3D mode shape visualization of machining robots using motion magnification

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Abstract:
Modal analysis of machining robots is necessary to characterize how the robot will respond to cutting-process induced excitations. Modal characterization includes estimating the robot's mode shapes – which must be done in 3D due to the robot's open-chain kinematic configuration. The traditional 3D mode shape estimation method using contact-type accelerometers and/or non-contact type laser vibrometers involves moving the sensor(s) over a spatial measurement grid. These procedures are time-taking and cumbersome. As a simpler and faster alternative, this paper leverages developments in visual vibrometry and motion magnification to demonstrate that 3D robot mode shapes can be easily visualized by processing two videos of the vibrating robot, recorded with a handheld smartphone camera from two different viewpoints. Method is illustrated on one large robot integrated with a machining spindle. 3D shape analysis reveals the dominant low-frequency mode of interest to be complex and coupled across directions.

Keywords: Visual vibrometry, Motion magnification, Modal analysis

1. Introduction

Retrofitting robots with motorized spindles makes it possible to cut with them. Lower costs and larger work volumes of robots as compared to machine tools make them an attractive alternative for machining complex free-form parts [1]. However, since robots were not designed to withstand excitations from cutting forces, and since they are generally open-chain and flexible, they tend to vibrate when excited by the cutting process [1]. It hence becomes necessary to characterize the robot's vibrations to guide its use for cutting.

Measuring robot vibrations is usually done using traditional modal analysis procedures. These involve the use of a modal hammer or shaker to excite and one or more accelerometers or laser sensors to measure response. Modal parameters constituting the natural frequencies, damping ratios and mode shapes are then extracted from the measured input-output data using one of the many modal parameter identification schemes. Though such procedures are routine, shape analysis requires measurements at several different spatial locations by moving the sensor or the actuator, or both. Moreover, since most robots have an open-chain kinematic configuration, their response is not symmetrical and is also often coupled in different directions – requiring a full 3D mode shape analysis. Robots also exhibit nonlinear dynamics. Furthermore, since the dynamics of robots are strongly pose-dependent, measuring robot dynamics using traditional modal analysis procedures becomes cumbersome, time-taking, and prone to errors.

As a simpler and faster alternative, this paper leverages developments in visual vibrometry [2] and motion magnification [3] to illustrate that 3D robot mode shapes can be visualized by processing videos of the vibrating robot. Such illustration is the main new technical contribution of this paper.

The main idea in visual vibrometry is to use image processing and computer vision schemes to register motion from video of vibrating artefacts. This is done by tracking/learning how pixel intensities change in every frame of the video [2]. Motion magnification involves magnifying subtle motion in video at specific frequencies of interest to aid visualization [3]. Vision-based motion registration and motion magnification offers advantages of being non-contact, full-field, and not requiring sophisticated data acquisition systems. Just a camera to record and a computer to process video are necessary. As such, these methods have already found use in measuring and visualizing vibrations of civil infrastructure [4] and machine tool systems [2]. Despite its use across other domains and applications, visual vibrometry and motion magnification have not been illustrated yet on robots. This brief paper addresses that.

The remainder of the paper is organized as follows. Section 2 discusses the experimental setup and plan to measure the vibration characteristics of a typical large machining robot. We excite with a modal shaker and measure response using a tripod-mounted smartphone camera. Section 3 discusses the method to register motion from the video and magnify it. We discuss robot as well as marker tracking to help aid visualization of the shape of vibration. Section 4 discusses the results. This is followed by discussions and conclusions.

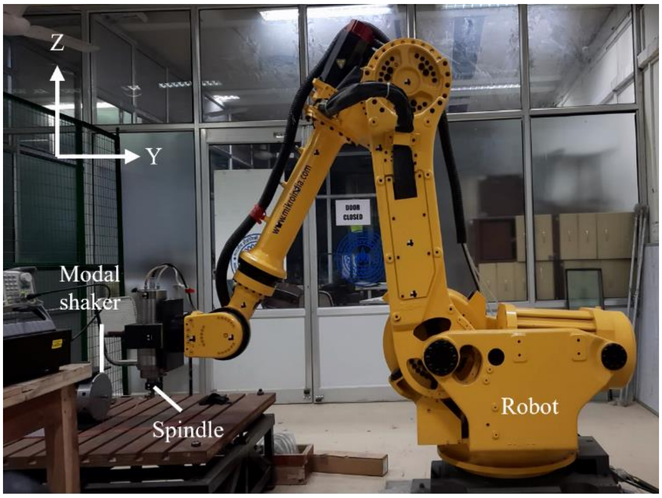

Fig. 1 Machining robot excited with a modal shaker and measured with a tripod mounted video camera. The view shows what the camera sees.

2. Experimental setup and plan

The robot used in this study to illustrate mode shape estimation and visualization is a Fanuc make S-430i series robot that has a payload of ~150 kg and that is retrofitted with a 7.5 kW machining spindle. The robot is shown in Fig. 1. The robot is excited with a B&K make modal shaker. Since a modal shaker can provide a consistent harmonic excitation, we prefer to use it over a modal hammer, with which providing a consistent and repeatable input force is difficult. Nonlinearities in response are avoided by providing the consistent input force. Response to harmonic excitation was recorded using a tripod mounted Samsung make A51 series smartphone camera. Fig. 1 shows only what the camera sees in the YZ plane. The response of the full robot was also separately recorded in the XZ plane with the excitation remaining in the Y direction. Since the robot's modes are coupled across directions, excitation was limited to only the Y direction.

Since motion magnification procedures require that the natural frequencies of the vibrating artefact are known apriori, at first, a slow sine-sweep excitation was provided to the robot in the frequency range of 9 Hz to 18 Hz. This range was selected based on prior information of the range of the dominant low-frequency mode of the robot. Response as recorded with the camera at 30+ frames per second with resolution of 3418 × 1920 pixels. Tool motion registered from this video using established image processing schemes [2] was benchmarked with acceleration also measured at the tool. The accelerometer is not shown in Fig. 1. A FFT of the response estimated from video showed the dominant low frequency mode to be at ~13 Hz. This mode was visible for response measured in the XZ plane as well as for response measured in the YZ plane - suggesting that this is a coupled mode.

The robot was then excited only at the natural frequency and its response was again recorded with the camera. Excitation was limited to the Y-direction. Two videos were recorded. One for response in the XZ plane, and another for response in the YZ plane. Response from this video was magnified as is discussed next in Section 3.

3. Magnifying motion

Motion magnification was carried out using the schemes reported in [3, 5, 6]. The magnification process is done using the λ·vue software developed by researchers at the MIT CSAIL and Quanta Research Institute. The software is readily accessible from the cloud [3, 5, 6]. The code takes the video recording of the robot as the input, examines the temporal variations in pixels in every frame, and using that information, it identifies small motion and amplifies the motion within the desired frequency range, which in our case is at ~13 Hz. We feed a 3-second-long video that takes about 10 minutes to process on the cloud.

For each magnified video, two frames with visible displacement are processed to get edges of the robot. The displacements of these edges are then magnified/amplified arbitrarily to aid visualization of the mode shape of the robot at this natural frequency. Local representative regions in one view are zoomed in and shown in Fig. 2.

Though the robot's continuous edges are extractable, since it is easier to visualize the shape by tracking how a few markers at fixed spatial locations change their position across frames/time, we also additionally place and track markers on the robot. We use a total of eleven markers, in both views (XZ and YZ). Positions of markers in XZ view are highlighted in Fig. 2. These markers are then used to construct a stick diagram which also helps to visualize the mode shape of the robot. The stick model may have some extra nodes to aid in visualization. Since we use markers, and since we are interested in a 3D shape, i.e., a shape of vibration in the XZ and the YZ planes, and since it is possible that a positive displacement in one direction is coupled to a negative displacement in the other direction, we use the displacement in the Z direction to establish this correlation. We reason that for a given frame of analysis, the marker location with a positive Z displacement in one plane will also have a positive displacement in the other plane at the same instant of time. This means that, if a frame with a higher Z coordinate for a marker has a positive X displacement among the two frames in the XZ view but a negative Y displacement among the two frames in the YZ view, a positive displacement in X would correspond to a negative displacement in Y for that marker node.

4. Results

The motion magnified response of the robot is shown in Fig. 3. That response is overlaid over the original undeformed configuration. Since showing the full shape with all details of the robot would clutter the figure and make shape estimation difficult, we show only the stick diagrams in the figure. The figure shows the stick diagram in its three planes, i.e., the XY (Fig. 3(a)), the XZ (Fig. 3(b)), and the YZ (Fig. 3(c)) planes. The 3D deformed shape is also shown in Fig. 3(d). As is evident, the robot clearly has a 3D shape of vibration at 13 Hz. From the XY plane it is clear that some links move to the left, some forward while others in both directions. From the XZ plane it is clear that most links move leftward, and from the YZ plane it is clear that the links connected to the spindle move forward, while those at the back move backwards.

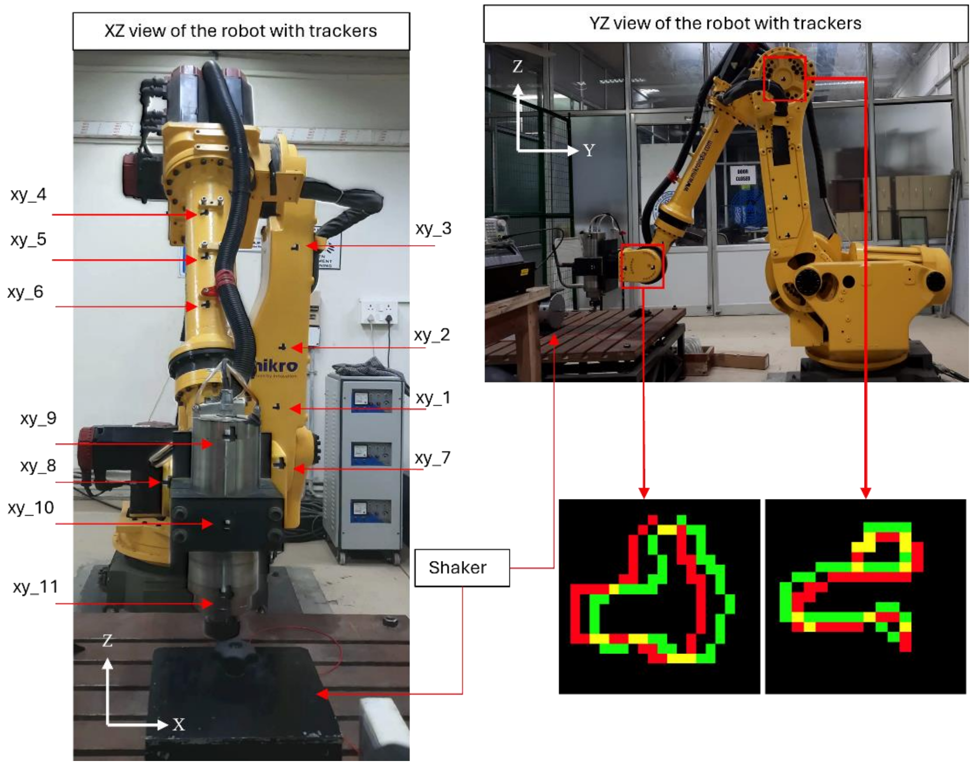

Fig. 2 Two views showing what the camera sees in the XZ and the YZ planes along with marker locations highlighted on the robots. Also shown are two representative local regions with their magnified displacements in terms of only their edges. In these magnified views, the red and green colors represent the location of the edges in two frames of the video.

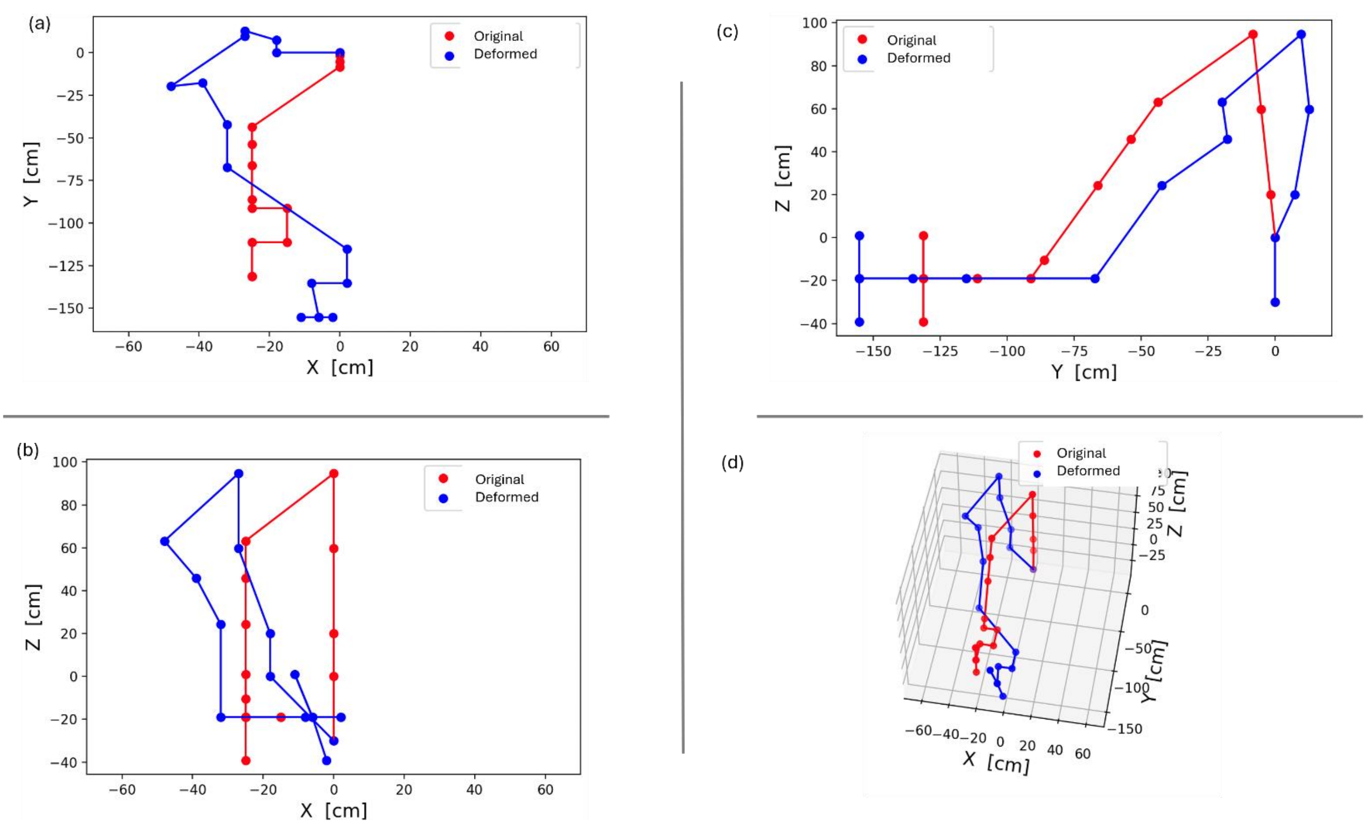

Fig. 3 3D mode shape of the robot. The figure shows the deformed configuration overlaid on the original configuration. (a) Deformation as seen in the XY plane, (b) deformation as seen in the XZ plane, (c) deformation as seen in the ZX plane, and (d) 3D representation. Note: The deformed configurations shown are arbitrarily scaled to aid visualization of the mode shape. As such, the units on the axes should not be conflated to be real displacements.

5. Discussions

Results shown in Fig. 3 were limited to only the shapes visualized using vision and motion magnification. Benchmarking this shape with the shape estimated by roving an accelerometer was tried but since the accelerometer data was not clean, those results are not presented herein. Shape analysis from measured input-output force-acceleration data requires the use of the real and imaginary parts of the frequency response functions (FRFs). A flip or a change in the sign of the imaginary part for measurements at different spatial locations suggests that those different locations are experiencing out of phase vibrations. However, when this test was applied to measure FRFs at the same spatial locations as the markers, the flips were not obvious. This is likely due to how flexible the robot is as well as difficulty in mounting the accelerometer such that the measured response was in line with the provided excitation such to avoid measuring projected components of accelerations. Though efforts are ongoing in trying to benchmark with acceleration measurements, since the proposed 3D mode shape visualization method is so easy to implement (excite, record video, and post process to magnify shape), we think that the proposed method already offers a viable alternative and can result in a paradigm shift in the way robot dynamics are measured.

6. Conclusions

This paper leveraged developments in visual vibrometry and motion magnification to demonstrate that 3D robot mode shapes can be easily visualized by processing two videos of the vibrating robot, recorded with a handheld smartphone camera from two different viewpoints. The proposed method has advantages of being non-contact, full-field, and not requiring sophisticated data acquisition and processing. And as such overcomes the disadvantages of the traditional 3D mode shape estimation method using contact-type accelerometers and/or non-contact sensors that are cumbersome. Though the method was demonstrated on one robot and only one mode was magnified for shape visualization, the method can be easily extended to measure and visualize other higher-frequency modes. Future work could also focus on estimating how these shapes change with the robot's posture and to uncover the robot's nonlinear dynamic behavior. Finally, such dynamic characterization can be used to guide how to machine with the robot.

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