Modal identification of machining robots in service

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Abstract

The requirement of high performance in the industry has led to the introduction of industrial robots in the machining field. Machining robots have become a potential and promising alternative to standard machine tools because of their important workspace and their high flexibility in the machining of complex parts. However, their lack of precision and rigidity is still a limit for precision tasks.

Therefore, the modal identification of a machining robot is important for an accurate knowledge of its dynamic behavior. Usually, the characterization is carried out through an experimental modal analysis performed at rest. However, the excitation, artificially, created by a hammer or a shaker is not representative of the real cutting force applied in machining. Unfortunately, the dynamic behavior of a machining robot in rest differs significantly from that identified in service.

In this paper, an experimental modal analysis of an ABB IRB 6660 robot is firstly investigated. Then, modal parameters are identified during a machining operation through an operational modal identification. A significant variability of modal parameters identified at rest from those identified in service is observed, which highlights the need to identify robot modal parameters under operational machining conditions.

1. Introduction

Industrial robots have an important role in the industry. They are used in a large area of applications such as welding, assembling and painting. Due to their significant advantages of high flexibility, large workspace, more accessibility, high productivity, and relatively low cost compared to a CNC machine tool (MOCN), industrial robots have been introduced in the machining field. However, many factors are degrading the accuracy of the machining operation performed. One of the main problem is the low performance of the robot in terms of stiffness that strongly affects the machining stability and the quality of the workpiece during machining operations. Therefore, it is interesting to evaluate the robot structure modal parameters. As a part of the proposed study, we focus on the identification of modal parameters of a poly-articulated industrial robot ABB IRB 6660 (located at SIGMA Clermont) equipped with a HSM Spindle (36000 rpm, 15.2kW).

Despite the huge amount of work present in the modal identification domain, the modal identification of machining robots is still nowadays considered as an open issue [1-2]. Most of the scientific works presented in literature are related to the modal parameters identification through an Experimental Modal Analysis (EMA) under an artificial excitation using an impact hammer or shaker tests, at rest [3]. However, the dynamic behavior of machining robots at rest is not the same as that observed in service, due to numerous differences such as the command influence and the machining interaction with the workpiece. Thereby giving rise to the need to identify this dynamic behavior in machining conditions, using an Operational Modal Analysis (OMA) approach.

The objective of this work is to identify modal parameters of a machining robot in order to point out the influence of the task position in the robot workspace concerning the modal behavior of the structure. The paper is organized as follows: in section 2, an experimental modal analysis of the ABB IRB 6660 robot is conducted in different configurations of the robots in its workspace. The identified modal parameters vary significantly from a configuration to another, at rest, which introduces the need to identify modal parameters continuously in operational conditions. For an accurate knowledge of the dynamic behavior of the considered robot, an operational modal analysis is carried out in section 3 during a milling test. The identification is investigated using the Transmissibility Function Based (TFB) method. Finally, section 4 concludes this paper.

2. Experimental modal analysis

2.1 Experimental setup and measurements

An experimental Modal Analysis (EMA) of the ABB IRB 6660 machining robot is conducted in different positions in its workspace, in order to observe the evolution of the modal behavior of the robot at rest. Four positions (P_1, P_2, P_3, P_4) along the *Y* direction, as shown in Figure 1, corresponding to four robot arm extension configurations are considered.

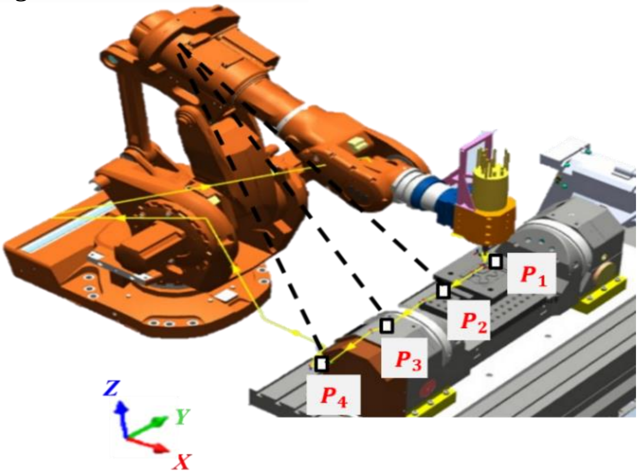

Figure 1: Robot Tool Center Point (TCP) positions along the *Y* direction in the robot's workspace

The EMA is based on an experimental identification of the Frequency Response Functions (FRFs), where the responses are measured with accelerometers and the excitation is performed using an impact hammer. Exciting forces are measured with force transducers. Two tri-axis PCB accelerometers, with a sensitivity of 99.9 mV/g and 101.2 mV/g respectively, were mounted on the spindle head in the two directions *X* and *Y*, as shown in Figure 3. Model identification was performed by applying impact hammer shocks in the two directions *X* and *Y*.

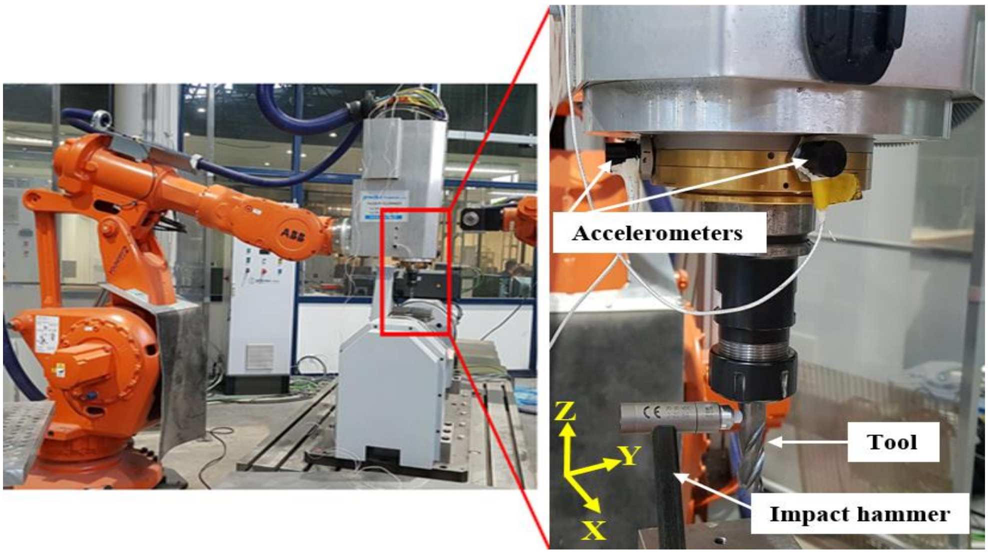

Figure 2: Experimental protocol for an impact testing on an ABB IRB 6660 machining robot

Two FRFs H_{xx} and H_{yy} were measured from the two experimental tests.

$$\begin{cases} H_{xx}(\omega) = \dfrac{X(\omega)}{F_x(\omega)} \\ H_{yy}(\omega) = \dfrac{Y(\omega)}{F_y(\omega)} \end{cases} \quad (1)$$

2.2 Results and discussion

The PolyMAX method is then investigated in order to estimate modal parameters from the two measured FRFs H_{xx} and H_{yy}. Natural frequencies f and damping ratios ξ identified from the measured FRF H_{xx} for each configuration of the robot in position 1 from are given in Table 1.

Mode	1st position (P_1)		2nd position (P_2)		3rd position (P_3)		4th position (P_4)	
	f (Hz)	ξ (%)	*f (Hz)*	ξ (%)	*f (Hz)*	ξ (%)	*f (Hz)*	ξ (%)
1	11.09	1.70	11.06	1.47	11.09	1.81	10.30	2.01
2	16.98	1.25	18.17	1.26	18.29	0.72	----	----
3	23.54	1.44	23.44	0.91	23.39	0.32	24.15	0.31
4	43.30	3.69	45.28	4.35	46.33	4.26	46.50	3.58
5	61.09	3.40	62.58	4.65	62.95	4.73	62.94	4.85
6	136.76	3.11	137.61	3.12	138.54	2.90	139.48	2.51
7	155.08	2.24	155.15	2.13	155.57	2.31	156.4	2.21
8	177.71	4.40	179.35	4.12	179.28	3.75	178.89	3.87
9	----	----	----	----	----	----	210.82	0.75
10	213.09	2.26	213.39	2.29	217.58	2.30	221.85	0.21
11	285.25	5.16	280.23	0.55	282.50	0.97	283.87	1.04
12	359.37	0.57	359.54	0.49	359.56	0.59	360.50	0.70
13	407.62	1.01	403.56	0.71	403.56	0.69	403.53	0.66
14	457.66	0.59	449.48	2.52	440.86	0.62	447.54	1.01
15	511.65	0.96	509.99	0.86	510.2	1.08	510.55	1.22
16	553.82	0.99	545.64	1.16	542.47	1.40	----	----

Table 1: Identified modal parameters of the robot ABB IRB 6660 in position 1 through an EMA

Results show that by changing the robot position, different structural modes are excited and identifiable. In order to quantify the variation of the identified natural frequency as a function of the configuration and the position of the robot in its workspace, the relative standard deviation is calculated as follows:

$$\varsigma = \frac{\sigma * 100}{\mu} \tag{2}$$

Where σ is the standard deviation and μ is the mean value of the identified frequencies.

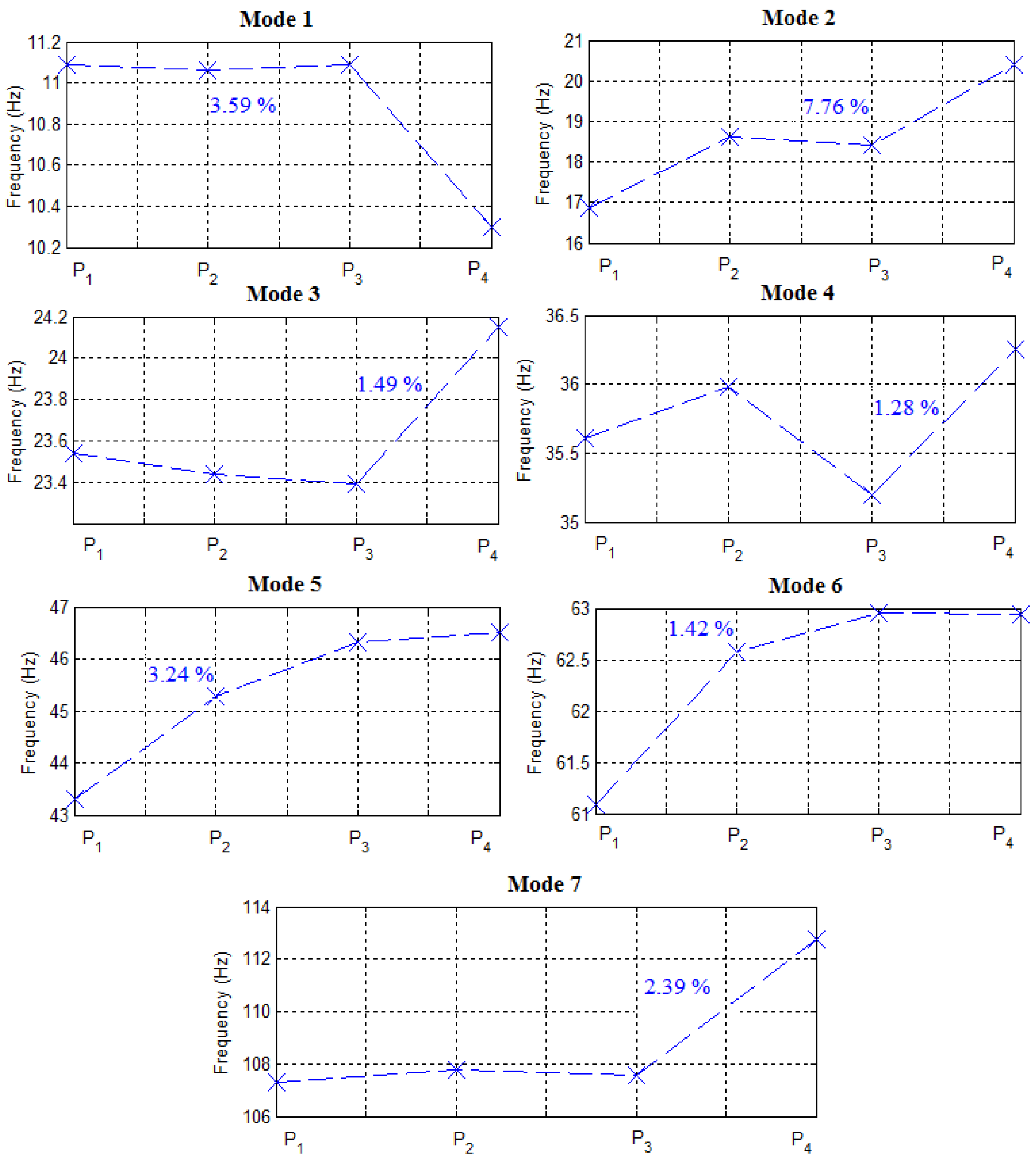

Figure 3: Evolution of the natural frequencies of the robot ABB IRB 6660 in function of its position

The figure 3 shows the evolution of the natural frequencies, corresponding to the first seven robot modes as a function of its position in its workspace. These modes are retained because they are systematically present in the four considered positions of the robot.

Results show that the identified natural frequencies of the considered modes vary between 1.28% and 7.76% in function of the robot position, at rest. This demonstrates that experimental modal analysis is not sufficient for an accurate knowledge of the dynamic behavior of the machining robot, and leads to the necessity of in-service modal parameter identification. Nevertheless, EMA provides an idea about the modal model of the robot structure. For this reason, EMA is carried out as a preparation step before performing an operational modal analysis of the machining robot ABB IRB 6660.

3. Operational modal analysis

3.1 Experimental setup

An operational modal analysis is carried out, when robot is in the first position (P_1), in order to identify modal parameters of the robot in service and compare results with those identifies through impact tests . Four different machining operations in the X and Y directions (pass 1, pass 2, pass 3 and pass 4), as illustrated in Figure 4, are performed with the ABB IRB 6660 robot, using a three-tooth, 16 mm end-mill cutting tool. Machining operations are carried out on a square aluminum (2017) piece of 100 mm per side, at a constant spindle speed of 10000 rpm. The axial and the radial depth of cut are equal to 3 and 12 mm, respectively. The feed rate is set to 0.3 mm/rev, resulting in chip loads of 0.1 mm/tooth.

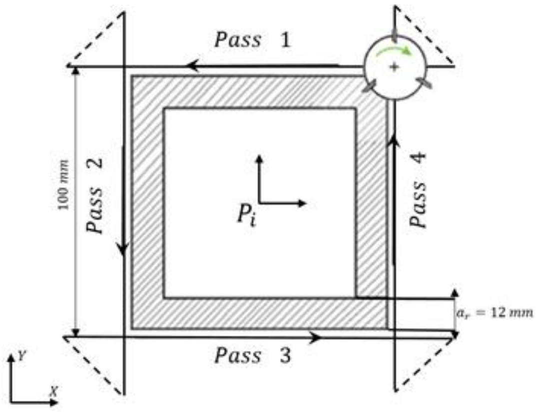

Figure 4: Machining operation when robot is in position 1 and configuration 1

Two PCB-type tri-axis accelerometers, with a sensitivity of 99.9 mV/g and 101.2 mV/g respectively, are mounted on the spindle head in the X and Y directions. Four each pass, two acceleration signals are recorded simultaneously using the LMS TEST.Lab acquisition system. The rotational spindle speed is equal to 10000 rpm, so harmonic components will be multiple of 166,66 Hz. It is clear in Figure 5, the first harmonic frequency is around 166 Hz.

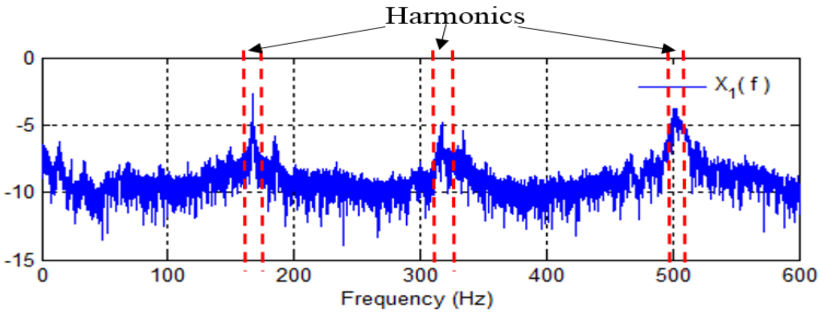

Figure 5: FFT of the measured acceleration in the x direction in pass 1 and presence of harmonics associated to the machining process

2.2 Operational modal identification by the Transmissibility Function Based (TFB) method

The operational modal analysis method based on transmissibility functions, proposed by Devriendt et al. [5], is the only OMA technique able to identify modal parameters in presence of preponderant harmonic components during machining process [6-7].
A transmissibility function is defined as the ratio between the motion response $X_i^k(\omega)$ and the reference motion response $X_j^k(\omega)$ under a single force located at k.

$$T_{ij}^{k}(\omega) = \frac{X_i^k(\omega)}{X_j^k(\omega)} \tag{3}$$

From the measured acceleration signals during the cutting path, four transmissibility functions are calculated:

$$\begin{cases} T_{xy}^{1}(\omega) = \dfrac{X_1(\omega)}{Y_1(\omega)} \\ T_{xy}^{2}(\omega) = \dfrac{X_2(\omega)}{Y_2(\omega)} \\ T_{xy}^{3}(\omega) = \dfrac{X_3(\omega)}{Y_3(\omega)} \\ T_{xy}^{4}(\omega) = \dfrac{X_4(\omega)}{Y_4(\omega)} \end{cases} \tag{4}$$

Transmissibility functions cross each other at the resonant frequencies, corresponding to the poles of the rational transmissibility functions ΔT_{ij}^{-1}.

$$\Delta^{-1} T_{ij}^{kl}(\omega) = \frac{1}{T_{ij}^{k}(\omega) - T_{ij}^{l}(\omega)} \tag{5}$$

When considering the TFB method, modal parameters are obtained from the transmissibility functions. In this case, six rational transmissibility functions ΔT_{ij}^{-1} are calculated:

$$\begin{cases} \Delta T_{12}^{-1}(\omega) = \dfrac{1}{T_{xy}^{1}(\omega) - T_{xy}^{2}(\omega)} \\ \Delta T_{23}^{-1}(\omega) = \dfrac{1}{T_{xy}^{2}(\omega) - T_{xy}^{3}(\omega)} \\ \Delta T_{34}^{-1}(\omega) = \dfrac{1}{T_{xy}^{3}(\omega) - T_{xy}^{4}(\omega)} \\ \Delta T_{14}^{-1}(\omega) = \dfrac{1}{T_{xy}^{1}(\omega) - T_{xy}^{4}(\omega)} \\ \Delta T_{13}^{-1}(\omega) = \dfrac{1}{T_{xy}^{1}(\omega) - T_{xy}^{3}(\omega)} \\ \Delta T_{24}^{-1}(\omega) = \dfrac{1}{T_{xy}^{2}(\omega) - T_{xy}^{4}(\omega)} \end{cases} \tag{6}$$

Theoretically, not all of the zeros of $\Delta^{-1} T_{ij}^{kl}$ are the system's poles. In Figure 6, the six rational transmissibility function are illustrated. The red dashed lines indicate the location of the harmonic frequencies. It's clear that in ΔT_{ij}^{-1} most of the harmonics are reduced or even eliminated. Hence, the rational transmissibility function contains harmonic components in addition to the system poles.

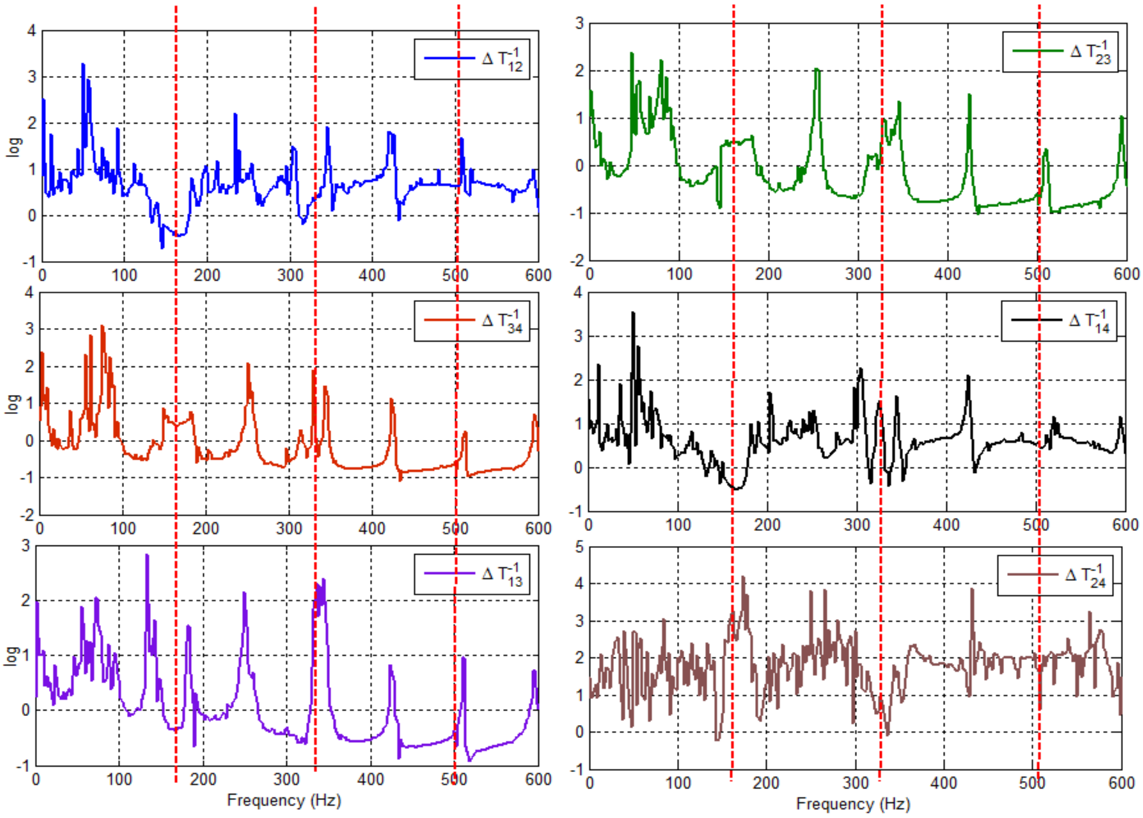

Figure 6: Rational transmissibility function ΔT_{ij}^{-1} and presence of harmonic components

It is therefore necessary to distinguish the physical poles of the system from spurious ones. For this reason, this two steps identification procedure is proposed:

a. Step 1: Stabilization diagram

Stabilization diagram shows the stability of the poles as a function of ΔT_{ij}^{-1} and as a function of increasing model order were used to distinguish the spurious modes from the physical poles. The identification of the modal parameters is performed by applying the frequency domain estimator "PolyMAX" to ΔT_{ij}^{-1}.Then, the modes corresponding to the order "*n*" are compared to the lower order modes "*n-1*". If the modal parameters variation doesn't exceed the defined tolerances (variation of 5% in frequency and 5% in damping ratio corresponding to the identified pole), the mode is considered stable and indicated by the letter (s), otherwise it is unstable and indicated by the letter (o).
The sum $\Delta^{-1}T$ of the six measured functions ΔT_{ij}^{-1} is plotted when the stability diagram is generated, in order to take the robot behavior in its entirety.

$$\Delta^{-1}T = \Delta^{-1}T_{12} + \Delta^{-1}T_{23} + \Delta^{-1}T_{34} + \Delta^{-1}T_{14}\Delta^{-1}T_{13} + \Delta^{-1}T_{24} \quad (7)$$

The figure 7 shows the stabilization diagram, established for an order varying from 33 to 72.

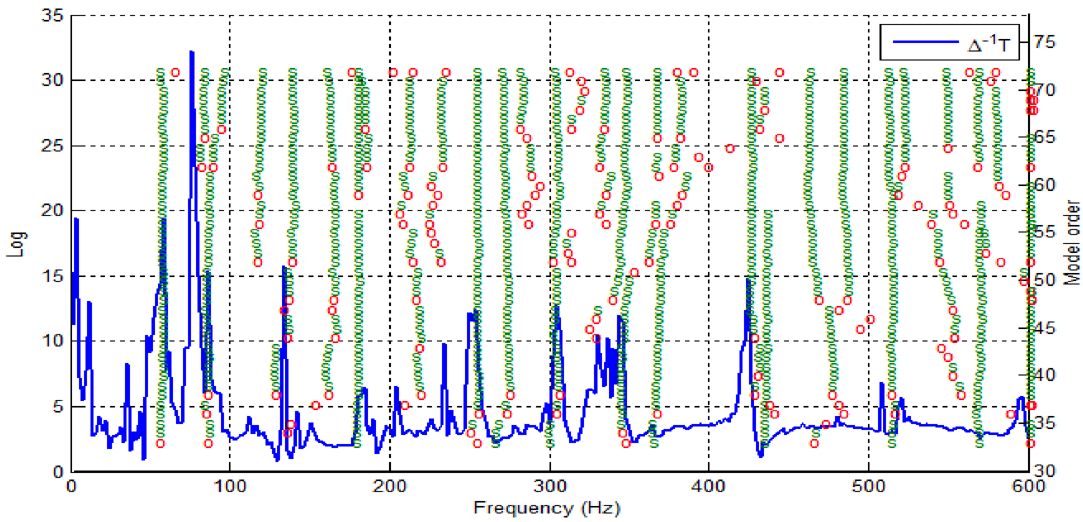

Figure 7: Stabilization diagram (s: stable pole, o: unstable pole)

The stabilization diagram is considered in order to identify the physical poles and to separate the digital poles. However, some modes are identified and verify the frequency and damping stability criteria, although they are not structural modes. This is largely due to the fact that the ΔT_{ij}^{-1} functions contain modes that are not related to the robot's modal behavior.

b. Step 2: Selection of the system's poles by means of singular value decomposition of the transmissibility matrix

To select only the correct system poles, the following transmissibility matrix **T** is considered, and a singular value decomposition is performed.

$$\boldsymbol{T} = \begin{bmatrix} T_{xy}^{1} & T_{xy}^{2} \\ T_{xy}^{3} & T_{xy}^{4} \end{bmatrix} \tag{8}$$

At the system poles λ_r, the rank of the transmissibility matrix is equal to one. Consequently, $\sigma_1(s) > \sigma_2(s) \geq 0$. The peaks of $\frac{1}{\sigma_2}$ as a function of frequency indicate the system's poles. Thus, from this curve, we obtain the information on the location of the robot's natural frequencies.

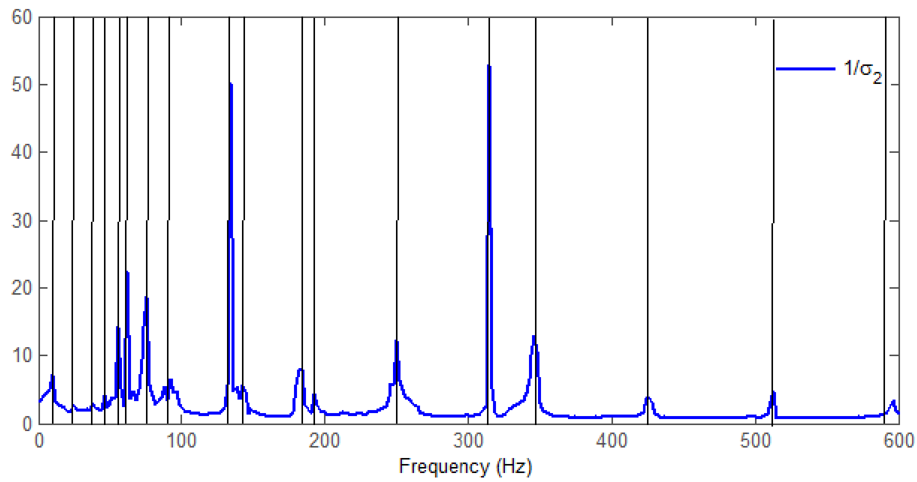

Figure 8: Selection of the system's poles by means of singular value decomposition

When applying the singular value decomposition of the proposed transmissibility matrix, all of the harmonics are eliminated and only the correct poles are selected, as shown in Figure 8. The modal parameters identified through an EMA and an OMA approach (TFB), when robot is in position 1, are illustrated in Table 2.

	AME		AMO	
Mode	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
1	11.09	1.70	10.29	2.54
2	16.98	1.25	----	----
3	23.54	1.44	22.69	0.29
4	----	----	38.04	0.24
5	43.30	3.69	49.96	0.45
6	----	----	56.98	1.24
7	61.09	3.40	63.67	3.58
8	----	----	75.50	0.48
9	----	----	93.67	0.91
10	136.76	3.11	134.04	0.25
11	155.08	2.24	141.24	2.55
12	177.71	4.40	182.37	0.98
13	213.09	2.26	190.27	0.45
14	----	----	252.05	0.31
15	285.25	5.16	----	----
16	----	----	316.48	0.53
17	359.37	0.57	346.35	0.43
18	407.62	1.01	----	----
19	457.66	0.59	424.82	0.31
20	511.65	0.96	512.25	0.19
21	553.82	0.99	595.55	0.18

Table 2: Identified modal parameters of the robot ABB IRB 6660 in position 1 and configuration 1 through an EMA/OMA

Firstly, an evolution of the identified modal parameters from the rest state to the machining state, can be noticed, due to the spindle rotation and the significant changes in the robot dynamic behavior. Also, structural modes which are not identified through experimental modal analysis, appear through the operational modal identification analysis. This proves that the energy delivered by the impact hammer is not sufficient to excite all of the structural poles of the machining robot ABB IRB 6660. Generally, the damping ratios, in service, are strongly reduced compared to those identified at rest. This is due to the tool/piece interaction that makes the robot structure more rigid. These results illustrate the importance of the modal parameters identification, in machining conditions. Although, the EMA is of great value in order to obtain a modal model as a reference for the validation of the modal parameters obtained, in service.

Conclusions

The evolution of the machining robot performance as a function of its position and the orientation of the tool center point is important in order to ensure stability during machining operations. This paper aims at characterizing the dynamics change of the robot dynamical behavior through several points of the workspace. Especially the evolution of its modal parameters for different configurations of the workspace is analyzed.

In this paper, the modal identification of a machining robot is proposed. This analysis is done, principally, in two stages. Firstly, the identification is conducted when robot is at rest, in different configuration in its workspace. Frequency analysis showed a small change in owns way their four configurations depending on the position. Results make it possible to evaluate the evolution of its modal behavior at rest and introduce the need to identify modal parameters of the robots in service. Thereafter, the operational modal analysis of the machining robots with the transmissibility function based method (TFB) was studied. The TFB method is adequate for machining conditions because of its ability to distinguish structural poles from spurious ones [7]. Modal parameters identified from an OMA are

different from those identified through an EMA. This is because the conditions of the machining robot at rest are not the same from its real conditions during machining, due to numerous differences such as the command influence and the machining interaction with the workpiece.
In perspective, an analysis of the measured vibration responses will be made in order to highlight the dynamic behavior in different work configurations of the robot, under machining process. Monitoring the evolution of the robot modal parameters in its workspace, in service, is one of the main insights of this future work.

Acknowledgments

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