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Bordatchev, E.V.

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ANALYSIS AND MAPPING OF THE DYNAMIC PERFORMANCE OF HIGH-PRECISION MOTION SYSTEMS

*Integrated Manufacturing Technologies Institute
National Research Council of Canada*

Abstract. The research reported in this paper aims at improving the dynamic performance of motion systems by analysing and mapping the non-uniformity of feed motion within the travel area. This paper (a) develops the real-time measuring of the feed motions through built-in position encoders, (b) considers the feed motion as a space-time random process, and (c) applies analysis in order to evaluate and map the dynamic performance. The dynamic performance as a "dynamic imprint" of the entire motion system is represented by the dynamic/statistic characteristics of feed motion. The transfer function of the motion system as a dynamic operator, which transforms prescribed motion into actual motion, is applied to model the dynamic performance. The results of the experimental investigations, analysis, and mapping of the dynamic performance indicate a wide range of industrial uses of the developed approach for certification, diagnostics, and tool path optimisation purposes to achieve highest accuracy for a particular motion system.

1. INTRODUCTION

The high-precision motion system is a complex electro-mechanical assembly consisting of a base, the electro-mechanical drives, and translation tables to provide the feed motions. The ideal motion system must provide good correlation of the actual motion attributes (tool path, feedrate, acceleration, *etc.*) to the predetermined ones. However, industrial and laboratory practice indicates that there are considerable tracking and contouring errors and variations within feed motions [1-5]. Up until now, the dynamic performance of motion systems has been associated with positional accuracy and trajectory tracking capabilities. The positional accuracy calibration is based on static measurements where the worktable is moved to a desired position several times and the distribution of the errors is analysed. This approach mainly deals with the repeatability of reaching a desired position and does not take into account the actual behaviour of motions. The accuracy of trajectory tracking is a measure of a motion system's ability to follow the prescribed trajectory [6]. Specifying trajectory-tracking accuracy is not always enough for some machining processes. For example, the laser machining process needs to synchronize the motion and laser pulses to provide constant material removal [7]. This discussion emphasizes the various aspects of a motion system operation to characterize its performance. Therefore, for this paper, the dynamic performance of a motion system is understood as the ability to provide a prescribed motion, and the manner in which a motion system provides the motion. Thus, the dynamic characteristics of a motion are indicators of the system dynamic performance.

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This paper develops a dynamic calibration approach [3-5] for analysing and mapping the dynamic performance of motion systems by means of the spatial distribution of feedrate variations within the travel area. Knowing the mapping allows us to recognize "sweet" spots with lowest non-uniformity of motion in order to optimise the workpiece location on the table to achieve the highest level of accuracy for a particular motion system. In addition, the mapping of motion is understood as a "dynamic imprint" of motion system dynamic performance and can be used for certification, diagnostics, and control purposes.

2. DEFINITION OF DYNAMIC PERFORMANCE

According to *Webster's Dictionary*, [8] performance is an ability to perform and the manner of reacting to stimuli. Applying this fundamental definition towards a motion system, the dynamic performance is the ability to provide a prescribed motion with specified attributes (tool path, feedrate, acceleration, etc.) and the dynamic manner in which the system provides the motion. To be unambiguous, the engineering meaning of the words "ability" and "manner" needs to be specified. Thus, the dynamic parameters and characteristics of a motion are suggested as indicators of system dynamic performance as shown in Figure 1. In other words, how an actual motion is similar to a prescribed one is analogous to the characterization of the system dynamic performance. In this case, the prescribed and actual motion is considered as a time-space random process; e.g., "feedrate with respect to (wrt) position" $v(x)$ or "feedrate wrt time" $v(t)$. Fundamentally, the representation of dynamic performance is based on the combined observation and analysis of position, feedrate (velocity) and acceleration as random processes. In addition, the dynamic performance can be modelled and estimated by the transfer function of the motion system. This definition is also useful if we mathematically model the motion system as a dynamic operator, which transforms prescribed motion into actual motion. The magnitude of the transfer function is commonly referred to as the gain factor wrt feedrate $|W_{vv}(j\omega)|$ and is shown as follows:

$$|W_{vv}(j\omega)| = \sqrt{S_{vv}(\omega)/S_{v_0v_0}(\omega)} \quad (1)$$

Figure 1. Motion system dynamic performance.

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where $S_{v_0v_0}(\omega)$ is the autospectrum of the prescribed (ideal) feedrate v_0 , $S_{vv}(\omega)$ is the autospectrum of the actual feedrate v , ω is the frequency, and $j = \sqrt{-1}$.

3. EXPERIMENTAL SET-UP AND FEEDRATE ANALYSIS PROCEDURE

A multi-axis positioning system was used for signal measurements and data collection. The worktable consists of a granite base fitted with precision translation tables (with air bearings) for X and Y movements. The travel area of XY-table is 203.2x203.2 mm. The linear motors #LM210-16.80-3-AC:WD2 (Trilogy Systems Corp.) provide the feed motions and the corresponding linear encoders LS403 (HEIDENHAIN Corp., encoder resolution $\Delta\ell = 0.5 \mu\text{m}$) furnish the positional feedback for the control system. The data related to linear motions was collected by using PCI-MIO-16XE-10 (National InstrumentsTM) I/O card. All measurements were carried out for 203.2 mm feed movement in X and Y directions. Data was collected during the experiments as a "feedrate wrt position" process along X-direction $v(x)$ and along Y-direction $v(y)$ with $\Delta x = \Delta y = 2.032 \text{ mm}$. The elements of matrixes $M_y(x)$, $G_y(x)$, $M_x(y)$, and $G_x(y)$, which are statistical parameters $v_{\max} - v_{\min}$ and σ_v , were calculated on length $\delta_x = \delta_y = 1.016 \text{ mm}$.

The investigations were carried out by using built-in positional encoders as a source of data for the feedrate analysis. The collected information represents a sequence of impulses, where the period of each impulse precisely corresponds to the encoder resolution $\Delta\ell = \text{const}$. The data acquisition technique consists of measurements of period for each impulse T_i , $i = 1:N$, where N is the number of measured periods. Calculations allow obtaining "feedrate wrt position" $v(x)$. This process $v(x)$ carries a significant property, such that the position scale $x = (1:N)\Delta\ell$ is even in space. This property permits the application of statistical analysis to determine the characteristics of the feed motion as a space-time random process. For the feedrate analysis the following parameters, which characterize actual dynamic performance, were calculated: highest $v_{\max}$ and lowest $v_{\min}$ values of $v(x)$; mean μ_v ; coefficient of non-uniformity K_v ; variance σ_v ; difference $\mu_v - v_0$.

4. MOTION SYSTEM BEHAVIOUR FOR DIFFERENT FEEDRATES

The observed acceleration stage was measured for different feedrates ranging from 2.52 mm/s to 12.7 mm/s. Figure 2 illustrates the dynamic behaviour of these motions corresponding to the individual feedrates. From this data it can be seen that the "manner" of the acceleration stage characterizes the dynamic performance of the motion system kinematics and the control system. The acquired data indicates that the length of the acceleration stage λ increases with the increase in the feedrate, along with the amplitude of the feedrate variations during the motion, resulting in a decrease in the overall system performance. The calculated values of feed motion

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parameters such as λ , $v_{\max}$, $v_{\min}$, μ_v , K_v , σ_v , and $\mu_v - v_0$ for motion feedrates from 2.52 to 12.7 mm/s are detailed in Table 1.

Figure 2. Actual acceleration stage of motions with different feedrates.

Table 1: Feed motion parameters

feedrate v_0 , mm/s	2.54	7.62	12.70
length of acceleration stage, mm	0.203	0.635	1.016
$v_{\max}$, mm/s	2.896	8.484	14.097
$v_{\min}$, mm/s	2.184	6.528	11.227
$v_{\max} - v_{\min}$, mm/s	0.712	1.956	2.870
μ_v , mm/s	2.54	7.62	12.70
K_v , %	28.301	25.456	22.472
σ_v , (mm/s) ²	0.01584	0.11198	0.31336

From Table 1, the following inferences can be drawn:

- Motion achieves the desired feedrate that characterizes excellent technical perfection for the motion system under consideration.
- The length of the acceleration stage increases with the increase in the prescribed feedrate, along with the amplitude of feedrate variations resulting in a decrease in the overall system performance.
- The coefficient of non-uniformity, K_v , remains relatively constant.
- The variance of the feedrate, σ_v , increases exponentially as feedrate increases.

The above analysis provides only an estimation for the non-uniformities of motion, which characterize the system dynamic performance. It does not recognize the sources and nature of disturbances which caused the non-uniformities. Comparing motion signatures at different feedrates can help to identify these

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disturbances. Figure 3 shows comparative motion signatures for feedrates 2.5 mm/s and 12.7 mm/s along the X axis. Although the dynamics of the motion system differs, the signature of motion does not change. Both motion signatures have uniform shape and a constant period of 20 μm ; however, the amplitude of fluctuations increases wrt feedrate. Figure 3 also illustrates power spectral densities for feedrates 2.5 mm/s and 12.7 mm/s. It was observed that the source of the kinematic disturbances for the period of feedrate fluctuations of 20 μm corresponds to a dominant spatial frequency of 50 periods/mm. The calculated coherence function demonstrates a linear relationship between the two motions with a corresponding spatial frequency of 50 periods/mm and its harmonics. In addition, the spatial frequency harmonics of 2x50 periods/mm, 3x50 periods/mm, *etc.* also indicate the presence of the kinematic disturbances wrt their location.

Figure 3. Spatial signatures (left) and power spectral densities (right) of different motions.

5. MAPPING PROCEDURE

Nowadays, the mapping procedure has been used as a method to reduce positional errors, such as lead-screw errors, backlash, *etc.* Based on prior measurements of the actual position of a table, the desired positions are corrected. Opposite to that static approach, the mapping of dynamic performance is based on measuring and recording the stable motion excluding the acceleration and deceleration stages. The measured data, for example, $v_{y=fix}(x)$, represents the dynamic signature of motion along the X direction for a given Y coordinate. The set of data for different $y = fixed$ shows the XY distribution of $v(x)$ for the total travel area for a prescribed feedrate v_0 and direction of movement. The data $v_{y=fix}(x)$ and $v_{x=fix}(y)$ are reorganized into matrixes $V_y(x)$ and $V_x(y)$, where each row $v_{k\Delta y}(1:N_x)$, $v_{l\Delta x}(1:N_y)$ represents the measured feedrate wrt position; Δx is the distance along the X direction between two consecutive measurements in the Y direction; Δy is the distance along the Y direction between two consecutive measurements in the X direction; $k = 0, \dots, K$; $\ell = 0, \dots, L$; $K+1$ is the number of measurements along the X direction, and $L+1$ is the number of measurements along the Y direction. The

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parameters $v_{\max} - v_{\min}$ and σ_v were calculated within the specified range of δ_x and δ_y correspondingly along Λ_x and Λ_y for each $v_{k\Delta y}(1:N_x)$, $v_{l\Delta x}(1:N_y)$. Afterwards, parameters were reorganized into corresponding matrixes of amplitude of feedrate variation $M_y(x)$ and variance $G_y(x)$ completely covering the XY travel area. The final result of mapping is the contour plot of $G_y(x)$ representing the dynamic performance.

6. MAPPING OF DYNAMIC PERFORMANCE

The mapping is targeted on analysing the dynamic performance over an XY travel area that is represented by the contour plots of matrixes $M(x)$ and $G(x)$. Results of the XY-table mapping are presented for two different feedrates (2.5 mm/s and 12.5 mm/s) as an example of dynamic performance distribution. Figure 4 illustrates XY distribution of $M_y(x)$ and $G_y(x)$ for forward (+X) and backward (-X) motions. The analysis shows that the dynamic performance of a motion system represented by the dynamic behaviour of XY motions has a quite complex spatial distribution. The contours and values in the XY distribution remain the same if experiments are repeated under the same conditions. The variations in the XY distribution are caused by the system response on resistance to feed motion. The feedrate signatures represent the system response. The dynamic and kinematic disturbances form the actual resistance. The system response to resistance depends on the direction and feedrate of the motion. It follows that XY distributions have similarly shaped contours and different values; for example, compare matrixes $M(x)$ or $G(x)$ for the same direction of motion but with different feedrates. Direction of motion (+X or -X) significantly changes the contours and the values of the XY distributions. Experiments show that the difference in feedrate variation is higher for +X motion than for -X motion. These features characterize the dynamic performance of a motion system and provide the potential for individual tool path optimisation to achieve the highest accuracy for a particular motion system.

7. SUMMARY AND CONCLUSIONS

To improve the dynamic performance of high-precision motion systems, a new approach to analysis and mapping has been developed using a time-based technique to measure the actual motions as a "feedrate wrt position" process. The definition of dynamic performance was introduced as the technical ability to provide a prescribed motion with specified attributes (tool path, feedrate, acceleration, *etc.*) and the dynamic manner in which the system provides the motion. The parameters of motions, such as a difference between process mean value and desired feedrate, coefficient of non-uniformity, variance, power spectrum density, and coherence function were analysed to characterize the actual dynamic performance of the motion system.

The time-based technique was applied to measure the motion as a space-time

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random process. Motions with different feedrates were investigated in order to evaluate dynamic performance. Experimental results indicate that:

- The length of the acceleration stage increases with the increase in the feedrate, along with the amplitude of prescribed feedrate variations, resulting in a decrease in the overall system performance.
- The coefficient of non-uniformity remains relatively constant for all feedrates.
- The variance of motion increases exponentially with feedrate.
- The statistical analysis of feed motions allows separation of kinematic and dynamic disturbances and locates the respective sources.

The mapping of feedrate non-uniformity was utilized to characterize the XY distribution of dynamic performance. The obtained contoured plots of feedrate parameters show that:

- The direction of motion significantly changes the dynamics of motion.
- The resistance to motion is formed by dynamic and kinematic disturbances; is estimated by the XY distribution of feedrate variations and variance; and represents the dynamic performance of the motion system.
- The XY distribution of the motion parameters symbolizes a “dynamic imprint” of a motion system and illuminates the “sweet” spots that correspond to the highest accuracy due to the lowest non-uniformity of feedrate.

In addition, the results of the experimental investigations, analysis, and mapping of dynamic performance indicate a wide range of industrial uses of the developed approach for certification, diagnostics, and tool path optimisation purposes to achieve highest accuracy for a particular motion system.

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Figure 4. Variations (left) and variances (right) of different motions.