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Analysis of Vibrations of the IRB 2400 Industrial Robot

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Abstract: This article provides an analysis of low-frequency vibrations in the IRB 2400 industrial robot using motion amplification technology based on image analysis. This technology allows visualisation of the vibration of the entire robot and analysis of the vibrations of the robot points that can be selected after the image acquisition process has been performed. Impulse force generated with a modal hammer was used to induce robot vibrations. A vibration analysis has been performed that takes into account the different positions of the robot arm. The analysis indicated a strong relationship between the system response and the robot arm position and the robot's interaction with the environment. The results obtained will be used to plan a robotic mechanical machining process, taking into account the minimisation of robot vibrations.

Keywords: vibration analysis, industrial robot, motion amplification

1. Introduction

Today, industrial robots are increasingly used in industry, inter alia, in machining, welding, assembly processes. For machining operations, industrial robots provide an economical and flexible alternative to standard CNC machines [1]. Machining operations performed by CNC machine tools are able to provide greater accuracy and stability for the process [11, 12]. However, their maintenance costs are higher and their mobility capabilities are lower than for robots. Therefore, CNC machines are often replaced by industrial robots [4]. Articles [2, 4] show the general technical limitations of robots that appear during the robotic machining operation, i.e. accuracy, susceptibility, and ability to excite the resonant frequencies of the robot The stability of the robot machining process is linked to the rigidity of the robot and to the vibrations that occur during machining. Therefore, studies are being carried out to reduce the impact of negative phenomena occurring during the robotic machining processes.

Proper planning of the robotic machining process requires knowledge of the dynamic properties of the robot. A mathematical model of the mechanical robot structure can be identified in the following experiments: modal analysis, measurement of robot structural stiffness, measurement of stiffness within the manipulator workspace [1]. This article discusses resonance frequencies analysis. Based on the review of existing solutions, examples of the use of modal analysis of ABB [10, 13] and KUKA robots were found. Articles [1, 5, 7, 9] performed a modal analysis for KUKA manipulators to determine the ex-cited frequencies of resonant vibrations. Impulse force generated by a modal hammer was used to excite vibrations and a frequency response function was then determined. The studies presented showed the relationship between the robot arm position and the excited natural vibration frequencies. Articles [6, 8] provide experimental modal analysis for the ABB manipulator. Another work [3] extends the frequency determination problem to include an analysis of the uncertainty of the determination of resonance zones.

As the literature has shown, determining a robot's natural frequencies is important for the estimation of stable parameters of the robotic process [3]. This is especially important when the robot is physically interacting with the environment. It is very important that robotic stations are in most cases adapted to the individual technological requirements. Therefore, the robots are differentiated by tools, tool holders connecting with the arms of the robots, force sensors between the arms of the robots and the tools, and the base on which the robots are mounted. All of this causes the weight and stiffness distribution for each robot to be different, therefore the frequency of the vibrations in the robot and the attachment are different. It follows that if the robot's vibration properties are to be considered in the planning and execution of processes, a study of these properties should be performed for each robot. Therefore, the study presented in this article carried out an analysis of vibrations in the IRB 2400 industrial robot. The results of this analysis will be used in the planning and implementation of a robotic milling process.

The available literature did not analyse the vibration of the robots when the machining tool and the workpiece interact. This issue seems to be worth examining because in the conditions of contact between the robot and the environment both the stiffness of the system and the limits of motion change. Comparison of the frequency of open system vibrations (without contact with the workpiece) and closed system vibrations (contact with the

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workpiece) is important in the context of preventing vibrations and this is the main contribution of the article.

2. Construction of the test station and test methodology

The study uses a built robotic test station, fitted with additional measurement elements for modal analysis (Fig. 1). The robotic station consists of an ABB IRB 2400 robot with a PDS electrospindle of 2.2 kW, an IRBP A positioner with T-table and an IRC5 controller. The robot is equipped with a force control package and has an ABB force sensor 660 mounted between the robot arm and the electrospindle holder.

The Iris M system, consisting of a camera and a computer with RDI Motion Amplification software, was used to record and analyse robot vibrations. This system allows acquisition of an image and its further processing. The main functions used in this study were:

- The amplification of the recorded motion;
- Analysis of the vibrations of selected regions (points) in the field of time and frequency.

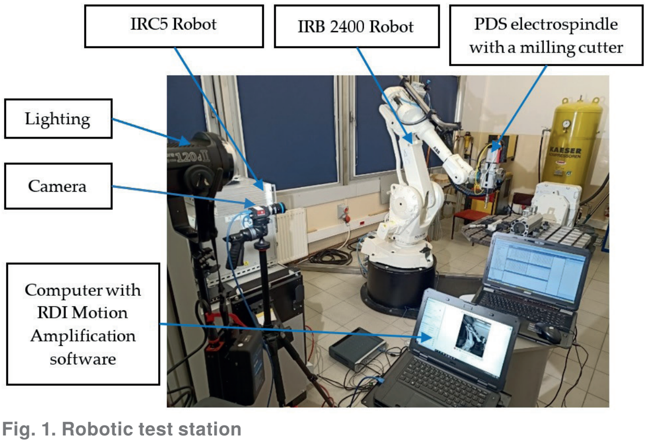

Fig. 1. Robotic test station
Rys.1. Zrobotyzowane stanowisko badawcze

The amplification of the recorded motion allows observation of motions with amplitude of several micrometers at multiple magnification, thus helping to understand the behaviour of the system. On the other hand, vibration analysis of the selected regions marked in the analysed image allows the determination of the motion parameters at a given point and performance of a Fourier transformation of the vibration course. The available filters allow the isolation of each vibration frequency and filtration of the image in such a way that each mode of the robot can be seen individually. This latter functionality is particularly useful in the context of robot vibration analysis because it allows determination of the direction of vibrations at a given frequency and the deformation form on the robot arm.

The frequency range at full resolution is 60 Hz, which limits the analysis to low-frequency vibrations associated with joint compliance. At full resolution, the method's accuracy is 2.5 micrometers from a distance of approximately 1 meter with a 50 mm focal length lens, allowing for the analysis of vibrations with very small amplitudes. It is possible to increase the frequency bandwidth of the analysis at the expense of the recorded image size. This is associated with an increase in frame rate and, consequently, a shorter exposure time, which leads to a deterioration in image quality. Based on the authors' experience, an acceptable frame rate is 400 frames per second, enabling vibration spectrum analysis in the range of 0–200 Hz while maintaining sufficient image quality for motion analysis.

During the test, an image was captured for 5 seconds at a resolution of 1920 × 1200 at a rate of 109 frames per second. Therefore, robot vibrations could be analysed in the frequency range 0–54.5 Hz and the spectral analysis frequency resolution was 0.2 Hz.

3. Results

The model of the tested IRB 2400 robot with the base frame and configuration co-ordinates is shown in Fig. 2. Vibration analysis was performed on several selected robot configurations as shown in Fig. 3. The TCP coordinates and angular coordinates of the robot arm in the configurations studied are shown in Table 1.

The vibrations of the robot were excited by impulse excitation. The PCB 086C03 modal hammer with soft tip was used

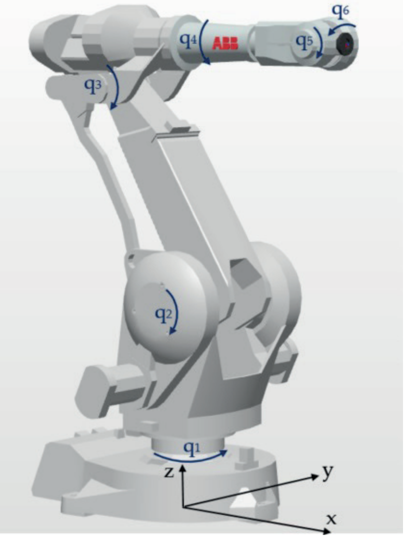

Fig. 2. ABB IRB2400 robot model with base frame xyz and configuration coordinates q1 – q6
Rys. 2. Model robota ABB IRB2400 z bazowym układem xyz i współrzędnymi konfiguracji q1 – q6

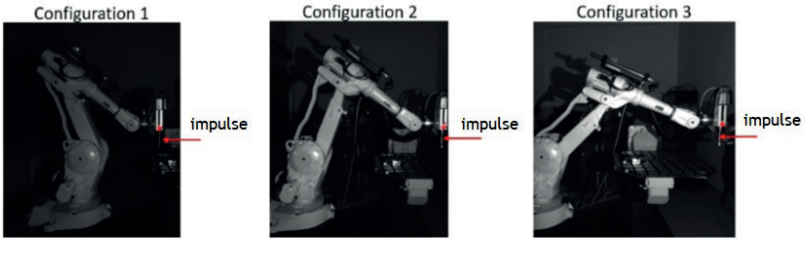

Fig. 3. Tested manipulator configurations along with the placement of a point located on the tool, for which the vibration spectra are determined
Rys. 3. Badane konfiguracje manipulatora wraz z umieszczeniem punktu zlokalizowanego na narzędziu, dla którego wyznaczane są widma drgań

to excite the structure, as low frequency manipulator vibrations related to susceptibility in the joints are the subject of the analysis. The force application point (tool) and its direction (horizontal) are shown in Fig. 3.

Tab 1. The TCP coordinates and angular coordinates of the robot arm in the configurations studied
Tab 1. Współrzędne TCP oraz współrzędne kątowe ramienia robota w badanych konfiguracjach

	Configuration 1	Configuration 2	Configuration 3
TCP coordinates [mm]	x = 880.8 y = −37.4 z = 1099.9	x = 1300.7 y = −37.4 z = 1099.9	x = 1615.1 y = −37.4 z = 1099.9
Articulated coordinates [rad]	$q_1 = 0.00$ $q_2 = -9.36$ $q_3 = 42.31$ $q_4 = 8.64$ $q_5 = -43.18$ $q6 = -6.48$	$q_1 = 0.00$ $q_2 = 23.13$ $q_3 = 38.23$ $q_4 = 9.82$ $q_5 = -39.12$ $q_6 = -7.81$	$q_1 = 0.00$ $q_2 = 47.94$ $q_3 = 24.06$ $q_4 = 14.84$ $q_5 = -25.28$ $q_6 = -13.62$

3.1. Robot vibration frequencies as a function of arm configuration

In the first step, the influence of the robot configuration on the resonance frequencies was investigated. Figure 4 shows the vibration spectra of the selected point located on the robot tool in the analysed manipulator configurations (red point in Fig. 2).

In the spectra diagrams in Fig. 4, the resonance zones are marked. They indicate that the resonant vibration frequencies of the robot arm depend on the configuration. Changes in resonance frequencies as a function of the robot configuration are not large and amount to 10 Hz.

For simple structures without quadrilateral articulation mechanisms, the resonance frequencies decrease with the extension of the robot arm. Changes can be in the range of several tens of Hertz [13, 14]. Due to the articulated quadrilateral mechanism used in a second link of the IRB 2400 robot, the dependency of the natural frequency values on the configuration is more complex than for the simpler manipulators analysed in the literature.

The highest values of the first and second resonance frequencies occur when the angle between the second and third link is 90 degrees. When this angle is either increased or decreased, the values of the first and second resonance frequencies decrease. As is well known, the resonance frequency values depend on the stiffness and the mass moments of inertia of the robot's links. When the configuration changes, the values of the mass moments of inertia of the links undergoing complex motion also change with respect to their instantaneous centers of rotation. The change in these mass moments of inertia results in a change in the resonance frequency values. However, the value of the third resonance frequency did not exhibit sensitivity to the configuration within the examined range.

3.2. Robot vibration in contact with the rigid constraints

Subsection 3.1 showed the results of the manipulator vibration analysis in three configurations when the tool is not in contact with the environment. This subsection presents the results for examining the impact of the robot's interaction force with the environment on the robot's resonant frequencies. The vibration analysis was performed for the first robot configuration, where the robot pressed the tool against an rigid aluminium plate attached to the positioner table. The down force was 44 N. Figure 5 shows the vibration spectra of the point located on the robot tool (red point in Fig. 2), both when the tool comes into contact with the aluminium plate and when there is no contact with it.

The analysis of the results shows that when the manipulator comes into contact with a workpiece, the values of the natural frequencies change. This is due to increased stiffness of the system as a result of contact with rigid sufrace. In addition, it can be seen that the amplitude of the vibrations in the vertical direction, which is normal to the surface of contact between the

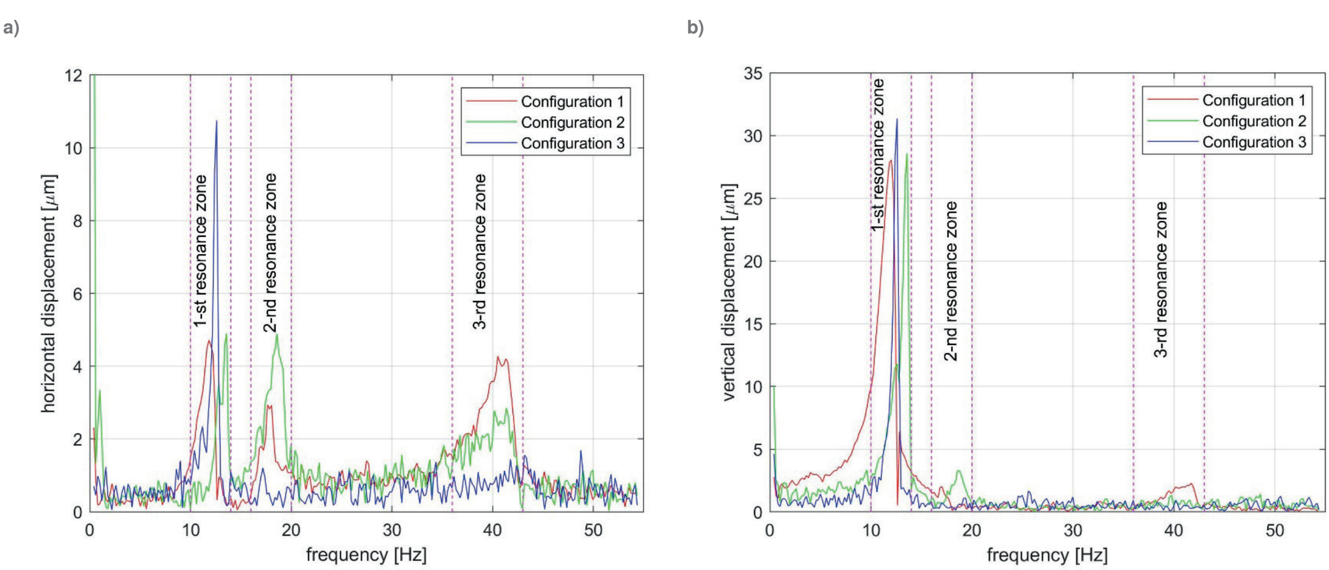

Fig. 4. The point vibration spectra located on the tool in the configurations studied: a) the vibration spectrum in the horizontal direction (x-direction); b) the vibration spectrum in the vertical direction (z-direction)
Rys. 4. Widma drgań punktu zlokalizowanego na narzędziu w badanych konfiguracjach: a) widmo drgań na kierunku poziomym (kierunek x); b) widmo drgań na kierunku pionowym (kierunek z)

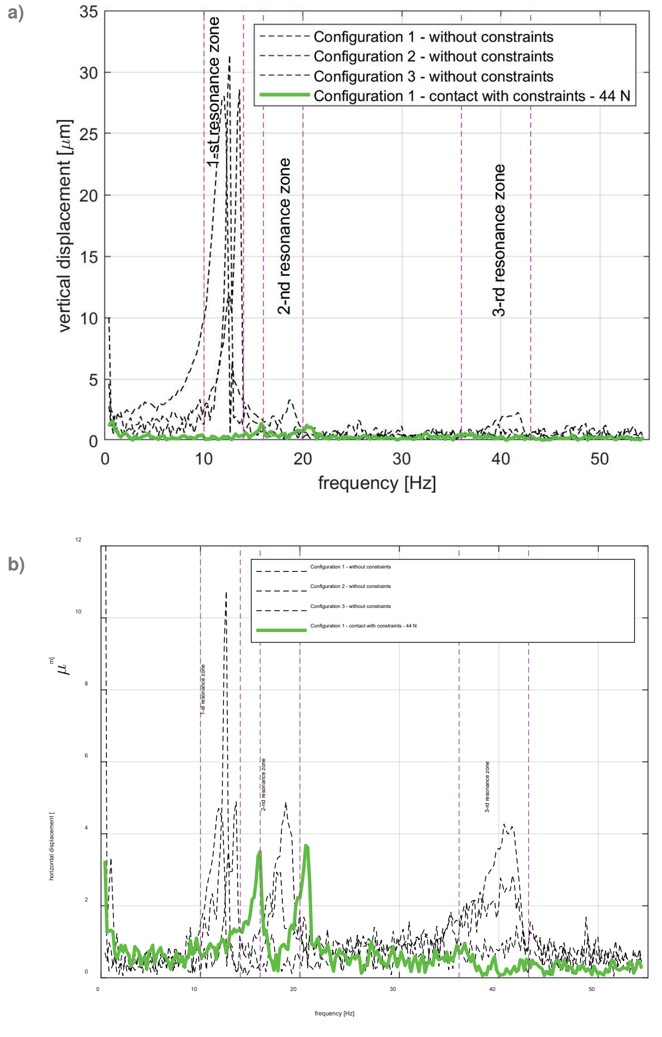

Fig. 5. The vibration spectra of point located on the tool in the first manipulator configuration with and without tool contact with the workpiece: a) the vibration spectrum in the horizontal direction (x-direction); b) the vibration spectrum in the vertical direction (z-direction). The dotted lines are the spectral characteristics of the arm's vibrations without limitations, while the solid lines are the spectral characteristics of the arm's vibrations in contact with the horizontal surface

Rys. 5. Widma drgań punktu zlokalizowanego na narzędziu w pierwszej konfiguracji manipulatora w przypadku kontaktu i braku kontaktu narzędzia z detalem: a) widmo drgań na kierunku poziomym (kierunek x); b) widmo drgań na kierunku pionowym (kierunek z). Linie przerywane to charakterystyki widmowe drgań ramienia bez ograniczeń, podczas gdy linie ciągłe to charakterystyki widmowe drgań ramienia w kontakcie z powierzchnią poziomą

tool and the workpiece, is much lower than when there is no contact. This is caused by motion restrictions when the robot interacts with the environment.

4. Conclusions

Low frequency vibrations in the robot are due to the susceptibility in the robot joints. The vibration analysis performed took into account the different positions of the robot arm. It has demonstrated a dependency of the system response on the robot arm position and the robot's interaction with the environment. The use of image analysis technology has made it relatively easy to link the frequency of vibrations to their modes. Changing position of the manipulator changes the resonant frequencies, while changing the motion constraints changes the direction of the vibration.

In industrial practice, in the context of process automation, the most commonly considered parameters are operation time and process repeatability. Low-frequency vibrations of robots have a significant impact on process repeatability. Knowledge of resonance frequencies and their variations under conditions of robot interaction with manufactured parts can be utilized during the selection of process parameters and tools in such a way as to avoid exciting resonance frequencies.

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Analiza drgań robota przemysłowego IRB 2400 z zastosowaniem technologii wzmocnienia ruchu

Streszczenie: W artykule przedstawiono analizę drgań niskoczęstotliwościowych robota przemysłowego IRB 2400 z zastosowaniem technologii wzmocnienia ruchu, bazującej na analizie obrazu. Technologia ta pozwala na wizualizację drgań całego robota oraz analizę drgań punktów robota, które można wybrać po przeprowadzeniu procesu akwizycji obrazu. Do wzbudzania drgań robota stosowano wymuszenie impulsowe generowane z zastosowaniem młotka modalnego. Przeprowadzono analizę drgań uwzględniającą różne pozycje ramienia robota. Analiza wskazała silną zależność odpowiedzi układu od pozycji ramienia robota oraz od siły interakcji robota z otoczeniem. Uzyskane wyniki zostaną zastosowane do planowania procesu zrobotyzowanej obróbki mechanicznej z uwzględnieniem minimalizacji drgań robota.

Słowa kluczowe: analiza drgań, robot przemysłowy, wzmacnianie ruchu

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