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Experimental protocol for the dynamic modeling of machining robots

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Résumé :

L'adaptation des robots industriels en vue de réaliser des opérations continues comme l'usinage représente aujourd'hui un besoin croissant de l'industrie manufacturière. Pour améliorer la qualité et la précision de l'usinage robotisé, il est nécessaire de réduire les vibrations causées par la flexibilité de la structure robotique. La connaissance de son comportement dynamique est ainsi primordiale. Dans cet article, une analyse modale expérimentale d'un robot poly-articulé à six degrés de liberté est réalisée afin d'en extraire les paramètres modaux que sont les fréquences propres, les amortissements modaux, et les déformées modales. Le robot étudié est de type ABB IRB 6660 et est équipé d'une électrobroche UGV. Dans cet article, un protocole expérimental décrit les différentes étapes des expérimentations conduites avec un marteau d'impact comme source d'excitation de la structure. L'influence du changement de pose du robot et d'orientation de la broche, sur les modes vibratoires, est investiguée durant les tests. Les résultats expérimentaux sont discutés et l'identification des paramètres modaux permet de simuler les vibrations du robot d'usinage et d'établir un premier modèle dynamique.

Abstract :

The adoption of robots for machining operations is now a growing need in manufacturing industries. To improve the quality and accuracy of robotic machining, it is necessary to reduce the vibrations caused by the flexibility of the robotic structure. The knowledge of its dynamic behavior is thus essential. An experimental modal analysis of a poly-articulated robot with six degrees of freedom is performed to extract its modal parameters: natural frequencies, modal damping ratios, and mode shapes. The robot under study is an ABB IRB 6660 robot equipped with a spindle. In this paper, an experimental protocol describes the different stages of experiments conducted using an impact hammer as a source of structure excitation. The influence of changes in the robot's configuration and the spindle orientation on the vibration modes is examined. The experimental results are discussed, and the identification of modal parameters enables a simulation of the vibration of the machining robot, providing a first dynamic model.

Mots clefs : Analyse modale expérimentale, Robot, Usinage, Vibration, Dynamique

1 Introduction

Robots are increasingly being used in industry, where they perform dangerous or repetitive tasks with accuracy at high speeds. Nevertheless, the use of machining robots in industry is not widespread compared to that of handling and welding robots [1], even though they represent a new alternative to the use of machine tools, because of their flexibility and low cost. Several reasons can be put forward to explain this. In addition to the difficulties associated with the handling of this kind of machine (integration into the production line, programming ...), there are robot performance issues. In Dumas thesis [2], machining operations were performed in order to evaluate the performances of an industrial robot executing a zig-zag groove. Accuracy and vibration issues were detected, due to the flexibility of the structure and the direct contact of the tool on the work-piece. The robot is subject to different forces (machining forces, inertia, and control) which cause static and dynamic deformation leading to tool vibration. This vibration can damage the spindle or the tool,

and the problem affects the quality of the work-piece surface [1]. To study the vibration phenomenon, it is important therefore to characterize the dynamic behavior of the machining robot through an experimental modal analysis. Giving a first modal model, this work will be a base for an operational modal analysis of the robot's dynamic behavior during machining and will define a more precise cartography of the robot's behavior. Then the main goal is to find the most favorable workspace for machining operations by managing two kinematic redundancies provided by an additional 2 axis tilting rotary table synchronized with the robot [3].

2 Experimental Modal Analysis

Modal analysis [4] is used to analyze the dynamic behavior of different structures in the aerospace, automotive, civil engineering and aims to determine the modal parameters of a structure. Using experimental modal analysis, a modal model is determined to describe the dynamic behavior of the machining robot: ABB IRB 6660 robot + High Speed Machining (HSM) spindle + Milling tool (figure 1). Experimental modal parameters respectively described by natural frequencies, modal damping ratios, and mode shapes are obtained from a set of Frequency Response Function (FRF) measurements. Impact testing is the most commonly used method for finding the modal parameters of structures. It requires a minimum of equipment, and is simple to perform at a low cost. However, its drawbacks lie mainly in its reproducibility (operator effect) and uncertainty with respect to the direction of the applied force.

2.1 Description of the machining robot

The machining robot is an ABB IRB 6660 robot with 6 degrees of freedom (DOF) corresponding to 6 active joints ($q_1, q_2, q_3, q_4, q_5, q_6$) and has also 3 passive joints (q_{p1}, q_{p2}, q_{p3}). It has a parallel arm structure that enhances its accuracy and payload capacity. With a positioning repeatability of 0.07 mm and a pose accuracy of 0.18 mm, the IRB 6660 is designed for pre-machining operations [5].

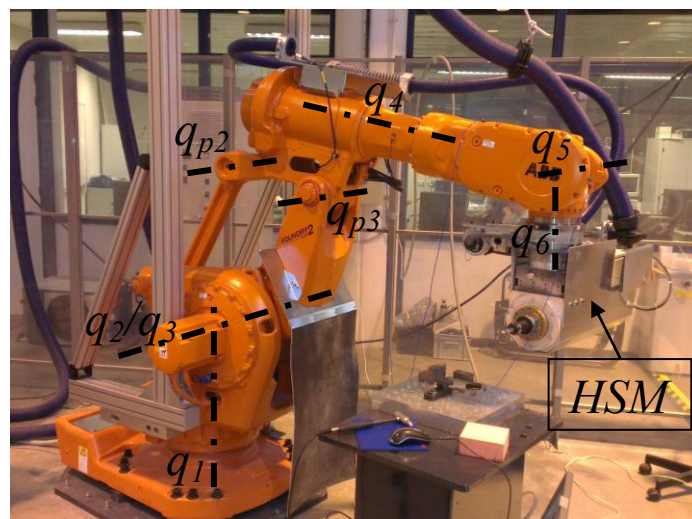


Figure 1: Machining robot ABB IRB 6660

2.2 Measurement Setup

Single Input Multiple Output (SIMO) testing with an impact hammer was found empirically, during the first tests, not to be suitable to obtain reliable FRFs, since the average FRF of the system was predominated by the FRF of the nearest response point to the excitation location. Thus, a roving hammer test was performed in the later experiments, where the structure of the robot was impacted in different locations.

The idea of using a huge number of measurement points in order to reproduce a reliable dynamic behavior is not always effective since a less number of points well positioned on the tested structure give the same results [6]. Therefore, before doing modal testing, it is important to select the best points (location + direction) where the vibration will be measured in order to provide a robust dynamic model. Several techniques exist to determine the optimal placement of sensors on a structure, and these techniques are essentially based on the structure's finite element model (FE) [7]. At this moment of the study, a

reliable FE model is not available, so it was decided to choose the adequate sensor placements using a trial and error process and through engineering judgments. 7 sensors, connected to the 8 channels data acquisition system, are used to measure the vibration response of the structure; these are unidirectional PCB accelerometers. Even The flexibility of the robot is located mainly in its joints [8], all the robot's structure parts were instrumented by accelerometers. In total, 32 points were selected on the machining robot (figure 2 (a)) three of them being measured in two different directions, giving vibration responses of a total of 35 DOF. With only 7 available accelerometers, the 35 DOF were separated into 5 measurement groups of 7 DOF each. Point "1" was defined at the tool tip, and point "29" on the HSM spindle; the other points were defined on the robot structure. For each measurement group, a roving hammer test was conducted with an impact hammer equipped with a force sensor, hitting 3 different DOF (1, 21, and 6).

In order to investigate the robot dynamic behavior in the whole working space, two sets of experimental investigation are carried out respectively characterized by a horizontal position of the HSM spindle working in a vertical plane (figure 2(a)) and a vertical position of the spindle working in a horizontal plane (figure 2(c)). For each direction, three different robot configurations were investigated in order to verify whether the configuration influences the robot's modal parameters or not. In the horizontal plane, the milling tool was displaced 380mm between two consecutive positions (CH1, CH2, and CH3), and in the vertical plane (CV1, CV2, and CV3), the displacement was 400 mm. In fact, the robot was moved within the range of its limits, which explains this choice of displacement distances.

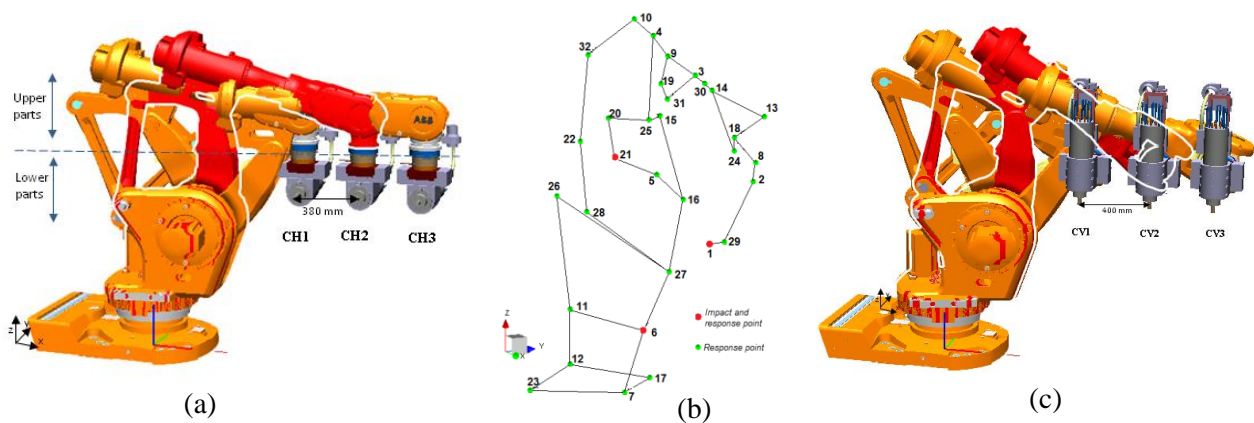


Figure 2: Machining robot (a) robot's pose with HSM spindle in the horizontal plane (b) wire form with measured DOF corresponding to CH2 configuration (c) robot's pose with the HSM spindle in vertical plane

3 Results

Influence of the command: The first modal test experiments were conducted with the robot's gears activated and non-activated in order to compare these two sets. A slight difference in the amplitude of the measured FRFs was observed, and the signals were noisier when the gears were activated, but they had the same shape.

Repeatability of the measure: A second test was performed by measuring the FRF of the whole system in configuration CH2, and then the robot was moved from this configuration and returned to it to measure the FRF again. 10 natural frequencies were identified in each of the two measurements, and then the difference between each pair of the frequencies was calculated. The average of the differences was about $0.83\text{Hz} \pm 5.69\%$, which indicates a good repeatability of the measures.

Later, in order to have similar conditions as in machining operations, vibrations measurements were conducted with robot's gears activated for the two directions of the HSM spindle; the identified natural frequencies were found in two frequency ranges: Range 1 [0-300 Hz] and Range 2 [300- 2500Hz].

Figure 3 shows the two frequency ranges where the range 2 has a higher amplitude than the range 1 for the measured FRF. In this figure, FRF curves are compared for the three configurations of the machining robot with the spindle in the horizontal plane. The natural frequencies of the system are determined on the amplitude peaks. The corresponding damping ratio is calculated using the PolyMAX method [9] (or polyreference least-squares complex frequency-domain method) implemented on the LMS Test.Lab software used to analyze the obtained FRFs.

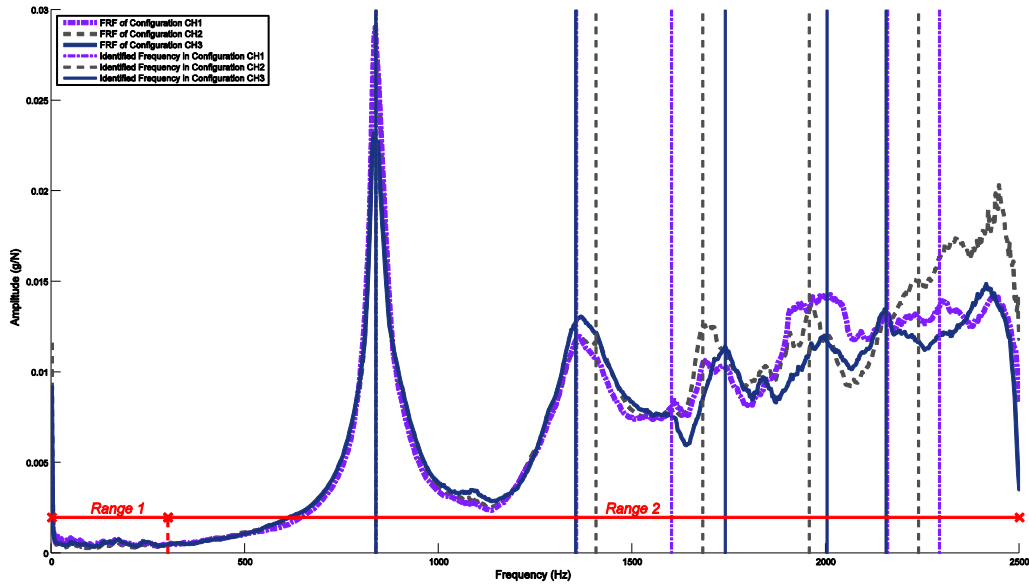


Figure 3: Measured FRF for different configurations of the machining robot with the spindle in the horizontal plane and the identified natural frequencies.

Tables 1 and 2 show 5 identified frequencies and their corresponding damping ratios for different configurations of the machining robot. The natural frequency of the first mode in the range 2 corresponds to the inherent modal properties of the milling tool. At this frequency, only the displacement of the measured DOF on the tool was observed in the animation of the whole system’s mode shape. The first mode did not vary greatly (frequency relative standard deviation is about 0.07%) since it doesn’t depend on the robot geometric configuration. It was noticed that there was a significant difference between the natural frequencies of the following modes according to the robot geometric configuration. This result confirms that the posture of the robot influences the values of its modal parameters.

| Modes of Range 2 | CH1 | | CH2 | | CH3 | | Frequency relative standard deviation (%) |
|------------------|------------------------|-------------------|------------------------|-------------------|------------------------|-------------------|---|
| | Natural Frequency (Hz) | Damping ratio (%) | Natural Frequency (Hz) | Damping ratio (%) | Natural Frequency (Hz) | Damping ratio (%) | |
| 1 | 838.098 | 1.64 | 836.943 | 1.42 | 837.307 | 1.69 | 0.07 |
| 2 | 1355.805 | 5.18 | 1405.344 | 1.63 | 1353.071 | 5.26 | 2.14 |
| 3 | 1600.899 | 0.89 | 1681.242 | 0.97 | 1739.929 | 2.14 | 4.16 |
| 4 | 2158.787 | 2.58 | 1956.837 | 0.79 | 2002.339 | 0.62 | 5.19 |
| 5 | 2292.898 | 1.25 | 2239.069 | 6.04 | 2155.372 | 2.05 | 3.1 |

Table 1: Identified natural frequencies and damping ratios in the range 2 of the different configurations of the machining robot with HSM spindle in the horizontal plane

| Modes of Range 2 | CV1 | | CV2 | | CV3 | | Frequency relative standard deviation (%) |
|------------------|------------------------|-------------------|------------------------|-------------------|------------------------|-------------------|---|
| | Natural Frequency (Hz) | Damping ratio (%) | Natural Frequency (Hz) | Damping ratio (%) | Natural Frequency (Hz) | Damping ratio (%) | |
| 1 | 835.742 | 1.60 | 834.518 | 2.37 | 835.621 | 2.38 | 0.08 |
| 2 | 1348.518 | 3.51 | 1353.574 | 4.29 | 1347.800 | 3.51 | 0.23 |
| 3 | 1602.272 | 0.29 | 1607.124 | 0.18 | 1603.657 | 0.14 | 0.15 |
| 4 | 1961.462 | 1.10 | 2034.108 | 4.99 | 1977.571 | 0.59 | 1.91 |
| 5 | 2176.779 | 1.81 | 2169.686 | 1.60 | 2294.202 | 1.13 | 3.15 |

Table 2: Identified natural frequencies and damping ratios in the range 2 of the different configurations of the machining robot with HSM spindle in the vertical plane

Figure 4 represents clear FRF curves in the range 1 and as for the range 2, it can be concluded that the robot's dynamic behavior depends on the robot's configuration. However, as can be seen in figure 3, the amplitude of the FRF curves in the range 1 is much lower than for those in the range 2.

Validation of the identified natural frequencies in both range 1 and range 2 is done using the AutoMAC matrix (figure 5). This method is based on MAC (Modal Assurance Criterion) matrix [10] which states the linear dependency between two vectors. A MAC value of 100% denotes that two vectors are collinear and a MAC value of zero indicates that two vectors are orthogonal. Here the AutoMAC compares a set of modes with themselves.

The mode shapes of the machining robot in the range 1 showed that DOF points in the upper parts of the robot were more influenced by the impact hammer, where a significant displacement of these DOF points was observed compared to those in the lower parts of the robot. However, in the range 2, DOF points in the lower parts were more excited by the impact hammer blows. Thus, we can conclude that to study the dynamic behavior of the machining robot in the range 1, the dynamic model can be reduced to the DOF points that are in the upper parts and specifically points: 2, 3, 4, 8, 13, 19, 20, and 32. If the range 2 is investigated, then DOF points placed in the lower parts of the robot can be primarily measured, and more specifically points: 5, 6, 16, 21, 22, 25, and 26.

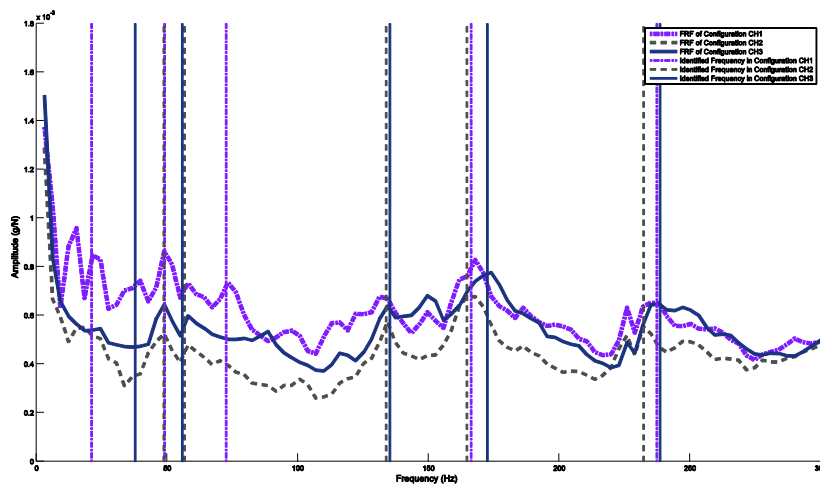


Figure 4: Measured FRF in the range 1 for different configurations of the machining robot with the spindle in the horizontal plane and the identified natural frequencies

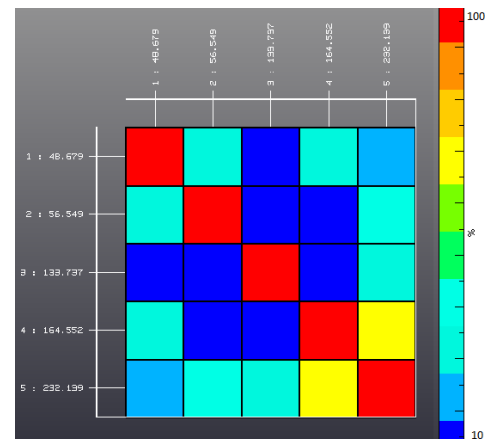


Figure 5 : AutoMAC matrix for the identified frequencies in the range 1 for configuration CH 2

| Modes | CH1 | | CH2 | | CH3 | | Frequency relative standard deviation (%) |
|-------|------------------------|-------------------|------------------------|-------------------|------------------------|-------------------|---|
| | Natural Frequency (Hz) | Damping ratio (%) | Natural Frequency (Hz) | Damping ratio (%) | Natural Frequency (Hz) | Damping ratio (%) | |
| 1 | 20.988 | 2.71 | 48.679 | 1.64 | 37.758 | 2.88 | 38.7 |
| 2 | 48.965 | 3.12 | 56.549 | 5.51 | 55.681 | 0.83 | 7.72 |
| 3 | 72.498 | 4.69 | 133.737 | 1.92 | 135.109 | 3.38 | 31.42 |
| 4 | 166.244 | 2.55 | 164.552 | 3.62 | 172.366 | 3.11 | 2.45 |
| 5 | 237.249 | 1.85 | 232.139 | 0.81 | 238.441 | 2.77 | 1.41 |

Table 3: Identified natural frequencies and damping ratios in the range 1 of the different configurations of the machining robot with HSM spindle in the horizontal plane

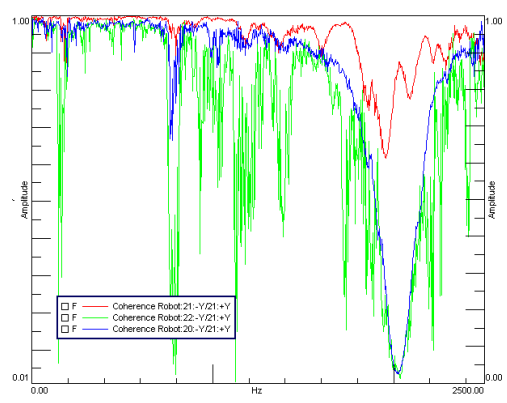


Figure 6 : Coherence functions of points 20, 21 and 22 when impact hammer hits on point 21 in configuration CH2

4 Conclusion

An experimental modal analysis of a machining robot has been performed and presented in this paper. This study was conducted using an impact hammer as an excitation source and 7 accelerometers to measure the vibration responses of the system. The measurements repeatability was enough satisfying to conclude about the influence of the robot's configuration on the modal parameters. However, the amount of energy delivered by the impact hammer was not sufficient to excite all of the measured DOFs, and this can be confirmed by observing the coherence function for each FRF, which was not near to the value 1 along the frequency range (figure 6). The non-linearity of the structure can also be accentuated by the impact hammer and be a source of variation in the coherence function [11]. Nevertheless, these experiments provided an idea about the DOFs to be measured when performing more complicated modal testing requiring more time than an impact hammer test. In this context, a characterization of the dynamic behavior of the robot using a shaker as an excitation source is under preparation before performing an operational modal analysis of the robot. The shaker test leads to a higher measured FRFs quality, and the force level of the excitation can be controlled, contrary to impact testing.

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