Suppressing of Multi-Axial Vibration Caused in Carried Objects by Robot Using a Heuristic Algorithm Based on Evaluation Actual Machine Information

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Abstract

Residual vibrations induced in objects carried by robots cause the positioning accuracy to deteriorate, which makes the installation of carried objects difficult. This study proposes a method for determining a trajectory that can suppress residual vibration using a heuristic algorithm, based on the behavior of a carried object, which is measured by actually operating a robot. Trajectories were generated for a commercially available industrial robot to suppress residual vibrations in two axial directions for a pendulum-shaped object to be transported. By optimizing the path shape and acceleration/deceleration, a trajectory that reduces the amplitude of residual vibration in each axis direction by 70% was successfully generated in a few actual machine operations.

Keywords: Robot arm, Residual vibration, Trajectory planning, Heuristic algorithm

1. Introduction

When an industrial robot transports an object at high speed, residual vibrations are likely to occur in the transported object after the robot has stopped. Residual vibrations in the carried object cause a deterioration in positioning accuracy and an increase in working time. Various methods for suppressing vibration by adjusting the trajectory, which is the change in the position and posture of the robots has been proposed [1], [2], [3]. However, most of them consider only the vibration characteristics of the robot itself and not the object to be transported. They also require an accurate kinetic analysis of the vibration control target. It is not easy to construct precise kinematic models for kinetic analysis for commercially available robots and transport objects, and it is difficult to carry out kinetic analysis [4], [5]. Therefore, this study proposes a method for generating trajectories that suppresses residual vibrations by a carried object without using kinetic analysis by optimizing the trajectory using a heuristic algorithm based on the evaluation value measured by actually operating the robot. In the present study, the residual vibration in two-axial directions caused by the object to be transported is targeted, and trajectories that reduce the vibration amplitude of the object are actually generated using a commercially available industrial robot to demonstrate the usefulness of the proposed method.

2. Outline of method for suppression residual vibration

2.1. *Variables to adjust*

Fig. 1 shows the outline of method for suppressing the residual vibration in two-axial direction. The output point of the robot with the carried object is moved from position S to the end position E. Normally, a trajectory prepared by the manufacturer is used for the movement of the load to be transported, with a straight line interpolated from position S to position E. In this study, this trajectory is defined as the standard trajectory. When two-axial vibration occurs in the carried object at position S, the vibration remains after the object is moved along the standard trajectory. In the proposed method, in order to suppress the residual vibration, new target positions P_1 and

P_2 are set in the horizontal plane immediately before the end position shown in the figure, and the output point in moved in the order of positions S, P_1, P_2 and E. By adjusting these target positions and the time required for movement between them, appropriate acceleration and deceleration is applied to the carried object in both directions perpendicular and parallel to the path of standard trajectory, thereby suppressing residual vibration in the two-axial direction. In this paper, position P_1 is placed on the path of standard trajectory and only position P_2 is placed outside the path. The operation displacement between each target position in the direction parallel to the path of standard trajectory and the operation displacement perpendicular to the path are defined as l_1, l_2, l_3 and e, respectively. The operation time between each target position is defined as t_1, t_2 and t_3. Here, if there are no constraints on the operation times t_1, t_2 and t_3, residual vibrations are suppressed but may increase the transport time. Therefore, the values of the aforementioned variables are adjusted such that the output point has the same transport time as the standard trajectory. Thus, these variables satisfy the following Eq. (1), where the operation displacement and target velocity measured in the standard trajectory are defined as L and V, respectively:

$$t_1+t_2+t_3=\frac{L}{V} \tag{1}$$

L and V were obtained from the standard trajectory measured by actually operating the robot. Thus, by determining t_1 and t_2, t_3 can be subordinately obtained from Eq. (1). In addition, since the end position E is fixed, l_3 is also obtained subordinately obtained by determining l_1, l_2 and e. In trajectory generation, the residual vibration measured by the actual operation of the robot was evaluated, and the optimal values of five variables (l_1, t_1, l_2, t_2, e) were determined using the heuristic algorithm described in next section.

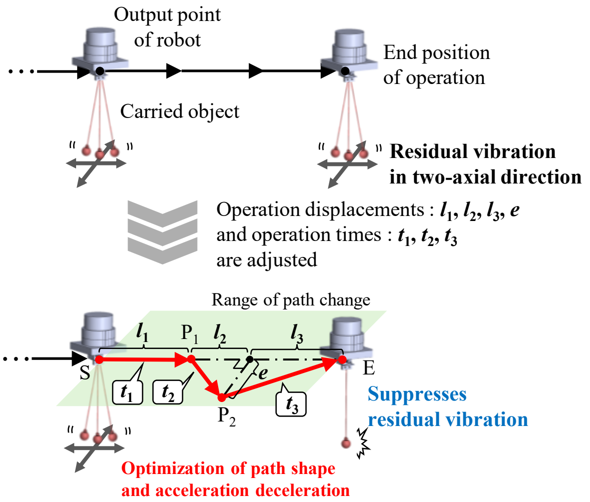

Fig. 1. Outline of method for suppressing the residual vibration.

2.2. *Heuristic Algorithm "SHA"*

Trajectory generation by the heuristic algorithm iteratively updates the trajectory based on evaluation of measurements obtained by operating the robot. Lin's heuristic algorithm (SHA) [6], [7], proposed by Lin et al. and confirmed by the authors in the trajectory generation of a robot manipulator [8], is used to update the trajectory. SHA is a type of heuristic algorithm which searches for the best combination of values of several variables in a short time so that set evaluation value is the best. The SHA expresses the design parameters in the variable matrix, as shown in Fig. 2. Each column from the first column to column n in the variable matrix represents a type of variable to be searched, and each element from the first row to row k in each column represents the discrete values taken by the variables. As indicated by the black circle in Fig. 2, The combination of discrete values determined by selecting elements from each column of the variable matrix one by one. In trajectory generation, one discrete value combination represents the robot's trajectory, as (l_1, t_1, l_2, t_2, e) is placed in the variables of the variable matrix. In SHA, multiple trajectories are generated by randomly selecting elements called look-ahead-base-points (LBPs) in a certain column, as shown by the red circles in Fig. 2. By repeatedly performing comparison of the evaluation values measured by operating the robot for each generated trajectory, the trajectory with the best evaluation value, i.e., the optimal trajectory, is determined.

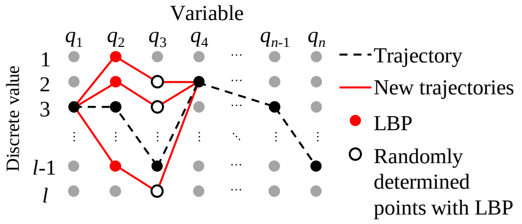

Fig. 2. Variable matrix.

3. Target Robot Arm and Carried Object

The method described above was applied to a commercial 6-DOF vertically articulated robot (Kawasaki Heavy Industries, Ltd., RS020N). The robot is shown in Fig. 3. As shown in the figure, the joints of the robot were designated as JT1 to JT6 from the base side of the robot. The motion and trajectory of the output point P of the robot are represented by the absolute coordinate system O-XYZ, in which the origin is the center of JT1 and the vertical direction is the Z-axis. Operational commands are given using the company's AS language, which is based on the Standard Language for Industrial Manipulators (SLIM) language. In this paper, trajectory generation is performed for residual vibration in elastic bodies. Therefore, a pendulum with a natural frequency of 1.5 Hz was used as shown in Fig. 4. The carried object was attached to the output point of the robot via the six-axis force sensor

(Leptrino CFS034CA301A). The residual vibrations induced by the motion of the robot are measured by measuring the reaction moment generated at the fixed end using the force sensor.

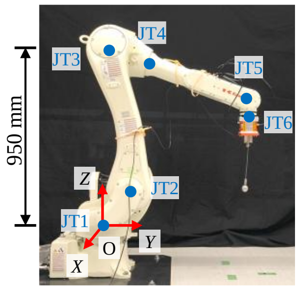

Fig. 3. Industrial manipulator RS020N.

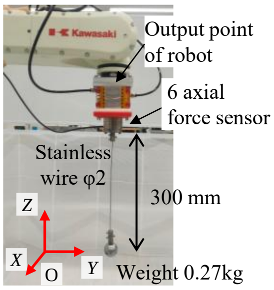

Fig. 4. Carried object.

4. Condition for Searching the Trajectory by SHA

Fig. 5 shows the path targeted by trajectory generation. As shown in the figure, the path S-E of the standard trajectory was a straight line parallel to the Y-axis direction with a length of 600 mm (L = 600 mm). In trajectory generation, the optimal trajectory was searched by repeatedly changing the trajectories within the operation range indicated by the green rectangle in the figure and evaluating the residual vibrations induced in the carried object at position E. To prevent breakdowns of the carried object, from preliminary experiments, the acceleration/deceleration of the output point at trajectory S-E was set to 20% and the operation range to ±150 mm in the X-axis direction. Before starting the motion at position S, the output point is moved in the order of positions A, B and S to apply initial vibration. To increase the amplitude of the initial vibration, in paths A-B and B-S by trial and error, the velocities were set to 10% and 5%, and the acceleration / deceleration were set to 30% and 15%, respectively. The output point was allowed to wait for 0.7 and 1.32 s at positions B and S. The output point with the carried object was moved while maintaining a constant attitude. During the search, the output point was returned to position S for the next operation after the evaluation of the residual vibration was completed. The vibrations induced during this process were suppressed by the plate shown in the bottom right-hand corner of the figure.

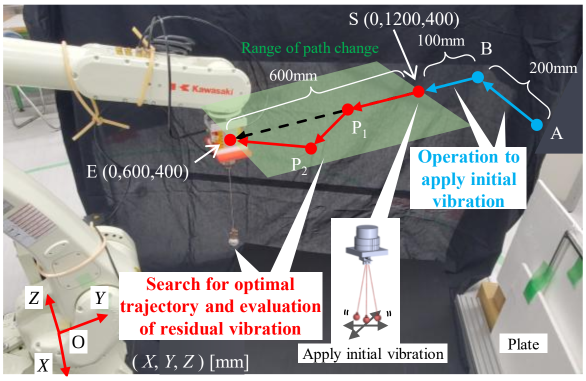

Fig. 5. Path of the robot.

The target velocity V of the standard trajectory was measured by moving the output point in a straight line from positions S to E at the maximum target velocity that the robot could exert. This resulted in V = 953 mm/s and L/V in Eq. (1) was 0.62 s. The evaluation value in SHA was the sum of the standard deviations of the moments about the X-axis and Y-axis at the fixed end of the carried object from 1 to 6 seconds after the end of the operation at position E. The sampling period of the moments was 32 ms. The number of elements in each row of the matrix and the number of LBPs were set to 100 and 3, respectively.

5. Result of the Trajectory Generation

Fig. 6 shows the changes in the evaluation value obtained during the search for the trajectory by the SHA. The red squares indicate the best value among the evaluation values obtained up to that operation. The dotted lines indicate the evaluation values obtained for the standard trajectory. The best evaluation value decreased as the search progressed. It generated 20 trajectories with evaluation values reduced by more than 70% compared to values obtained for standard trajectory. The trajectory with the smallest evaluation value, namely the optimal trajectory was obtained at 37th. The reduction in the evaluation value of the optimal trajectory was 78.2%. The search test required approximately 50 min in all 76 robot operations.

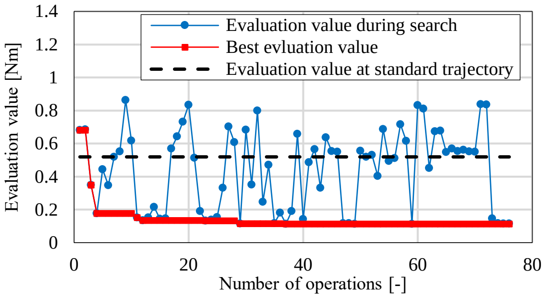

Fig. 6. Change in the evaluation value with the number of operations during a search by the SHA.

Fig. 7 shows the change in the velocity of the output point and X-axis moment, Y-axis moment with time for the optimal trajectory. As shown figure, the output point stopped at a time of about 6.5 s for both the optimal and standard trajectories. The waveform after that time represents the residual vibration caused in the carried object. In the optimal trajectory, the moments in both the X-axis and Y-axis decreased remarkably at the end of the operation in contrast to the standard trajectory. The amplitudes of the moment about both axes were reduced by more than 70% in comparison to that of the standard trajectory.

Fig. 8 shows the paths of the output point and the weight of the carried object in optimal and standard trajectories. The blue circle in the figure indicates the position of the weight. Here, the positions of the weight were determined by calculating the proportionality constant between the moment and the displacement of the weight from a static load test on the carried objects. As shown in the figure, the initial vibration with large amplitudes occurs in both axial directions at position S. In the standard trajectory, the output point is only moved in a straight line, resulting in a residual vibration at position E with an amplitude equivalent to the initial vibration. On the other hand, in the optimal trajectory, the output point is meandered to position P_2 so that the displacement direction of the weight matches that of path P_2-E. This changes the two-axial vibration occurring in the carried object to a one-axial vibration along the motion in path P_2-E. The residual vibration is suppressed by accelerating the output point in the same direction as the weight is followed.

As described above, in the optimal trajectory obtained by SHA, the two-axial vibration is changed to one-axial vibration by adjusting the path, and the subsequent acceleration motion applies vibration in the opposite phase to the one-axal vibration. Thus, the vibrations cancel each other out and the vibration amplitude.

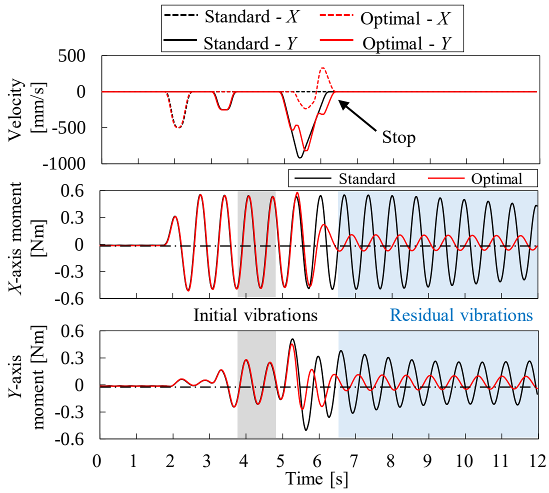

Fig. 7. Changes in the output point velocity and moment with time.

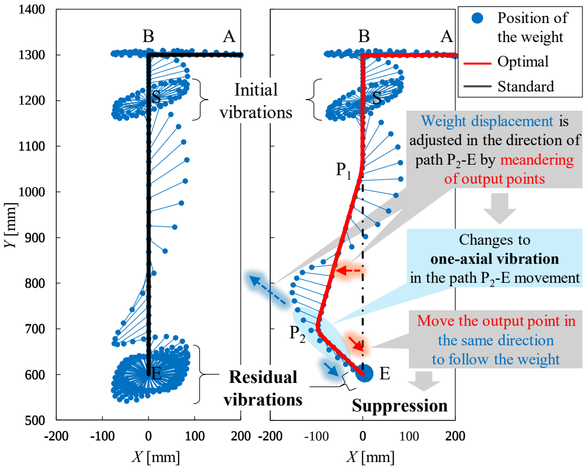

Fig. 8. Paths of the output point and the weight of the carried object for optimal and standard trajectories.

6. Conclusion

In this study, we propose a method for suppressing the residual vibration in the two-axial direction caused by a robot in a carried object using the heuristic algorithm SHA. In the proposed method, because the residual vibration is measured by actually operating the robot is evaluated, a vibration suppression trajectory can be generated without requiring kinetic analysis of the robot or the carried object. Trajectory generation was performed by adjusting the path and acceleration / deceleration using a commercial industrial robot with a pendulum as the carried object. The result was a trajectory in which the amplitude of the residual vibration was reduced by more than 70% compared to the amplitude in the manufacturer's standard trajectory in both axial directions. For carried objects with same specifications, the proposed method can generate trajectories with a sufficiently small number of robot operations, approximately 40 times. However, when the specifications often change, the time required for trajectory search becomes unacceptable. Therefore, in the future, we will plan to construct a method for generating trajectories in a real-time by training a neural networks using obtained optimal trajectories for various carried objects by SHA.

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