experiments. Video was recorded in its mp4 format at a frame rate of 960 frames per second. Since the higher frequency structural mode of interest is at ~64 Hz, this rate of recording video satisfies the Nyquist rate. The resolution of the video at this rate was 720 × 1280 pixels. Since the field of view was 1089 mm x 1176 mm, the per-pixel density was 1.97 mm/pixel. Since we use the phase-based motion magnification technique

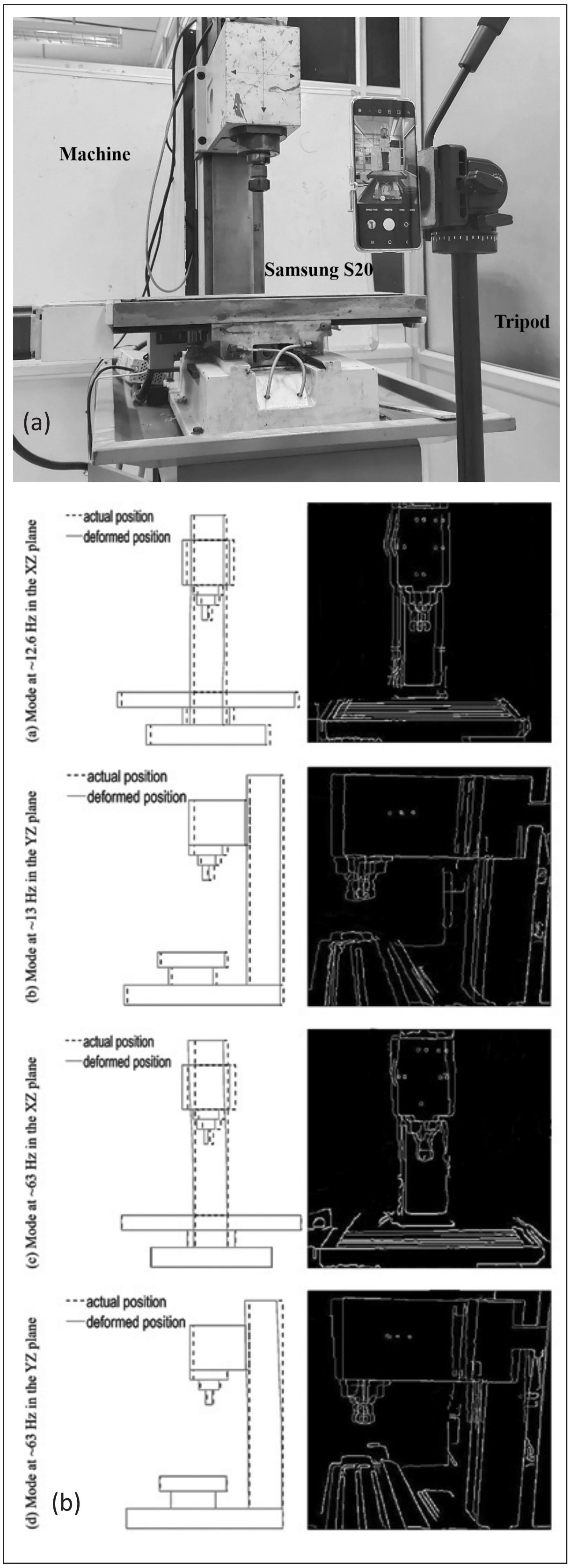

Fig. 2. (a) Setup for vision-based measurements. (b) Shapes from EMA and from vision-based measurements.

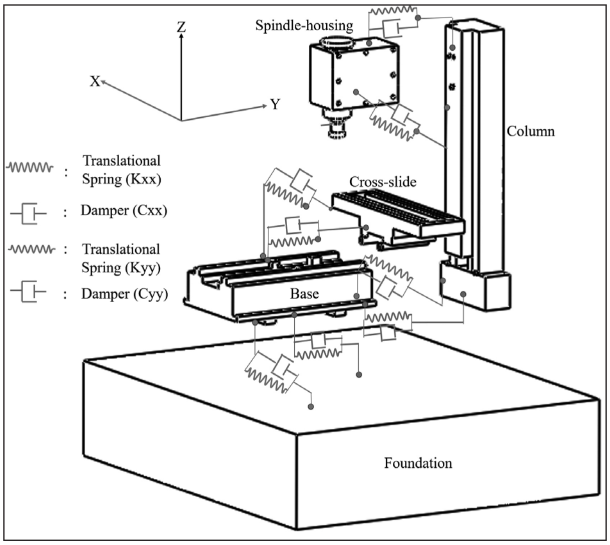

Fig. 3. Multibody dynamic model of the machine.

(Chen et al., 2015), we can resolve motion to estimate the shape of vibration.

We magnify motion of the two separate far-field video recordings of the machine in its orthogonal directions by appropriately setting the motion amplification factor to 100% and the noise attenuation factor was set to 20% for the lower frequency mode, and for the higher frequency mode, the amplification was 70%, and the noise attenuation was set to 5%, respectively. To aid visualization, we estimate the edge (Law et al., 2020) in a frame showing the deformed configuration of the machine and overlay that edge on an edge detected from a frame when the machine is at rest. Those detected edges are shown in Fig. 2(b) together with the shape obtained from the EMA. And as is evident, shapes estimated from both methods agree with each other. Since such mode shape analysis requires just one video recording of the machine, and since results are comparable to those obtained from EMA, the method is an advocate for itself. Knowledge of these shapes localizes the parameters to be updated in the multibody dynamic model of the machine.

3. Machine Tool Multibody Dynamic Model

The multibody dynamic model for the machine under investigation is shown in Fig. 3. The substructural elements of interest consist of the spindle with its housing, the column, the base, and the cross-slide with a table on it. Tool, tool-holder, spindle shaft, spindle bearings, and drive elements for each of the axes are neglected in this preliminary investigation. The inertia properties of the main substructural elements are obtained from their CAD models. All elements of the machine tool under investigation are cast, and, as such their density is assumed to be 6800 kg/m^3.

Substructural elements are connected to each other through linear springs and dampers. These interface characteristics are to be identified from the updating procedure. Joints are assumed to have stiffness in orthogonal directions only, and cross-directional characteristics are ignored. The machine is stiff in its Z direction, i.e., along its tool axis direction. Interfaces are hence assumed flexible only in the XZ and the YZ planes.

For the interfaces that are of the fixed kind, i.e., the interface between the foundation and the base, and the interface between the base and the column, joint stiffness is taken to be equivalent to the fixing bolt’s stiffness. For the case of the moving interfaces, i.e., the interfaces between the spindle housing and the column, and in between the cross-slide and the table, since these interfaces are of the dovetail and box guideway types, and since these are interfaces with continuous and distributed contact, idealizing the contact stiffness for such interfaces is not trivial. Hence, as a preliminary guess, the initial stiffness values for these interfaces is taken to be one order less than the stiffness of a bolted joint. Since modelling damping is also not trivial, as a starting guess, all interfaces are assumed to have a damping of 100 N-s/m. Since there are four interfaces of interest, there are a total of 16 different stiffness and damping elements that could potentially influence the response of the machine, and which need to be identified in the updating procedure.

The multibody model was developed in MATLAB’s Simscape™ environment that uses blocks representing substructural elements, constraints for the foundation, joints for the interfaces, and force elements for where the force excites the machine tool structure. We directly import CAD models of machine substructural elements and define interface springs and dampers as variables for them to be updated as necessary. An impulse like input is provided to the spindle separately in each of the orthogonal directions of interest and the resulting impulse response was obtained by solving the equations of motion. The input-output time series data was decomposed to the frequency domain to obtain the FRFs at the spindle nose. These FRFs are shown in Fig. 4.

As is evident from the FRFs, there are two modes each in the X and Y directions. This is consistent

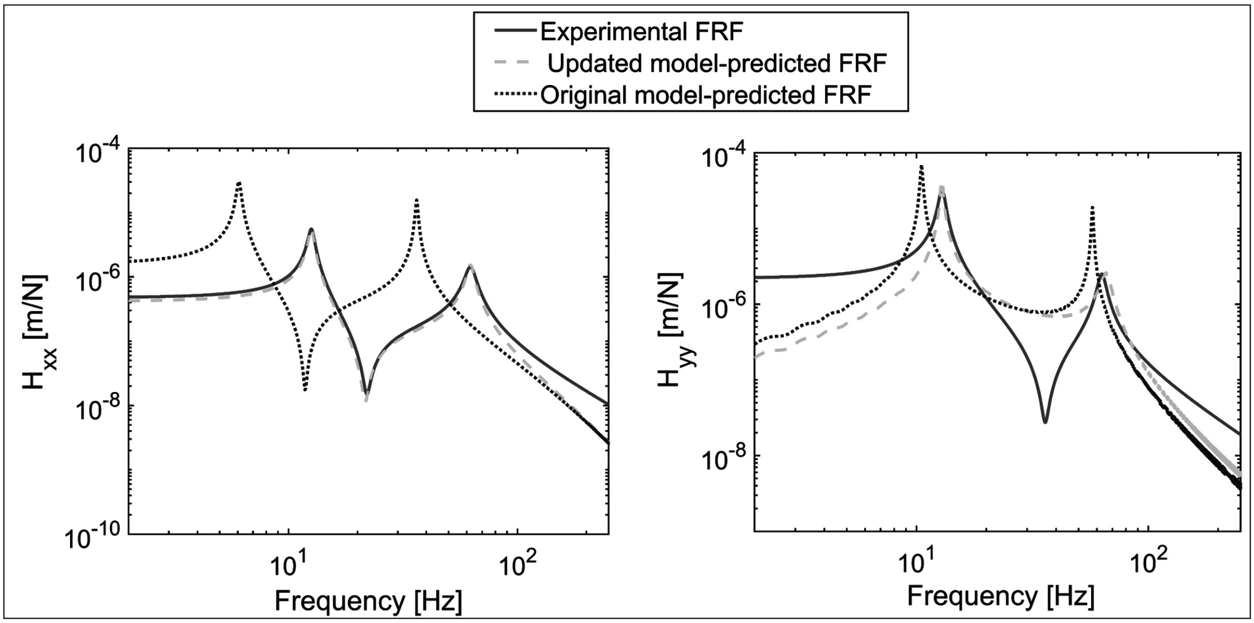

Fig. 4. Comparisons of modelled, updated, and measured FRFs.

with the measured FRFs shown in Fig. 1. Since our model ignores details of the tool, the tool holder, the spindle bearing, and of the drive elements for each axis, the low-frequency modes observed in Fig. 4 correspond to the vibrations of the main substructural elements. To get a sense of the shapes associated with each of the predicted modes, an eigenvalue analysis was performed and the eigenvectors from that give us the shapes. The Simscape environment can animate these, and the shapes observed were the same as those measured.

The measured frequencies are different than those predicted. The differences are attributable largely to modelled interface characteristics not being correct, which must hence be updated to make the model more representative of actual measured response. Procedures to update the model are discussed next.

4. Model Updating

We update the interface characteristics by minimizing the error, e between model predicted and measured FRFs:

$$e = \text{Minimize} \sum_{i=\omega_i}^{\omega_m} (\text{FRF}_{\text{measured}} - \text{FRF}_{\text{modelled}}) \quad ...(1)$$

wherein ω_i and ω_m are the range of frequencies of interest. We evaluate the evolution of this error for all joint parameters of interest. Of all the parameters, those in between the foundation and the base and in between the column and the spindle housing were observed to significantly influence the error between the measured and modelled FRFs in both orthogonal planes of interest, i.e., in the XZ plane and in the YZ plane. Stiffness and damping values in both directions at each of these interfaces were selected at which the error tends towards a local minimum. Each of these joint parameters settles to a different value than what was originally assumed. Since these parameters are not unique, they are not listed here. Interestingly, the error does not change with changing interface parameters for the joints in between the base and the column and in between the base and the cross-slide. This suggests that these joints do not contribute much to the global modes, and as such their parameters are kept at their initial guess and are not updated.

Predicted response with these updated parameters is compared with the response predicted with the originally assumed parameters and with the measured response. These FRFs are shown in Fig. 4. And as is evident, the updated model-predicted response is in very good agreement with the measured response in the XZ plane. In the YZ plane however, the trough between two peaks is missed in the updated response, as is the low frequency behaviour. This suggests that the model can be improved further.

5. Conclusions

This paper presented a new and simpler way to estimate global machine tool mode shapes using vision-based modal analysis procedures such that those shapes could help localize which machine tool joint parameters must be updated for the development of a more accurate multibody dynamic model of the machine. Estimated shapes were found to agree with shapes estimated using the more traditional experimental modal analysis procedures.

Global measured mode shape analysis was used to guide the development of a multibody dynamic model of a machine with the main substructural elements modelled as rigid bodies in flexible contact with each other. Joint parameters were identified by updating the model using a simple minimization scheme in which the goal was to minimize the difference between model-predicted and measured response. Updated model-predicted response was found to agree with measured response.

The multibody dynamic machine tool model could be refined further to include details of the spindle and different drive elements. That updated machine tool multibody dynamic model would be a step towards realizing an accurate digital twin that can be used to guide design changes, for mechatronic simulations, and to study complex process-machine interactions

Acknowledgments

This work was supported by the Government of India's Science and Engineering Research Board's Core Research Grant number CRG/2020/001010.

References

Bianchi, G., Paolucci, F., Braembussche, P. D., Brussel, H., & Jovane, F. (1996). Towards virtual engineering in machine tool design. *CIRP Annals, 45,* 1. https://doi.org/10.1016/S0007-8506(07)63085-6

Chen, J. G., Wadhwa, N., Cha, Y-J., Durand, F., Freeman, W. T., & Buyukozturk, O. (2015). Modal identification of simple structures with high-speed video using motion magnification. *Journal of Sound and Vibration, 345,* 58-71. https://doi.org/10.1016/j.jsv.2015.01.024

Gupta, P., Rajput, H. S., & Law, M. (2022). Vision-based modal analysis of cutting tools. *CIRP Journal of Manufacturing Science and Technology, 32,* 91-107. https://doi.org/10.1016/j.cirpj.2020.11.012

Gupta, P., & Law M. (2021). Evaluating tool point dynamics using smartphone-based visual vibrometry. *Procedia CIRP, 101,* 250-253. https://doi.org/10.1016/j.procir.2020.09.196

Huynh, H. N., & Altintas, Y. (2020). Modeling the dynamics of five-axis machine tool using the multibody approach. *ASME J. Manuf. Sci. Eng., 143*(2). https://doi.org/10.1115/1.4048854

Lambora, R., Nuhman, A. P., Law, M., & Mukhopadyay, S. (2022). Recovering cutting tool modal parameters from fractionally uncorrelated and potentially aliased signals. *CIRP Journal of Manufacturing Science and Technology, 38,* 414-426.

Law, M., & Ihlenfeldt, S. (2014). A frequency-based substructuring approach to efficiently model position-dependent dynamics in machine tools. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 229*(3), 304-317. https://doi.org/10.1177%2F1464419314562264

Law, M., Ihlenfeldt, S., Wabner, M., Altintas, Y., & Neugebauer, R. (2013a). Position-dependent dynamics and stability of serial-parallel kinematic machines. *CIRP Annals, 62,* 375-378. https://doi.org/10.1016/j.cirp.2013.03.134

Law, M., Phani, A. S., & Altintas, Y. (2013b). Position-dependent multibody dynamic modeling of machine tools based on improved reduced order models, *ASME J. Manuf. Sci. Eng., 135* (2).

Law, M., Altintas, Y., & Phani, A. S. (2013c). Rapid evaluation and optimization of machine tools with position-dependent stability. *International Journal of Machine Tools and Manufacture, 68,* 81-90. https://doi.org/10.1016/j.ijmachtools.2013.02.003

Law, M., Gupta, P., & Mukhopadhyay, S. (2020). Modal analysis of machine tools using visual vibrometry and output-only methods. *CIRP Annals, 69*(1), 357-360. https://doi.org/10.1016/j.cirp.2020.04.043

Law, M., Lambora, R., Nuhman, A. P., & Mukhopadhyay, S. (2022). Modal parameter recovery from temporally aliased video recordings of cutting tools. *CIRP Annals, 71*(1), 329-332.

Nuhman A. P., Singh, A., Lambora, R., & Law, M. (2022). Methods to estimate subpixel level small motion from video of vibrating cutting tools. *CIRP Journal of Manufacturing Science and Technology, 39*, 175-184.

Vishal Singh is a Data Scientist at Verizon Data Services India. He received his Master's degree from the Indian Institute of Technology Kanpur, India. His research interests were focused on updating a machine tool multibody dynamic model, modal analysis and visual vibrometery. (E-mail: vishal.me14@gmail.com)

Mohit Law is an Associate Professor at the Department of Mechanical Engineering at the Indian Institute of Technology Kanpur, India. He received his Ph.D from the University of British Columbia, Canada. His research interests centre on understanding how and why machine tools vibrate, measuring those vibrations, and on how best to mitigate them.