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Dynamic machining and motion performance in state-of-the-art linear motor and ball screw-based CNC machine tools

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Abstract

Linear motor-based CNC machine tools have been competitively advanced for higher machining and motion performance. While linear motor and ball screw-based feed drives have been reviewed in academics and industries, performance differences between the two drive systems have yet to be rigorously examined with machining and motion analysis. This article details the performance comparisons between the direct drive and ball-screw-based feed systems with dynamic tool paths and external impulse responses. The tracking errors from dynamic motion were measured using a linear-scale encoder and analyzed for both feed drive systems. From experimental comparisons for the given adaptive machining paths, it is found that the linear motor-based direct drive system generates errors of 0.023 mm less in one direction and 0.012 mm less in the other direction than the ball screw-based one. While the linear motor-based feed drive was known to have less servo stiffness than a ball screw-based system, the difference in servo displacements at external impulse forces of 4000 N is found to be only within a few micrometers. Based on the test result, the configured linear motor-based machine is capable of performing heavy machining like face milling as well as adaptive dynamic machining, and it can maintain a precision motion without backlash over disturbance. In addition, a comprehensive evaluation is tabularized to contrast the strengths and weaknesses of two different drive-based machine tools.

Computer Numerical Control (CNC), Drive, Machining, Motion

1. Introduction

Linear motor-based feed drive systems in CNC machine tools have recently made significant strides in terms of machining and motion performance. The benefit of linear motor-based direct drive is that it achieves higher acceleration and speeds with less wear and tear than a ball screw-based machine [1-2]. Moreover, it is widely acknowledged that the linear motor-based feed drive maintains better tracking accuracy in complex tool paths and high-speed motion than the conventional feed drive system. Despite the extensive academic and industrial reviews of linear motor and ball screw-based feed drives, the performance between the two drive systems has yet to be experimentally examined and compared under actual CNC tool paths and external disturbances.

CNC tool paths are composed of constant speed vectors and transient varying speed ones, which may generate errors during acceleration and deceleration [3-4]. The feed rates for the tool paths critically affect machining quality and productivity [5-7]. Since the feed drive performance has been dramatically improved in the last decades, various dynamic tool paths, such as rapid trochoidal ones, have been enabled and exploited [8-10]. The adaptive toolpaths aim to maintain constant tool engagement or constant material removal at each point along the path. The tool paths have the advantages of reducing cutting forces, reducing tool wear, minimizing vibration, etc. However, it is not to overlook control tracking accuracy, which may worsen at such rapid speed vector changes during the trochoidal motion. Tracking errors need to be examined at high accelerations and decelerations of adaptive transient speed. In order to benefit from trochoidal motion, dynamic tracking errors should be minimized when speed vectors change frequently. This article compares tracking accuracy from linear motor-based and ball screw-based feed drives during the adaptive motion.

The drawback of the linear motor drive system was known as less damping due to less contact stiffness from mechanical components, and researchers worked on the compensation method against disturbance [11-12]. As impulse responses exhibit how the system acts against disturbance forces, two feed drive responses are benchmarked under the same magnitude of impulse forces. In this article, the precise feed drive motion is measured with a resolution of less than 0.05 micrometer and 3-millisecond sampling using the linear scale encoder attached between the moving table and the fixed bed as the impulse force is applied to the table connected to the feed drive.

Overall, two modern commercial CNC systems, linear motor-based feed drives (LMFD) and ball screw-based feed drives (BSFD), installed with linear scale encoders, are selected to compare the servo responses at the adaptive motion and the impulse disturbance. The experimental results are analyzed to explain the characteristics of the feed drives in terms of the tracking errors and disturbance responses from both systems. Finally, further comparisons and discussions are summarized, and future direction is suggested based on these experimental comparisons.

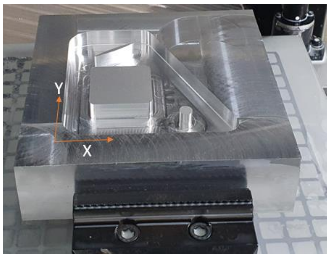
2. Feed drive performance under dynamic tool path

In order to utilize dynamic feed motion, the feed drive should be able to provide a rapid dynamic response that encompasses acceleration and jerk. While the controller could be tuned with high acceleration and jerk values, it should still be noted that the tracking errors may be accordingly increased by fast-moving mass, which is a bottleneck for high-speed dynamic motion. The feed drivers' responses can be benchmarked under the moving velocity profiles by comparing the tracking errors under the same dynamic tool path.

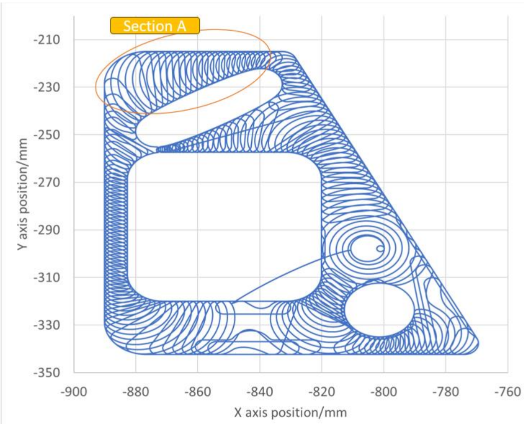
Figure 1 illustrates the machined geometry and tested adaptive tool path at the feed drive systems. The dynamic tool path has 0.25 mm lifts in the tool axis when the tool returns to the machining position, which induces more cooling and less tool wear, as depicted in Figure 2. The return feed rate is 8000 mm/min, the cutting feed rate is 4500 mm, and the cutting depths are Ae = 1.5 and Ap = 5 mm for the dynamic motion. The solid carbide flat-end mill tool has four flutes and a diameter of 12 mm. Limited information from commercial controllers is listed for control parameters in Table 1; it is not permissible to change or disclose the detailed controller parameter sets of the commercial system. As the tested LMFD system has a higher maximum acceleration and jerk setting than the BSFD system, the LMFD system may have a disadvantage regarding tracking error, which tends to increase at high acceleration and jerk for the comparisons.

Table 1 Commercial machine controller setting

	The tested commercial LMFD	The tested commercial BSFD
Maximum acceleration setting	X 10000, Y 10000, Z 10000 mm/s^2	G0 X 5263, Y 4412, Z 3750 G1 X 2222, Y 2222, Z 2222 mm/s^2
Maximum feed rate	60000 mm/min	X 48000 Y 36000 Z 36000 mm/min
Controller version	Heidenhain TNC 620	Fanuc professional P
Look ahead function	HSC mode on	AICC2 mode on
Position control	Closed loop control with linear scale encoder	Closed loop control with linear scale encoder
Interpolator cycle time	3 msec	3 msec



(a) The machined geometry with the material Al6061-T6



(b) The adaptive tool paths in XY plane

Figure 1. The machined geometry with the material Al6061-T6 and the adaptive tool path

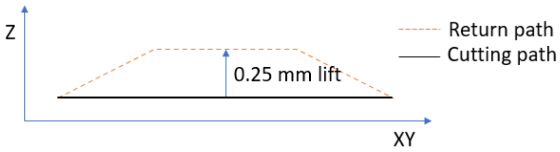
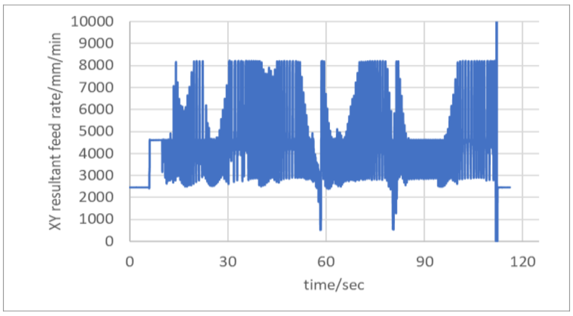


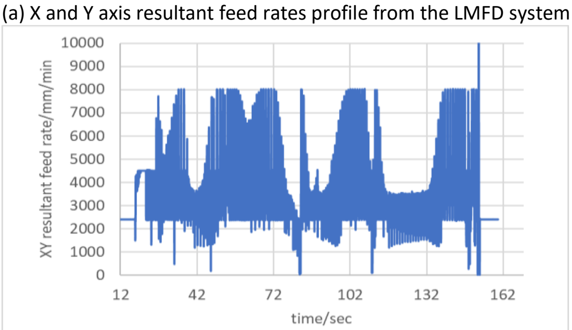
Figure 2. Return and cutting feed rates

According to the total adaptive tool paths shown in Figure 1(b), Figures 3(a) and 3(b) display the resultant feed rates in the XY plane from the LMFD and BSFD systems, respectively. Due to the different controller settings, the actual feed rates cannot be the same for the given adaptive tool path. Figure 3(c) illustrates the comparisons of the resultant feed rates for the path section A. As expected from the maximum acceleration setting shown in Table 1, LMFD may lead to a shorter operation time than the BSFD.

In order to perform a fair comparison over the different controller settings, the analysis is performed to benchmark the ratio of tracking error over acceleration in both systems since changing the controller parameters in the commercial system is not allowed. Tracking errors are generated by the acceleration or deceleration of the fast-moving masses in each axis, as those may excite the structure from the acceleration or deceleration force. For example, if acceleration increases, the tracking error is expected to increase accordingly.



(a) X and Y axis resultant feed rates profile from the LMFD system



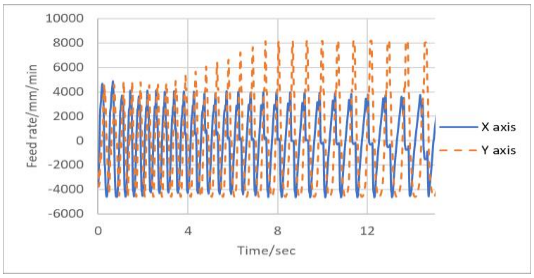
(b) X and Y axis resultant feed rates profile from the BSFD system

(c) XY resultant feed rates for section A

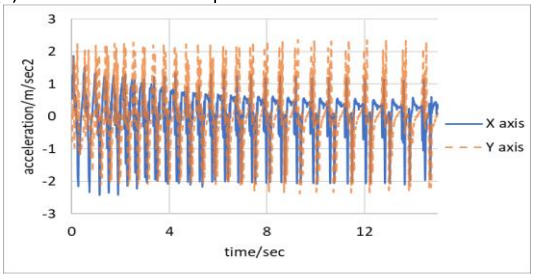
Figure 3. Resultant feed rates for LMFD and BSFD system for the adaptive tool path

The actual feed rate and acceleration profiles are measured from the linear encoder of LMFD for the tool path section A, as displayed in Figures 4(a) and 4(b), respectively. The tracking errors in the x and y directions are visualized in Figures 4(c) and

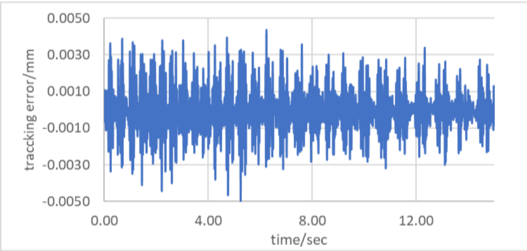
4(d). The x-axis tracking errors are from -0.005 mm to 0.00438 mm, while the x-axis acceleration ranges from -2.420 g to 1.870 g. The y-axis tracking errors are from -0.0194 mm to 0.0189 mm, while the y-axis acceleration ranges from -2.370 g to 2.370 g. The ratio (mm/g) of displacement over acceleration in terms of the range magnitude is 0.0022 and 0.0081 in the x-axis and y-axis, respectively.



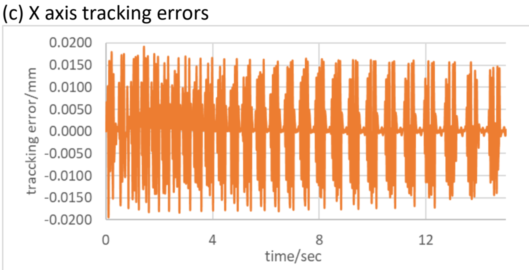
(a) X and Y axis feed rate profiles measured from linear encoder



(b) X and Y axis acceleration profiles measured from linear encoder



(c) X axis tracking errors

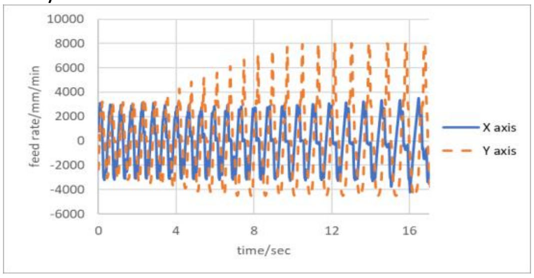


(d) Y axis tracking errors

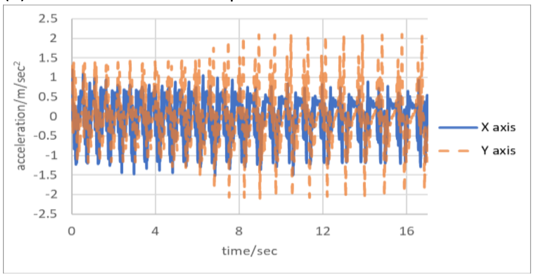
Figure 4. Corresponding tracking errors for feed rate and acceleration profiles from the tested LMFD system for the tool path section A

The experimental velocity and acceleration profiles and the corresponding tracking errors from BSFD are displayed in Figure 5. The BSFD system has a lower range of acceleration profiles during the adaptive motion, as shown in Figure 5(b), than the LMFD system, as displayed in Figure 4(b). The x-axis tracking errors range from -0.0168 mm to 0.0145 mm, while the x-axis acceleration ranges from -1.512 g to 1. 198g. The y-axis tracking errors are from -0.0366 mm to 0.0221 mm, while the y-axis acceleration ranges from -2.078 g to 2.098 g. The ratio (mm/g) of displacement over acceleration in terms of the range is 0.0116 and 0.0140 in the x-axis and y-axis, respectively.

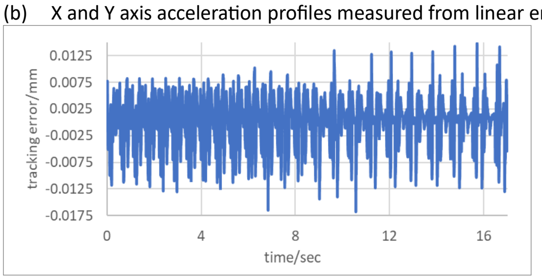
The x-axis motion driven by the BSFD has larger tracking errors in the adaptive motion than the LMFD. From the tested results, the LMFD generates lower ranges of tracking errors over acceleration than the BSFD. Even though higher acceleration is executed in the LMFD system, the tracking error over acceleration is smaller than in the BMFD system, which is found to be the benefit of the LMFD system from the experimental study.



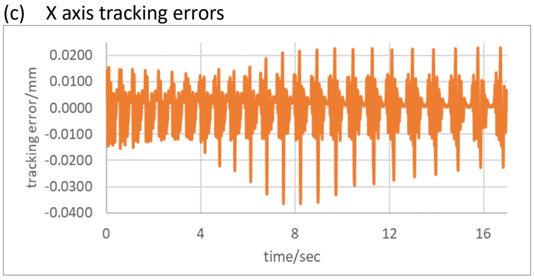
(a) X and Y axis feed rate profiles



(b) X and Y axis acceleration profiles measured from linear encoder



(c) X axis tracking errors



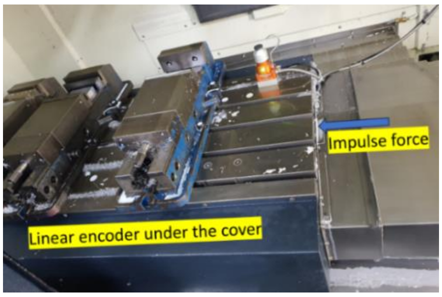
(d) Y axis tracking errors

Figure 5. Corresponding tracking errors for feed rate and acceleration profiles from the tested BSFD system for the tool path section A

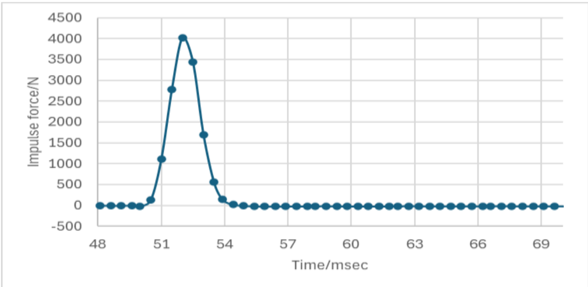
3. Feed drive response under external impulse forces

Impulse responses of two feed drive systems have been compared to analyze the dynamic responses against disturbance. The impulse magnitude of 4000 N with a bandwidth of less than 1KHz was applied to the table feed axis center using the Kistler impact force hammer (9728A20000). Both feed drive responses are measured using the linear scales installed beside the linear guide of the feed drive system. Linear scale encoder measurements display the relative motion of the machine bed and the moving table, which is a precise indicator of feed drive motion.

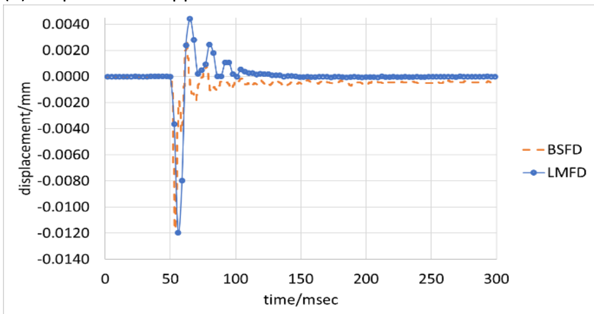
Figure 6(a) displays the test configuration example in the BSFD. As the impulse force shown in Figure 6(b) is applied, the linear scale measurements from the LMFD and the BSFD are displayed in Figure 6(c). With an impulse force of 4000 N, the LMFD system has a peak-to-valley response of 0.0164 mm, which is larger than the BSFD system's response of 0.0144 mm. This is because the linear motor-based feed drive has less damping than the ball screw-based feed drive due to fewer mechanical components. Both systems' dynamic displacements are reduced within 1 micrometer in less than 50 msec. However, it takes longer for the displacement to reduce to less than 0.5 micrometer in the case of BSFD (129 msec) compared to LMFD (50 msec). This phenomenon may be attributed to the pitch error of the ball screw tested, which can be minimized by using a fine-pitch ball screw with backlash compensation.



(a) Impulse response test in BSFD



(b) Impulse force applied to table center in X direction



(c) Impulse responses from LMFD and BSFD

Figure 6. Feed drive responses with external impulse forces

It is commonly understood that the linear motor, which has fewer mechanical components, generally has less damping than the ball screw-based feed drive system. However, the difference between the two system responses is found to be insignificant. For a 4000 N impulse disturbance, the difference is only 0.002 mm.

For additional insights regarding the analysis, it is important to note that the response to disturbances can vary depending on factors such as motor performance, control algorithm, and structural design, regardless of whether a linear or rotary motor is used. By implementing advanced control algorithms and optimizing the structural design of the system, the dynamic stiffness of each system can be further enhanced, thus improving the system's ability to resist disturbances.

4. Summary and discussions

As linear motor-based feed drive (LMFD) has been increasingly adopted, it is necessary to compare it with a ball screw-based feed drive (BSFD) in terms of control accuracy under dynamic motion and disturbances. This article compares two different systems' dynamic responses under the adaptive motion requiring moving mass control with continuous acceleration and deceleration. For the machining tool paths, the tested LMFD generates less tracking error (0.023 mm difference in the X-axis and 0.012 mm in the Y-axis) than the BSFD. This relative comparison indicates that the tested LMFD has better control accuracy in dynamic motion than the BSFD and can generate better control accuracy for complex motion profiles requiring frequent acceleration and deceleration.

Another aspect is whether the systems have high dynamic stiffness and damping against external disturbance. In order to see the relative dynamic response between the table and the base, linear encoder data was recorded and analyzed with the application of impulse forces around 4000 N. As BSFD is known to have more damping than the other, it exhibits less peak-to-valley displacement, but the difference between the two systems' responses is within a few micrometers at 4000 N. Even though BSFD also has a shorter time to settle within 0.001 mm, it has a 79 msec longer time to settle within 0.0005 mm than LMFD, which may be due to ball screw specifications like screw pitch. Based on the test result, the configured LMFD is capable of performing heavy machining like face milling as well as dynamic machining, and it can maintain a precision motion without backlash over disturbance.

Two kinds of test results provide some insights into the different commercial feed drive systems, and with other well-known facts, the relative comparisons are presented in Table 2. As cycle time mainly depends on control setting and motor power, it is not meaningful to mention which system is faster in cycle time. In addition, LMFD has an advantage in terms of life span and backlash compared to BSFD. As LMFD has relatively better control accuracy than BSFD under acceleration or deceleration, precision engineering industries are also increasingly adopting LMFD to achieve fine surface finish and tight dimensional requirements.

The insights gained from the experimental results will be used to further study the feed drive design and control and to overcome the drawbacks of each drive. Furthermore, by optimizing the physical properties and structures of the entire machine tool based on the studied feed drive characteristics, better performance can be achieved for high precision and high-performance cutting.

Table 2 Relative comparisons between LMFD and BSFD

	LMFD	BSFD
Disturbance dynamic stiffness or damping	++	+++
Backlash	+++	++
Tracking error under dynamic motion	+++	++
Cycle time	++	++
Life span considering wear/tear	+++	++

(+ means positive point. More + means better only in relative manner.)

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