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Research on Radial Double Velocity Measurement Method of Laser Tracker

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Abstract: For the dynamic problem that the low-speed sliding table is unable to meet the radial measuring speed of the laser tracker, this paper takes the sliding table of the indoor large-length standard device as the moving object to double the measuring distance by adding a pyramid prism, thereby doubling the radial speed of the laser tracker. In this paper, the measurement data are analyzed through equal interval measurement experiments, equal sampling frequency experiments and repeatability measurement experiments using a pyramid prism to obtain the following conclusions, respectively: Firstly, the stability of the actual interval of the laser tracker is optimal when the rated speed of the sliding table is 50 mm/s. When the pyramid prism is not used, the minimum standard deviation obtained by the laser tracker at a sampling interval of 5 mm is 0.0158 mm. Secondly, during the equal sampling frequency measurement, the stability of the laser interferometer is better than that of the laser tracker when the pyramid prism is not used. With two instruments at a sampling frequency of 10 Hz, the standard deviations of the local velocity of the laser interferometer are 0.1466 mm/s, 0.0693 mm/s and 0.1106 mm/s, respectively. The standard deviations of the laser tracker are 0.1582 mm/s, 0.1033 mm/s and 0.2008 mm/s, respectively. The same conclusion is obtained at a sampling frequency of 20 Hz. The stability of the laser tracker is better than that of the laser interferometer when the pyramid prism is used. Thirdly, the stability and reliability of the local velocity of the laser tracker are better than that of the laser interferometer. For example, at 10 Hz, the standard deviations of the local velocity of the laser tracker are 0.2745 mm/s and 0.2097 mm/s, respectively, and the repeatability of the local velocity is 0.9140 mm/s. The standard deviations of the local velocity of the interferometer are 0.6141 mm/s and 0.6368 mm/s, respectively, and the repeatability of the local velocity is 1.4886 mm/s. And the local velocity of the two measuring instruments is more reliable and stable at a low frequency (10 Hz). This experimental scheme provides a way to measure the high speed of a laser tracker using a sliding table at low speed.

Keywords: laser tracker; radial measuring speed; indoor large-length standard device; laser interferometer; pyramid prism; equal sampling frequency; equal measurement interval; repeatability measurement

Citation: Lv, F.; Hu, C.; Li, J.; Xu, Y. Research on Radial Double Velocity Measurement Method of Laser Tracker. *Processes* **2024**, *12*, 649. https://doi.org/10.3390/pr12040649

Academic Editor: Zhihua Wang

Received: 21 February 2024
Revised: 22 March 2024
Accepted: 22 March 2024
Published: 24 March 2024

1. Introduction

With the development of the manufacturing industry, measurement means and technologies are constantly updated and developed. Recently, measurement methods have also undergone new changes, and the research on measurement is gradually shifting to some emerging fields. In the field of precision measurement, large-scale measurement technology has gradually emerged. Static measurement technology mainly refers to the measurement of spatial coordinates and relative position of the measured object under static conditions, and the research on its measurement technology is relatively mature.

The development trend of measurement is shifting from static measurement to dynamic measurement and from a single measuring device to collaborative measurement using multiple measuring devices. In addition, it is developing and changing towards online measurement, intelligent measurement and other application scenarios, as well as fast measurement [1]. Dynamic measurement technologies are mainly used to measure the dynamic trajectory of assembly, docking and test processes. The large-scale dynamic measuring instruments mainly include laser tracker, indoor GPS, photogrammetric system, and total station, among others [2]. Moreover, the retention rate of visual dynamic sensors, namely digital photogrammetric systems, also shows a trend of significant increase, and the demand for non-contact real time dynamic measurement using a digital photogrammetric system is also becoming increasingly clear. Some scholars at home and abroad have conducted a lot of research. Wang Weiming et al. proposed a large-space dynamic angle measurement method based on machine vision and servo control, which expanded the measuring range of a large space angle to 18.788 m [3]; Gan Yu et al. proposed a dynamic frequency scanning interferometry method to separate and compensate the phase errors in measurement [4]; Esward applied modeling and simulation to dynamic measurement technology and found that it was helpful to improve the understanding of dynamic measurement tasks [5]; Zhang Qingsong et al. used a 2D laser displacement sensor to achieve dynamic non-contact measurement of wheelset geometric parameters such as flange height and wheel diameter [6]; Wang Xiqi et al. proposed a missing detection compensation algorithm based on a constant velocity model and a region growing algorithm to improve the semantic segmentation accuracy, which eliminated the impact of dynamic objects on visual SLAM trajectory accuracy [7]; Zhang Hongwen et al. proposed a set of working time series for aerial surveying and mapping cameras and a new high-precision calibration method, the effectiveness of which was verified by simulation results and experimental data [8]; Li Lin et al. applied embedded multi-scale deep learning to the dynamic performance measurement system of radio frequency identification, which can improve the reading distance of multiple tasks from the physical structure and collision resistance of the system [9]; Li Li analyzed and modeled the dynamic positioning errors of the CNC machine tool guide system, and proved that there is a regular variation between the dynamic positioning error of XY workbench and the movement velocity [10]; Li Guofang et al. studied the automatic tool-changing system of a machining center and the dynamic force measurement system of the drag link mechanism to identify the time start and offset of each force value time in the dynamic force record [11]; Yang Juqing et al. applied a fuzzy adaptive PID tracking algorithm to single-axis laser tracking and rapid prototype tracking experiments, which made the angular acceleration of dynamic tracking exceed $200^\circ/s^2$ [12]. As the most important large-scale dynamic measuring instrument, a laser tracker must have a good dynamic tracking ability and accurate dynamic measurement ability [13]. We have also conducted some research on the dynamic performance of the laser tracker. Zheng Wang et al. experimentally evaluated the dynamic performance of iGPS when measuring robots and compared it with the performance of laser trackers when measuring industrial robots [14]; Lin Jiarui et al. built a 6-DOF measuring system based on the measurement data of a laser tracker, a permanent magnet synchronous inertial navigation system and a strapdown inertial navigation system [15]; Wang Zheng et al. used a laser tracker to correct the absolute volume errors of a three-axis machine tool in real time, which significantly improved the dynamic path accuracy of the machine tool [16]; for some miniaturized machine tools, Hoon-Hee Lee et al. used a laser tracker to study the servo mismatch technique for bidirectional circular test and confirmed the effectiveness of the proposed method by comparing it with the results of a double ball bat [17]. Regarding dynamic measurement technology, there are studies focusing not only on geometric measurement, but also on flow measurement and vibration measurement. Considering the liquid flow fluctuation and turbulent pulsation, Shchelchkov et al. modified the mass flow measurement equation and conducted a comparative experiment with the transfer standard [18]; Jia Binghui proposed a method to measure the vibration at the tip of a 2D tool with the mirror light beam and to measure the transverse and longitudinal vibration displacement at the tip of the tool [19]. At present, there are many studies on static calibration of tracker performance in China.

The research on the dynamic performance of the laser tracker focuses more on its use and less on its own dynamic performance. The manufacturer of the laser tracker provides lateral and radial tracking speeds in the product's specifications. The technical indicators of each laser tracker are roughly the same, and the radial tracking velocity is basically (5–6) m/s. At present, the lateral tracking velocity of the laser tracker generally adopts circular trajectory generator, which has been studied by the author of this paper [20]. There is a lack of research on radial tracking velocity.

In this paper, the radial velocity of the laser tracker is studied based on the indoor large-length standard device and pyramid prism, and the dynamic performance of the laser tracker is studied in an all-round way through equal interval measurement, equal sampling frequency measurement and repeatability at an equal sampling frequency, which are common for the laser tracker. The measuring distance of the laser tracker is doubled by a pyramid prism, which doubles the radial velocity of the laser tracker for the first time. The proposed method is also suitable for the measurement of other dynamic measuring instruments.

2. Large-Length Standard Device and Measurement Diagram

Figure 1 shows a large-length standard device and its measurement diagram. Figure 1a is a simulated measurement diagram of the large-length standard device, Figure 1b is a physical diagram, and Figure 1c is an optical path diagram. There are three parts in the figure: a large-length standard device, a laser tracker, and a laser interferometer. The large-length standard device is mainly composed of a mechanical structure and a calibration module. The mechanical structure mainly includes the base, moving sliding table, grating ruler, linear motor and control system. The calibration module mainly consists of a pyramid prism. A linear motor is used as the driving unit to connect the sliding table to move it, and a grating ruler is used as the feedback distance signal to achieve closed-loop control. A calibration prism is installed on the moving sliding table, and a laser tracker prism and a reflector interferoscope for laser interferometer are installed on the stationary sliding table. The laser tracker and laser interferometer carry out measurement synchronously.

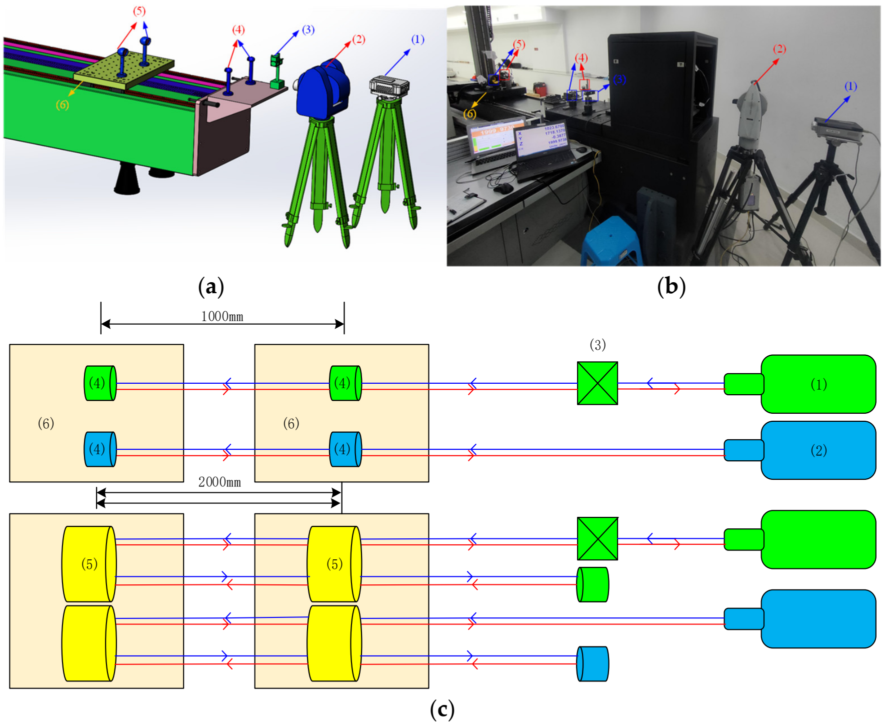

Figure 1. Large-length standard device and measurement diagram; (**a**) simulation diagram; (**b**) actual measurement diagram; (**c**) optical path diagram (1—laser interferometer, 2—laser tracker, 3—interferoscope, 4—reflector, 5—corner prism, 6—sliding platform).

Figure 1c shows the measured optical path diagram. Blue light is the outgoing light, and red light is the incoming light. When the pyramid prism is not used, the movement distance of the sliding platform (6) is 1000 mm, and the measuring distance of the laser tracker and laser interferometer is 1000 mm. After the pyramid prism (5) is used, the measuring distance of the laser tracker and laser interferometer is 2000 mm, and doubling the measuring distance doubles the measuring speed.

3. Measurement Scheme and Basic Concept

Figure 2 shows the schematic diagram of the dynamic measurement scheme. The measurement is mainly carried out from four aspects: measuring instrument, measuring distance, measuring speed, and a measurement setup mode. Measuring instruments are the laser tracker and laser interferometer; the measuring distance depends on the movement distance of the sliding table, including 1000 mm direct measurement (without a pyramid prism) and doubling it to 2000 mm (with a pyramid prism); for the sliding platform, the measuring speed can be set to 50 mm/s, 100 mm/s and 150 mm/s; the measurement setup mode is suitable for the laser tracker and laser interferometer. The laser tracker can be set in four measurement modes: 5 mm equal interval, 10 mm equal interval, 10 Hz equal sampling frequency, and 25 Hz equal sampling frequency. The laser interferometer is only available to set the frequency rather than equal interval measurement; so, there are two measurement modes. Since the dynamic repeatability of measurements needs to be analyzed, it is necessary to measure the laser tracker and laser interferometer twice at equal sampling frequencies of 10 Hz and 25 Hz, respectively. Therefore, the measurement data of 26 laser trackers and 14 laser interferometers can be obtained. The measurement environment is set as the standard environment (temperature is 20 °C, atmospheric pressure is 1013 KPa, and humidity is 50%RH).

Stability: The stability discussed in this paper refers to the speed stability of the laser tracker or laser interferometer. More precisely, it refers to the speed stability of the instrument at the constant speed stage, which reflects the constant ability of the speed of the laser tracker or laser interferometer over time, and is measured by the standard deviation of the speed in this paper. The greater the value of the standard deviation, the worse the stability; on the contrary, the smaller the value of the standard deviation, the better the stability.

Reliability: The reliability discussed in this paper is another indicator of the local velocity of the laser tracker or laser interferometer, which can be understood as the repeatability of two local measuring speeds. It is the maximum value of the difference between two local measuring speeds when the measuring points are selected in the same position as far as possible. The greater the repeatability value of local measuring speed, the worse the measurement reliability. On the contrary, the smaller the repeatability value of local measuring speed, the better the measurement reliability.

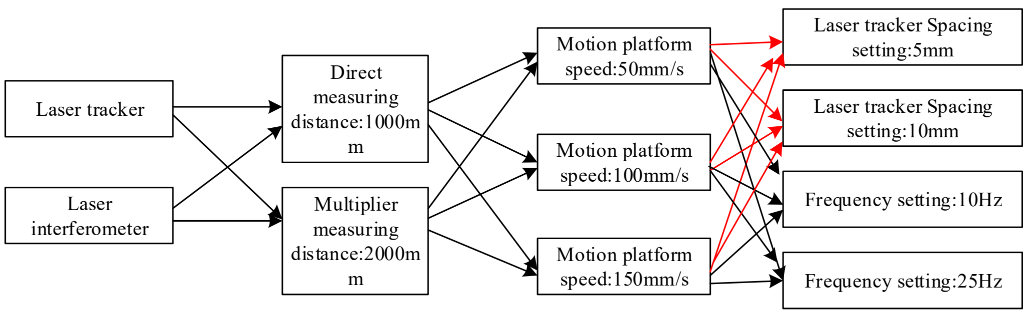

Figure 2. Schematic diagram of dynamic measurement scheme.

4. Dynamic Measurement Data Analysis

When the moving sliding platform moves in a straight line in an ideal state, the measuring system can truthfully reflect the actual measurement. After the speed of the large-length standard device is set, the moving sliding table will experience three stages:

acceleration, constant velocity, and deceleration. Dynamic data analysis is mainly divided into three parts: data analysis of the laser tracker at equal intervals, data analysis of the two measuring instruments at equal sampling frequency, and analysis of the dynamic repeatability data of the two instruments at equal sampling frequency.

4.1. Equal Interval Data Analysis of Laser Tracker

The equal interval measurement of the laser tracker is very common in dynamic measurement, and is an important measurement mode which dynamically analyzes the measurement state with a fixed measuring distance. This part mainly focuses on the data analysis of the laser tracker at an equal interval of 5 mm when the pyramid prism is not used, an equal interval of 10 mm when the pyramid prism is not used, an equal interval of 5 mm when the pyramid prism is used, and an equal interval of 10 mm when the pyramid prism is used.

4.1.1. Data Analysis of Laser Tracker with a Sampling Interval of 5 mm When the Pyramid Prism Is Not Used

Table 1 shows the measurement data statistics of the laser tracker at a sampling interval of 5 mm when the pyramid prism is not used and the movement distance of the sliding table is 1000 mm. It is found from Table 1 that when the rated speed of the sliding table increases, both the actual sampling interval and the standard deviation of the actual interval increase with the increase in the rated speed of the sliding table. When the rated speeds of the sliding table are 50 mm/s, 100 mm/s and 150 mm/s, the measuring distances of the laser tracker are 990.1864 mm, 999.7872 mm and 992.2742 mm, respectively.

Table 1. Measurement data statistics of laser tracker at a sampling interval of 5 mm (without a pyramid prism).

Rated Speed of the Sliding Platform (mm/s)	Number of Measuring Points	Average of Actual Sampling Interval (mm)	Difference in the Maximum Interval (mm)	Standard Deviation of Actual Interval (mm)	Measuring Distance of Laser Tracker (mm)
50	197	5.0262	0.0500	0.0158	990.1864
100	198	5.0494	0.1017	0.0396	999.7872
150	195	5.0886	0.1374	0.0312	992.2742

Figure 3 shows the data graph of the laser tracker at a sampling interval of 5 mm (without a pyramid prism, the movement distance of the sliding table is 1000 mm). In the figure, the horizontal coordinate is the number of measured points, and the vertical coordinate is the actual sampling interval of the laser tracker, in mm. The pink five-pointed star indicates the actual interval when the rated speed of the sliding table is set to 50 mm/s, the blue quadrangle indicates the actual interval when the rated speed of the sliding table is set to 100 mm/s, and the red triangle indicates the actual interval when the rated speed of the sliding table is set to 150 mm/s. It can be clearly seen from the figure that the lower the rated speed of the sliding table, the closer the actual interval of the laser tracker is to the set value of 5 mm; when the speed of the sliding table is 50 mm/s, the actual interval value fluctuates between 5.00 mm and 5.05 mm. When the speed of the sliding table is 100 mm/s, the actual interval value fluctuates significantly and data separation is obvious. When the speed of the sliding table is 150 mm/s, the actual interval value deviates significantly and the actual interval of the laser tracker is closer to the set value only during the acceleration and deceleration stages.

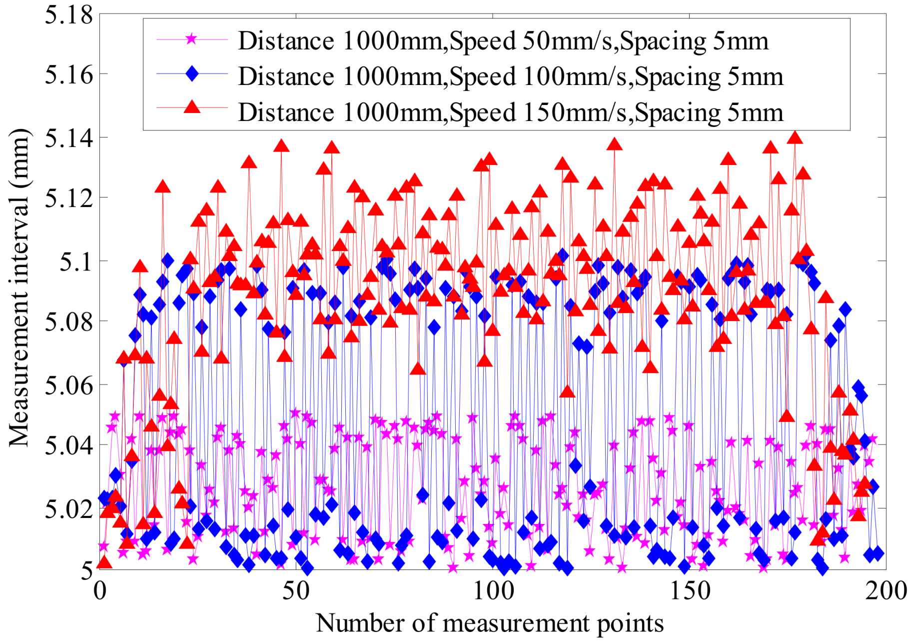

Figure 3. Data Graph of laser tracker at a sampling interval of 5 mm (without a pyramid prism, the movement distance of the sliding table is 1000 mm).

4.1.2. Data Analysis of Laser Tracker at a Sampling Interval of 10 mm When the Pyramid Prism Is Not Used

Table 2 shows the measurement data statistics of the laser tracker at a sampling interval of 10 mm when the pyramid prism is not used and the movement distance of the sliding table is 1000 mm. It is found from Table 2 that when the rated speed of the sliding table increases, both the actual sampling interval and the standard deviation of the actual interval increase with the increase in the rated speed of the sliding table. When the rated speeds of the sliding table are 50 mm/s, 100 mm/s and 150 mm/s, the measuring distances of the laser tracker are 992.6326 mm, 994.9222 mm, and 994.7996 mm, respectively.

Table 2. Measurement data statistics of laser tracker at a sampling interval of 10 mm (without a pyramid prism).

Rated Speed of the Sliding Platform (mm/s)	Number of Measuring Points	Average of Actual Sampling Interval (mm)	Difference in the Maximum Interval (mm)	Standard Deviation of Actual Interval (mm)	Measuring Distance of Laser Tracker (mm)
50	99	10.0266	0.0500	0.0178	992.6326
100	99	10.0497	0.0994	0.0397	994.9222
150	99	10.0485	0.0916	0.0181	994.7996

Figure 4 shows the data graph of the laser tracker at a sampling interval of 10 mm (rated distance of 1000 mm). It can be clearly seen from the figure that when the rated speed of the sliding table is 50 mm/s and 150 mm/s, the actual interval of the laser tracker is closer to the set value of 10 mm; when the rated speed of the sliding table is 100 mm/s, the actual interval data fluctuate significantly and are separated, which is consistent with the maximum standard deviation of the actual interval.

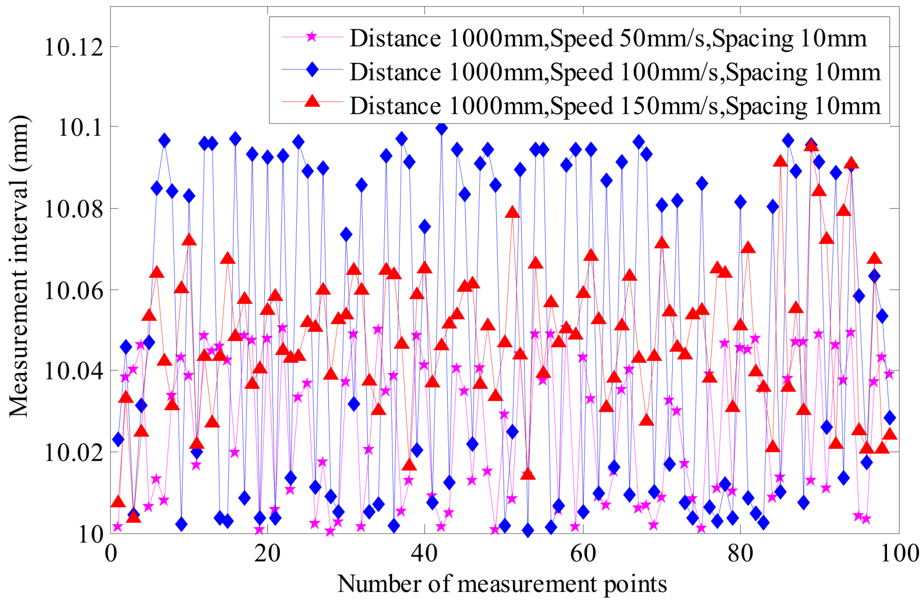

Figure 4. Data graph of laser tracker at a sampling interval of 10 mm (without a pyramid prism).

4.1.3. Data Analysis of Laser Tracker at a Sampling Interval of 5 mm When the Pyramid Prism Is Used

Table 3 shows the measurement data statistics of the laser tracker at a sampling interval of 5 mm when the pyramid prism is used and the movement distance of the sliding table is 1000 mm, and the measured value of the laser tracker is 2000 mm. It is found from Table 3 that when the rated speed of the sliding table increases, both the actual sampling interval and the standard deviation of the actual interval increase with the increase in the rated speed of the sliding table. When the rated speeds of the sliding table are 50 mm/s, 100 mm/s and 150 mm/s, the measuring distances of the laser tracker are 1994.5089 mm, 1995.0838 mm, and 1993.9067 mm, respectively.

Table 3. Measurement data statistics of laser tracker at a sampling interval of 5 mm (with a pyramid prism).

Rated Speed of the Sliding Platform (mm/s)	Number of Measuring Points	Average of Actual Sampling Interval (mm)	Difference in the Maximum Interval (mm)	Standard Deviation of Actual Interval (mm)	Measuring Distance of Laser tracker (mm)
50	395	5.0494	0.0999	0.0338	1994.5089
100	392	5.0895	0.0829	0.0829	1995.0838
150	391	5.0995	0.2931	0.0371	1993.9067

Figure 5 shows the data graph of the laser tracker at a sampling interval of 5 mm (rated distance of 2000 mm). It can be clearly seen from the figure that when the rated speed of the sliding table is 50 mm/s, the measurement data of the laser tracker fluctuate between 5.00 mm and 5.10 mm, and data fluctuation is significantly larger than that at 1000 mm; when the rated speed of the sliding table is 100 mm/s, the actual interval value of the laser tracker is also significantly separated. Some data fluctuate between 5.00 mm and 5.03 mm, while other data fluctuate between 5.16 mm and 5.20 mm, and data fluctuation is larger than that at 1000 mm; when the rated speed of the sliding table is 150 mm/s, there is some fluctuation in the actual interval between the first 50 sets of data and the last 50 sets of data, which is identical at 1000 mm.

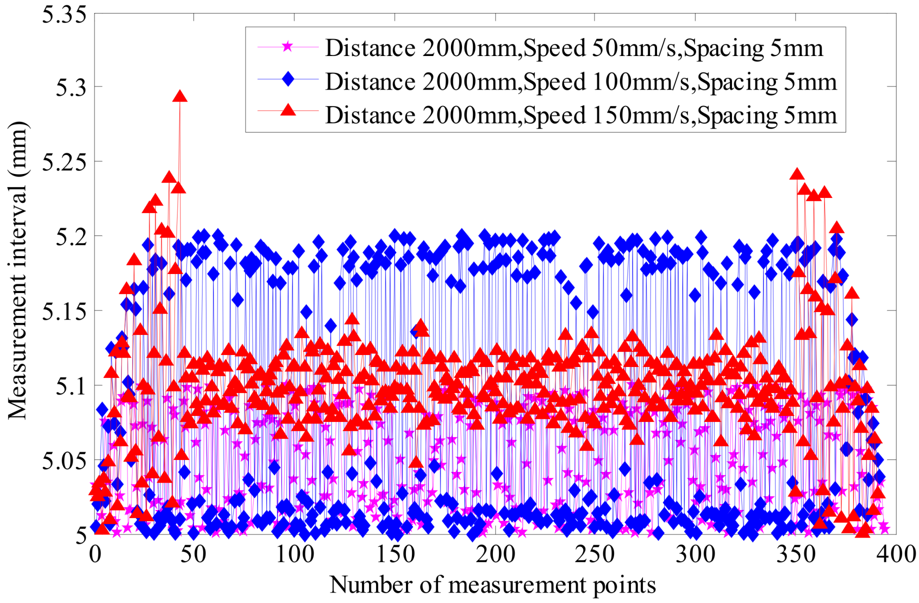

Figure 5. Data graph of laser tracker at a sampling interval of 5 mm (with a pyramid prism).

4.1.4. Data Analysis of Laser Tracker at a Sampling Interval of 10 mm When the Pyramid Prism Is Used

Table 4 shows the measurement data statistics of the laser tracker at a sampling interval of 10 mm when the pyramid prism is used and the movement distance of the sliding table is 1000 mm. It is found from Table 4 that when the rated speed of the sliding table increases, both the actual sampling interval and the standard deviation of the actual interval increase with the increase in the rated speed of the sliding table. When the rated speeds of the sliding table are 50 mm/s, 100 mm/s and 150 mm/s, the measuring distances of the laser tracker are 1999.6199 mm, 1998.7900 mm, and 1984.7167 mm, respectively.

Table 4. Measurement data statistics of laser tracker at a sampling interval of 10 mm (with a pyramid prism).

Rated Speed of the Sliding Platform (mm/s)	Number of Measuring Points	Average of Actual Sampling Interval (mm)	Difference in the Maximum Interval (mm)	Standard Deviation of Actual Interval (mm)	Measuring Distance of Laser Tracker (mm)
50	198	10.0483	0.1004	0.0354	1999.6199
100	198	10.0949	0.2002	0.0809	1998.7900
150	195	10.1780	0.2523	0.0568	1984.7167

Figure 6 shows the data graph of the laser tracker at a sampling interval of 10 mm (with a pyramid prism). It can be clearly seen from the figure that when the rated speed of the sliding table is 50 mm/s, the actual interval value of the laser tracker fluctuates between 10.00 mm and 10.10 mm, and the fluctuation is more obvious than that at 1000 mm; when the rated speed of the sliding table is 100 mm/s, the data fluctuate significantly and are separated; when the speed of the sliding table is set to 150 mm/, most of the actual interval data of the laser tracker fluctuate between 10.15 mm and 10.25 mm, and data fluctuation is significantly higher than that at 1000 mm; when the rated speeds of the sliding table are 100 mm/s and 150 mm/s, the data at both ends fluctuate significantly.

At equal sampling intervals, some conclusions are drawn for the laser tracker based on the data from the above four scenarios:

(1) As the rated speed of the sliding table increases, the actual sampling interval of the laser tracker continues to increase. For example, when the pyramid prism is not used,

the rated speed of the sliding table is set to 50 mm/s and the sampling interval of the laser tracker is set to 5 mm, the average of the actual interval is 5.02 mm. When the rated speed of the sliding table is set to 100 mm/s, the average of the actual interval is 5.04 mm. When the rated speed of the sliding table is set to 150 mm/s, the average of the actual interval is 5.08 mm. The same is true in the other three cases.

(2) When the rated speed of the sliding table is set to 100 mm/s, the standard deviation of the average actual interval is the worst. Figures 3–6 show that the data are significantly separated, indicating that the stability of the actual interval is the worst in this case. For example, when the pyramid prism is not used, the rated speed of the sliding table is set to 50 mm/s and the sampling interval of the laser tracker is set to 10 mm, the standard deviation of the actual interval is 0.0178 mm. When the rated speed of the sliding table is set to 100 mm/s, the standard deviation of the actual interval is 0.0397 mm. When the rated speed of the sliding table is set to 150 mm/s, the standard deviation of the actual interval is 0.0181 mm.

(3) At different actual intervals, the measuring distance of the laser tracker cannot reach the set distance of the sliding table because the actual interval value is larger than the set interval value. When the pyramid prism is used and the rated speed of the sliding table is set to 50 mm/s, the measuring distance of the laser tracker is 1994.5089 mm; when the rated speed of the sliding table is set to 100 mm/s, the measuring distance of the laser tracker is 1995.0838 mm; and when the rated speed of the sliding table is set to 150 mm/s, the measuring distance of the laser tracker is 1993.9067 mm.

(4) The actual interval of the laser tracker fluctuates slightly in the acceleration and deceleration stages of the sliding table. For example, when the pyramid prism is used and the interval of the laser tracker is set to 5 mm, the first 50 sets of data and the last 50 sets of data fluctuate significantly. When the interval of the laser tracker is set to 10 mm, the first 25 sets of data and the last 25 sets of data fluctuate significantly.

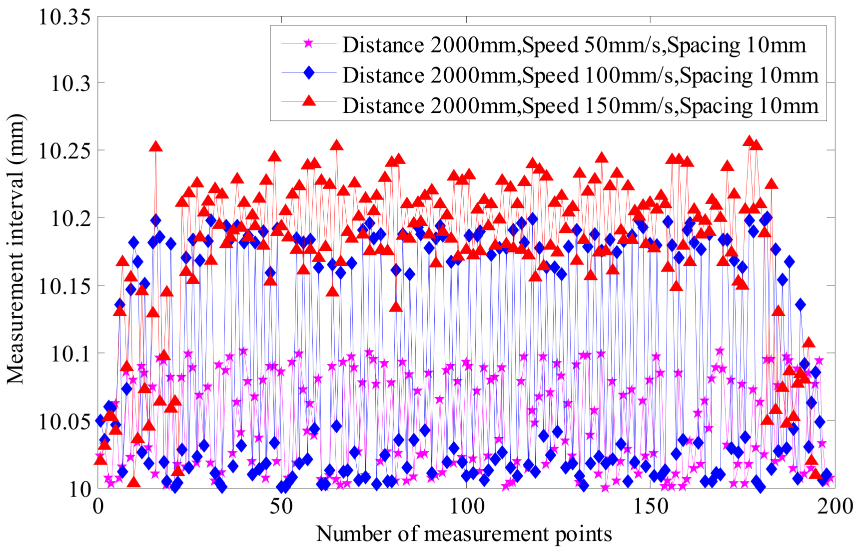

Figure 6. Data graph of laser tracker at a sampling interval of 10 mm (with a pyramid prism).

4.2. Equal Sampling Frequency Data Analysis

The equal sampling frequency measurement methods of the laser tracker and laser interferometer are widely used. This part mainly focuses on the analysis of the two instruments (i.e., laser tracker and laser interferometer) at equal sampling frequencies. It is mainly divided into the data analysis of the two instruments at an equal sampling frequency of 10 Hz when the pyramid prism is not used, at an equal sampling frequency of 25 Hz when the pyramid prism is not used, at an equal sampling frequency of 10 Hz when the pyramid prism is used, and at an equal sampling frequency of 25 Hz when the pyramid prism is used.

The movement stage of the sliding table is divided into three phases: acceleration, constant velocity, and deceleration. Firstly, it is necessary to agree on the acceleration phase time, constant velocity phase time, and deceleration phase time. The acceleration phase time is the time when the speed of the instrument accelerates from 0.01 mm/s to the rated speed for the first time, the constant velocity phase time is the time from the first time the instrument reaches the rated speed to the last time it reaches the rated speed, and the deceleration phase time is the time when the speed decreases to less than the rated speed to the time when the speed decreases to a value greater than or equal to 0.01 mm/s. For example, when the rated speed of the sliding table is 50 mm/s, the acceleration phase time of the laser tracker is the movement time from the measuring speed of 0.01 mm/s to less than 50 mm/s, the constant velocity phase time of the laser tracker is the movement time from the first time the measuring speed reaches 50 mm/s to the last time it is greater than 50 mm/s, and the deceleration phase time of the laser tracker is the movement time when the measuring speed decelerates below 50 mm/s to a value greater than or equal to 0.01 mm/s.

4.2.1. Data Analysis of Two Instruments at a Sampling Frequency of 10 Hz When the Pyramid Prism Is Not Used

Table 5 shows the measurement data of the two instruments at a sampling frequency of 10 Hz when the pyramid prism is not used. The data of the sliding table in the constant velocity phase are analyzed as the average value and local standard deviation of the local velocity. The following conclusions can be drawn from Table 5:

(1) The data stability of the laser interferometer is better than that of the laser tracker in the constant velocity phase. The standard deviations of the local velocity of the laser interferometer are 0.1466 mm/s, 0.0693 mm/s, and 0.1106 mm/s, respectively. The standard deviations of the laser tracker are 0.1582 mm/s, 0.1033 mm/s, and 0.2008 mm/s, respectively. The standard deviation of the laser interferometer is generally smaller than that of the laser interferometer in the constant velocity phase.

(2) The dynamic performance of the laser interferometer and laser tracker is optimal when the rated speed of the sliding table is 100 mm/s. When the speed of the sliding table is set to 100 mm/s, the standard deviation of the local velocity of the laser tracker is 0.1033 mm/s, which is smaller than 0.1582 mm/s and 0.2008 mm/s. The same is observed for laser interferometers. Therefore, when dynamic measurement is required, it is preferred to carry out the measurement when the rated speed of the sliding table is 100 mm/s.

Table 5. Measurement data statistics of two instruments at a sampling frequency of 10 Hz (without a pyramid prism).

Measuring Instrument	Rated Speed of Sliding Table (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (Constant Velocity Phase) (mm/s)	Standard Deviation of Local Velocity (Constant Velocity Phase) (mm/s)	Average Global Velocity (mm/s)	Measuring Distance Value (mm)
Laser tracker	50	0.8	19.2	0.8	20.8	49.9996	0.1582	48.0757	999.9865
	100	1.2	8.8	1.4	11.4	99.9993	0.1033	87.7176	999.9861
	150	2.0	4.9	1.9	8.8	149.997	0.2008	113.6345	999.9859
Laser interferometer	50	0.7	19.2	1.0	20.9	50.0003	0.1466	47.8462	999.9861
	100	1.4	8.4	1.6	11.4	100.0013	0.0693	87.7180	999.9865
	150	1.9	4.7	1.9	8.5	150.0005	0.1106	117.6453	999.9860

To display the measurement details more clearly, Figure 7 shows the velocity diagrams of the two instruments at a sampling frequency of 10 Hz (without a pyramid prism). The blue graph shows the dynamic performance of the laser tracker, and the red graph shows the dynamic performance of the laser interferometer. It can be seen from the graphical display that the overall data of the two instruments are relatively stable, and local data are indented.

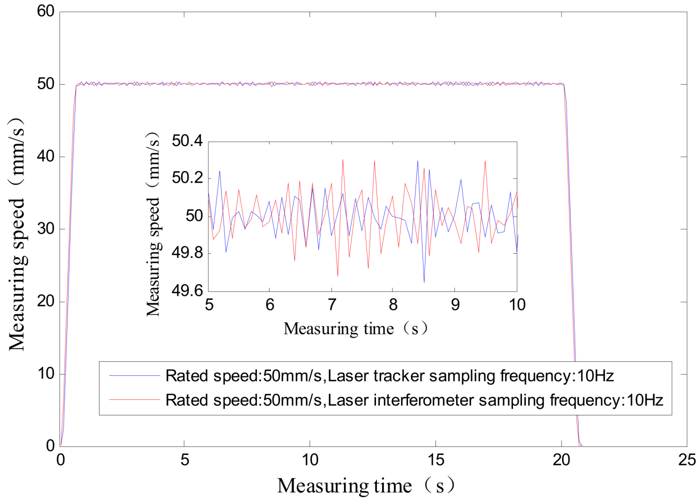

Figure 7. Velocity diagrams of two instruments at a sampling frequency of 10 Hz (without pyramid prism).

4.2.2. Data Analysis of Two Instruments at a Sampling Frequency of 25 Hz When the Pyramid Prism Is Not Used

Table 6 shows the measurement data of the two instruments at a sampling frequency of 25 Hz when the pyramid prism is not used. The following conclusions can be drawn from Table 2:

(1) The data stability of the laser interferometer is better than that of the laser tracker in the constant velocity phase. The standard deviations of the local velocity of the laser interferometer are 0.3579 mm/s, 0.2531 mm/s, and 0.2897 mm/s, respectively. The standard deviations of the laser tracker are 0.3884 mm/s, 0.2858 mm/s, and 0.3571 mm/s, respectively. The standard deviation of the laser interferometer is generally smaller than that of the laser interferometer in the constant velocity phase.

(2) The dynamic performance of the laser interferometer and laser tracker is optimal when the rated speed of the sliding table is 100 mm/s. The standard deviation of the local velocity of the laser tracker is 0.2858 mm/s, which is smaller than 0.3884 mm/s and 0.3571 mm/s. The same goes for laser interferometers. Therefore, when dynamic measurement is required, it is preferred to carry out measurement when the rated speed of the sliding table is 100 mm/s.

(3) Compared to the sampling frequency of 10 Hz, the velocity standard deviation of the two instruments is poor at 25 Hz, indicating that the velocity stability is poor. For example, when the rated speed of the sliding table is 50 mm/s, the standard deviation of the local velocity of the laser tracker is 0.1582 mm/s at 10 Hz, while the standard deviation of the local velocity is 0.3884 mm/s at 25 Hz. The same is true in the other five cases.

(4) When the sampling frequency of the laser tracker is 10 Hz, the local average velocity is closer to the rated speed of the sliding table. When the sampling frequency of the laser interferometer is 25 Hz, the local average velocity is closer to the rated speed of the sliding table. The local average velocities of the laser tracker are 49.9996 mm/s, 99.9993 mm/s, and 149.9997 mm/s, respectively, at 10 Hz, which are closer to 50 mm/s, 100 mm/s and 150 mm/s than 49.9982 mm/s, 99.9957 mm/s and 149.9920 mm/s.

To display the measurement details more clearly, Figure 8 shows the velocity diagrams of the two instruments at a sampling frequency of 25 Hz (without a pyramid prism). It can be seen from the graphical display that the overall data of the two instruments oscillate more violently than at 10 Hz.

Table 6. Measurement data statistics of two instruments at a sampling frequency of 25 Hz (without a pyramid prism).

Measuring Instrument	Rated Speed of Sliding Table (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (Constant Velocity Phase) (mm/s)	Standard Deviation of Local Velocity (Constant Velocity Phase) (mm/s)	Average Global Velocity (mm/s)	Measuring Distance Value (mm)
Laser tracker	50	0.64	19.44	0.76	20.84	49.9982	0.3884	47.9837	999.9863
	100	1.12	8.88	1.2	11.2	99.9957	0.2858	89.2839	999.9863
	150	1.56	5.08	1.72	8.36	149.9920	0.3571	119.6147	999.9857
Laser interferometer	50	0.72	19.24	0.8	20.76	50.0004	0.3579	48.1688	999.9865
	100	1.08	8.88	1.36	11.32	99.9999	0.2531	88.3380	999.9865
	150	1.6	5.00	1.88	8.48	149.9998	0.2897	117.9228	999.9864

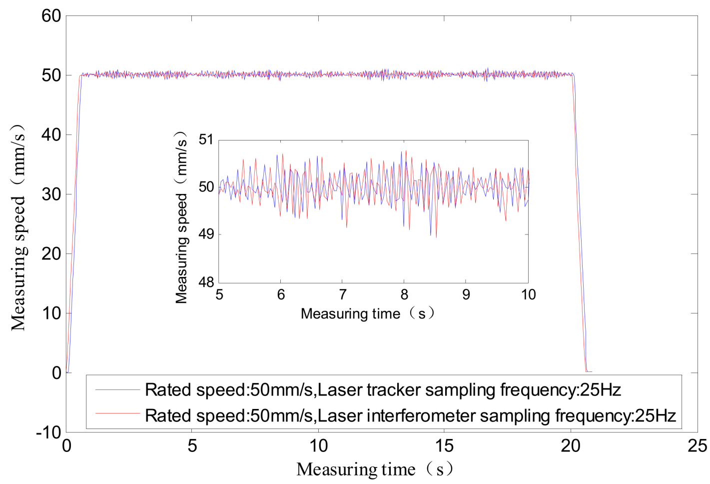

Figure 8. Velocity diagrams of two instruments at a sampling frequency of 25 Hz (without pyramid prism).

4.2.3. The Equal Sampling Frequency of the Laser Tracker Is 10 Hz When the Pyramid Prism Is Used

Table 7 shows the measurement data of the two instruments at a sampling frequency of 10 Hz when the pyramid prism is used. The measuring distance of the sliding table is 1000 mm, and the distance is doubled to 2000 mm after the pyramid prism is used. The following conclusions can be drawn from Table 3:

(1) When the measuring distance is doubled by a pyramid prism, the average local velocities of the laser tracker and laser interferometer are also doubled, and the standard deviation of the local velocity becomes larger after the velocity is doubled. For example, the rated speed of the sliding table is set to 150 mm/s, the local velocity measured by the laser tracker is 299.9922 mm/s, the local velocity measured by the laser interferometer is 300.0036 mm/s, the standard deviation of the local velocity measured by the laser tracker is 0.2891 mm/s after the pyramid prism is installed and 0.1582 mm/s before the pyramid prism is installed.

(2) The dynamic performance of the laser interferometer and laser tracker is optimal when the rated speed of the sliding table is 100 mm/s. The standard deviation of the local velocity of the laser tracker is 0.1461 mm/s, which is smaller than 0.2891 mm/s and 0.2745 mm/s. The same goes for the laser interferometers. Therefore, when dynamic measurement is required, it is preferred to carry out measurement when the rated speed of the sliding table is 100 mm/s.

(3) The data stability of the laser tracker is better than that of the laser interferometer in the constant velocity phase. The standard deviations of the local velocity measured by the laser tracker are 0.2891 mm/s, 0.1461 mm/s, and 0.2745 mm/s, respectively. The standard deviations of the local velocity measured by the laser interferometer are 0.2992 mm/s,

0.1907 mm/s, and 0.6144 mm/s, respectively. The standard deviation of the laser tracker is generally smaller than that of the laser interferometer in the constant velocity phase.

To display the measurement details more clearly, Figure 9 shows the velocity diagrams of the two instruments at a sampling frequency of 10 Hz when the pyramid prism is used. It can be seen from the graphical display that the overall data of the two instruments oscillate more violently than at 10 Hz.

Table 7. Measurement data statistics of two instruments at a sampling frequency of 10 Hz (with a pyramid prism).

Measuring Instrument	Rated Speed of Sliding Table (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (Constant Velocity Phase) (mm/s)	Standard Deviation of Local Velocity (Constant Velocity Phase) (mm/s)	Average Global Velocity (mm/s)	Measuring Distance Value (mm)
Laser tracker	50	0.8	19.2	1.3	21.3	99.9973	0.2891	93.8951	1999.9716
	100	1.6	8.5	1.6	11.7	199.9965	0.1461	170.9370	1999.9720
	150	1.8	4.9	1.8	8.5	299.9922	0.2745	235.2901	1999.9717
Laser interferometer	50	0.8	19.2	1.1	21.1	100.0010	0.2992	94.7854	1999.9720
	100	1.2	8.7	1.6	11.5	200.0039	0.1907	173.9106	1999.9730
	150	1.8	5.0	1.8	8.6	300.0036	0.6144	232.5543	1999.9700

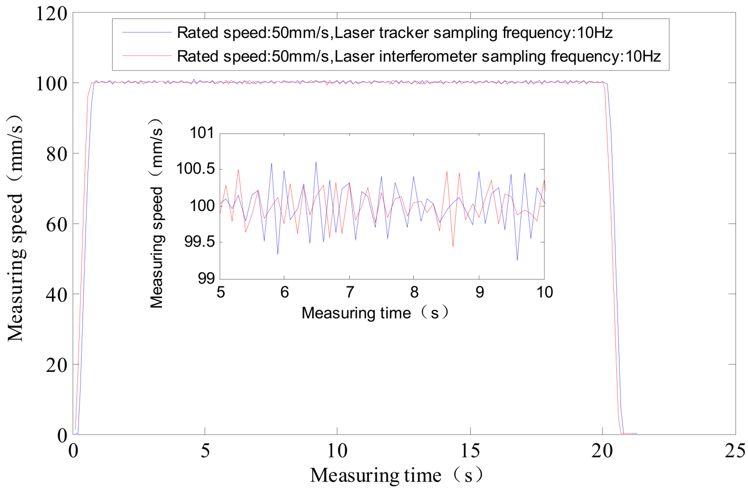

Figure 9. Velocity diagrams of two instruments at a sampling frequency of 10 Hz (with pyramid prism).

4.2.4. The Equal Sampling Frequency of the Laser Tracker Is 25 Hz When the Pyramid Prism Is Used

Table 8 shows the measurement data of the two instruments at a sampling frequency of 25 Hz when the pyramid prism is used. The measuring distance of the sliding table is 1000 mm, and the distance is doubled to 2000 mm after the pyramid prism is used. The following conclusions can be drawn from Table 4:

(1) When the measuring distance is doubled by a pyramid prism, the average local velocities of the laser tracker and laser interferometer are also doubled, and the standard deviation of the local velocity becomes larger after the velocity is doubled. For example, the rated speed of the sliding table is set to 150 mm/s, the local velocity measured by the laser tracker is 299.9922 mm/s, the local velocity measured by the laser interferometer is 300.0036 mm/s, the standard deviation of the local velocity measured by the laser tracker is 0.7297 mm after the pyramid prism is installed and 0.3884 mm before the pyramid prism is installed.

(2) The dynamic performance of the laser interferometer and laser tracker is optimal when the rated speed of the sliding table is 100 mm/s. The standard deviation of the local measurement of the laser tracker is 0.5029 mm, which is smaller than 0.7297 mm and

0.6141 mm. The same is observed for laser interferometers. Therefore, when dynamic measurement is required, it is preferred to carry out measurement when the rated speed of the sliding table is 100 mm/s.

(3) The data stability of the laser tracker is better than that of the laser interferometer in the constant velocity phase. The standard deviations of the local velocity measured by the laser tracker are 0.7297 mm/s, 0.5029 mm/s, and 0.6141 mm/s, respectively. The standard deviations of the local velocity measured by the laser interferometer are 0.7586 mm/s, 0.6073 mm/s, and 0.8508 mm/s, respectively. The standard deviation of the laser tracker is generally smaller than that of the laser interferometer in the constant velocity phase.

To display the measurement details more clearly, Figure 10 shows the velocity diagrams of the two instruments at a sampling frequency of 25 Hz (with a pyramid prism). It can be seen from the graphical display that the overall data of the two instruments oscillate more violently than at 10 Hz.

Table 8. Measurement data statistics of two instruments at a sampling frequency of 25 Hz (with a pyramid prism).

Measuring Instrument	Rated Speed of Sliding Table (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (Constant Velocity Phase) (mm/s)	Standard Deviation of Local Velocity (Constant Velocity Phase) (mm/s)	Average Global Velocity (mm/s)	Measuring Distance Value (mm)
Laser tracker	50	0.64	19.44	0.8	20.88	99.9969	0.7297	95.7838	1999.9716
	100	1.12	8.88	1.36	11.36	199.9925	0.5029	176.0530	1999.9713
	150	1.72	5.08	1.8	8.60	299.9853	0.6141	232.5545	1999.9717
Laser interferometer	50	0.72	19.32	0.76	20.80	100.0011	0.7571	96.1524	1999.9725
	100	1.08	8.88	1.48	11.44	200.0016	0.6073	174.8228	1999.9728
	150	1.6	5.0	1.84	8.44	300.0165	0.8508	236.9632	1999.9726

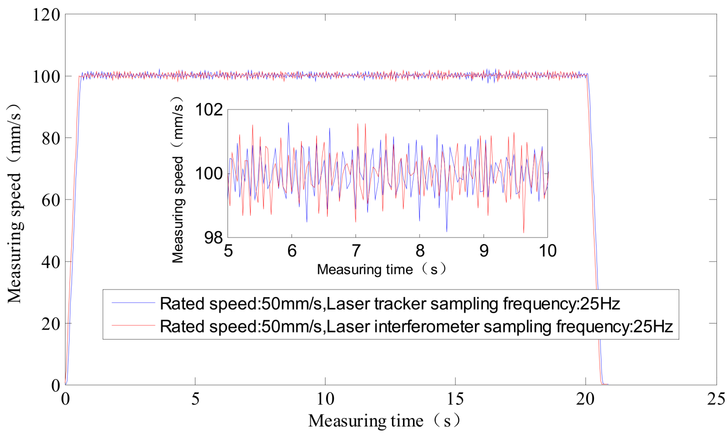

Figure 10. Velocity diagrams of two instruments at a sampling frequency of 25 Hz (with pyramid prism).

In summary, the following conclusions can be drawn from the data analysis of the two instruments at an equal sampling frequency:

(1) At a sampling frequency of either 10 Hz or 25 Hz, the velocity stability of the laser interferometer is better than that of the laser tracker in the constant velocity phase when the pyramid prism is not used. When the measuring distance is 2000 mm after the pyramid prism is used, the velocity stability of the laser tracker is better than that of the laser interferometer in the constant velocity phase, indicating that the laser interferometer is more affected by the pyramid prism, while the laser tracker is less affected by the pyramid prism.

(2) The standard deviation of the local velocity of the laser interferometer and laser tracker is the smallest and the dynamic performance is optimal when the speed of the

sliding table is set to 100 mm/s, compared to the rated speeds of 50 mm/s and 150 mm/s. Therefore, in the process of dynamic measurement, the rated speed of the sliding table can be set to 100 mm/s.

(3) At a sampling frequency of either 10 Hz or 25 Hz, the local measuring speeds of the laser interferometer and laser tracker are doubled when the distance is doubled by a pyramid prism. After the local velocity is doubled, the standard deviation increases, and the stability deteriorates.

4.3. Data Analysis of Equal Frequency Repeatability When the Pyramid Prism Is Used

This part mainly focuses on the repeatability data analysis of the two instruments (i.e., laser tracker and laser interferometer) when the pyramid prism is used. It is mainly divided into repeatability data analysis of the laser tracker at equal sampling frequencies of 10 Hz and 25 Hz and of the laser interferometer at equal sampling frequencies of 10 Hz and 25 Hz. Two measurements are required in each case. The movement distance of the sliding table is 1000 mm, and the rated speed of the sliding table is set to 150 mm/s.

4.3.1. Repeatability of Laser Tracker at a Sampling Frequency of 10 Hz

Table 9 shows the measurement data of the laser tracker at a sampling frequency of 10 Hz. When the rated speed of the sliding table is 150 mm/s, the measuring distance is doubled by the pyramid prism. The average measuring speeds in the constant velocity phase are 299.9922 mm/s and 299.9909 mm/s, respectively. The difference between the two local average speeds is 0.0013 mm/s, and the movement time in the constant velocity phase is 4.9 s and 4.8 s, respectively. The standard deviations of the local velocity are 0.2745 mm/s and 0.2097 mm/s, respectively. The measurement repeatability of the local velocity is 0.9140 mm/s.

Figure 11 shows the repeatability of the laser tracker at a sampling frequency of 10 Hz when the pyramid prism is used (constant velocity phase). The selected measuring points should be in the same position as far as possible, and the data of 48 points are analyzed twice.

Table 9. Measurement data of laser tracker at a sampling frequency of 10 Hz (two measurements when the pyramid prism is used).

Rated Speed of the Sliding Platform (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (mm/s)	Standard Deviation of Local Velocity (mm/s)	Measurement Repeatability (mm/s)	Average Global Velocity (mm/s)	Tracker Measurement Value (mm)
150	1.8	4.9	1.8	8.5	299.9922	0.2745	0.9140	235.2901	1999.9717
150	1.8	4.8	2.0	8.6	299.9909	0.2097		232.5535	1999.9718

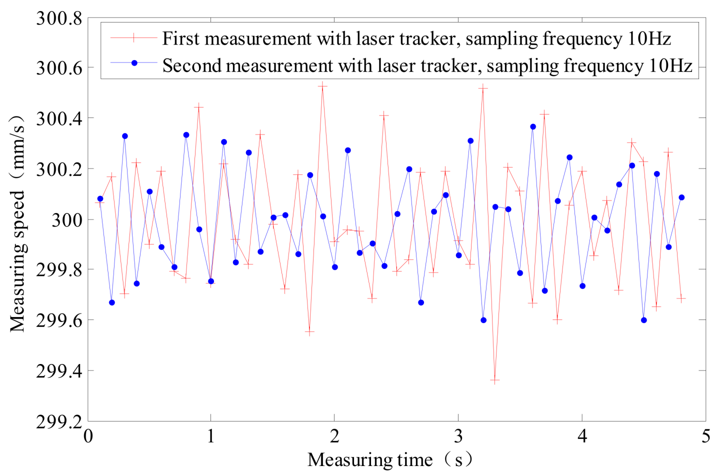

Figure 11. Repeatability of laser tracker at a sampling frequency of 10 Hz (with a pyramid prism).

4.3.2. Repeatability of Laser Tracker at a Sampling Frequency of 25 Hz

Table 10 shows the measurement data of the laser tracker at a sampling frequency of 25 Hz. When the rated speed of the sliding table is 150 mm/s, the measuring distance is doubled by the pyramid prism. The average measuring speeds in the constant velocity phase are 299.9853 mm/s and 299.9879 mm/s, respectively. The difference between the two local average speeds is 0.0026 mm/s, and the movement time in the constant velocity phase is 5.08 s and 5.12 s, respectively. The standard deviations of the local velocity are 0.6141 mm/s and 0.6368 mm/s, respectively. The measurement repeatability of the local velocity is 2.3600 mm/s.

Table 10. Repeatability of laser tracker at a sampling frequency of 25 Hz (two measurements when the pyramid prism is used).

Rated Speed of the Sliding Platform (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (mm/s)	Standard Deviation of Local Velocity (mm/s)	Measurement Repeatability (mm/s)	Average Global Velocity (mm/s)	Tracker Measurement Value (mm)
150	1.72	5.08	1.8	8.60	299.9853	0.6141	2.3600	232.5545	1999.9717
150	1.52	5.12	1.8	8.44	299.9879	0.6368		236.9630	1999.9722

Figure 12 shows the repeatability of the laser tracker at a sampling frequency of 25 Hz (constant velocity phase). The selected measuring points should be in the same position as far as possible, and the data of 127 points are analyzed twice.

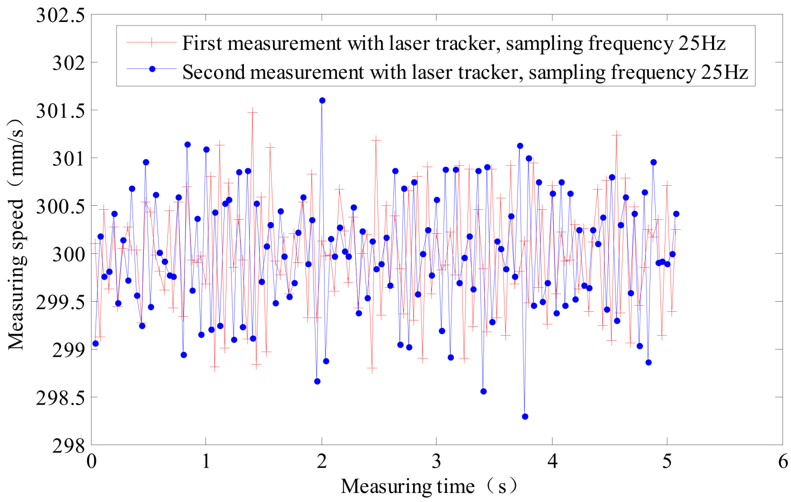

Figure 12. Repeatability of laser tracker at a sampling frequency of 25 Hz (with a pyramid prism).

4.3.3. Repeatability of Laser Interferometer at a Sampling Frequency of 10 Hz

Table 11 shows the results of the two repeatability measurements of the laser interferometer at a sampling frequency of 10 Hz. When the rated speed of the sliding table is 150 mm/s, the measuring distance is doubled by the pyramid prism. The average measuring speeds in the constant velocity phase are 300.0036 mm/s and 300.0100 mm/s, respectively. The difference between the two local average speeds is 0.0064 mm/s, and the movement time in the constant velocity phase is 5.0 s and 5.1 s, respectively. The standard deviations of the local velocity are 0.6200 mm/s and 0.6011 mm/s, respectively. The measurement repeatability of the local velocity is 1.4886 mm/s.

Figure 13 shows the repeatability of the laser interferometer at a sampling frequency of 10 Hz (constant velocity phase). The selected measuring points should be in the same position as far as possible, and the data of 49 points are analyzed twice.

Table 11. Repeatability data of laser interferometer at a sampling frequency of 10 Hz (two measurements when the pyramid prism is used).

Rated Speed of the Sliding Platform (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (mm/s)	Standard Deviation of Local Velocity (mm/s)	Measurement Repeatability (mm/s)	Average Global Velocity (mm/s)	Tracker Measurement Value (mm)
150	1.8	5.0	1.8	8.6	300.0036	0.6200	1.4886	232.5543	1999.9696
150	1.6	5.1	2.2	8.9	300.0100	0.6011		224.7161	1999.9726

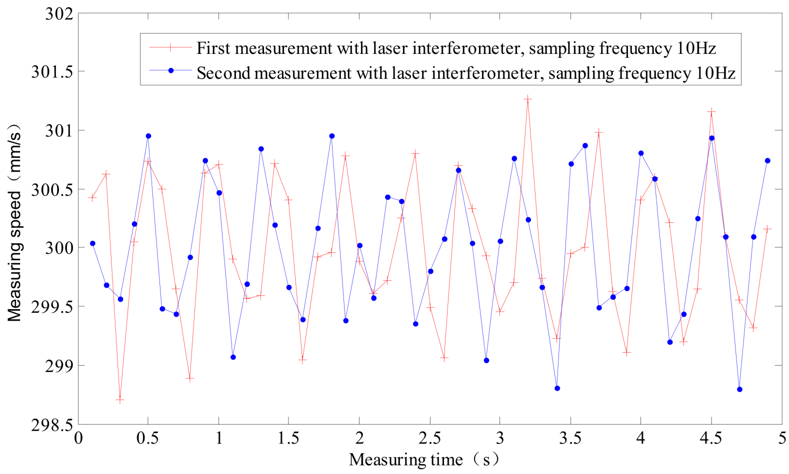

Figure 13. Repeatability of laser interferometer at a sampling frequency of 10 Hz (with a pyramid prism).

4.3.4. Repeatability of Laser Interferometer at a Sampling Frequency of 25 Hz

Table 12 shows the results of the two repeatability measurements of the laser interferometer at a sampling frequency of 25 Hz. When the rated speed of the sliding table is 150 mm/s, the measuring distance is doubled by the pyramid prism. The average measuring speeds in the constant velocity phase are 300.0165 mm/s and 300.0204 mm/s, respectively. The difference between the two local average speeds is 0.0039 mm/s, and the movement time in the constant velocity phase is 5.0 s and 5.0 s, respectively. The standard deviations of the local velocity are 0.8508 mm/s and 0.9158 mm/s, respectively. The measurement repeatability of the local velocity is 2.1681 mm/s. The standard deviation and measurement repeatability of the local velocity of the laser interferometer are significantly higher at 25 Hz than at 10 Hz.

Figure 14 shows the repeatability of the laser interferometer at a sampling frequency of 25 Hz (constant velocity phase). The selected measuring points should be in the same position as far as possible, and the data of 125 points are analyzed twice.

Table 12. Repeatability data of laser interferometer at a sampling frequency of 25 Hz (two measurements when the pyramid prism is used).

Rated Speed of the Sliding Platform (mm/s)	Acceleration Phase Time (s)	Constant Velocity Phase Time (s)	Deceleration Phase Time (s)	Total Time (s)	Average Local Velocity (mm/s)	Standard Deviation of Local Velocity (mm/s)	Measurement Repeatability (mm/s)	Average Global Velocity (mm/s)	Tracker Measurement Value (mm)
150	1.6	5.0	1.84	8.44	300.0165	0.8508	2.1681	236.9632	1999.9726
150	1.68	5.0	1.84	8.52	300.0204	0.9158		234.7383	1999.9729

When the pyramid prism is used, the following conclusions can be drawn from the data results of the two measuring instruments at two measuring frequencies:

(1) The standard deviation value of the local measuring speed of the laser tracker and laser interferometer at 10 Hz is smaller than that at 25 Hz, and the data are more stable.

The standard deviations of the local velocity of the laser tracker are 0.2745 mm/s and 0.2097 mm/s, respectively, at 10 Hz, while the standard deviations of the local velocity are 0.6141 mm/s and 0.6368 mm/s, respectively, at 25 Hz.

(2) The measurement repeatability of the local measuring speed of the laser tracker and laser interferometer at 10 Hz is smaller than that at 25 Hz, and the data are more stable. The repeatability of the local velocity of the laser tracker is 0.9140 mm/s at 10 Hz and 2.3600 mm/s at 20 Hz. The same is observed for laser interferometers.

(3) At a sampling frequency of 10 Hz or 25 Hz, the data stability and the reliability of the laser tracker are stronger than those of the laser interferometer. At 10 Hz, the standard deviations of the local velocity of the laser tracker are 0.2745 mm/s and 0.2097 mm/s, respectively, and the repeatability of the local velocity is 0.9140 mm/s. The standard deviations of the local velocity of the laser interferometer are 0.6141 mm/s and 0.6368 mm/s, respectively, and the repeatability of the local velocity is 1.4886 mm/s. The same is true at 25 Hz.

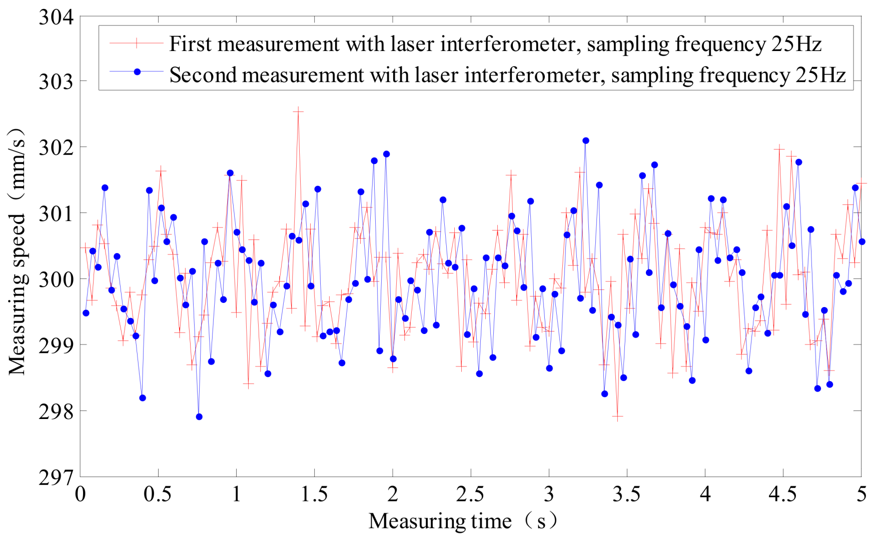

Figure 14. Repeatability of laser interferometer at a sampling frequency of 25 Hz (with a pyramid prism).

5. Discussion

With the continuous improvement in measurement requirements in industrial production, especially the requirements for measurement efficiency, large-scale measuring systems represented by laser trackers are gradually starting to be used in dynamic measurement processes such as target tracking and component alignment. Thus, laser trackers must have good dynamic tracking ability and accurate dynamic measurement ability. There are many studies on a laser tracker's static calibration, but there are few studies on its dynamic performance. To understand the dynamic performance of the laser tracker, the radial velocity of the laser tracker is studied using an indoor large-length standard device. In this paper, the following conclusions are drawn through the equal distance measurement of the laser tracker, equal sampling frequency measurement of the laser tracker and laser interferometer, and repeatability measurement experiments after the distance is doubled:

(1) When the laser tracker is used for equal interval measurement, the actual measurement interval value is greater than the set interval value, and the difference between them increases as the rated speed of the sliding table rises. Regardless of whether the pyramid prism is used, the standard deviation of the actual interval of the laser tracker is the smallest and the stability is optimal when the rated speed of the sliding table is 50 mm/s compared to the rated speeds of 100 mm/s and 150 mm/s.

(2) During the equal sampling frequency measurement of the laser tracker and laser interferometer, the effect of a pyramid prism on the laser tracker is less pronounced than

that on the laser interferometer. When the pyramid prism is not used, the stability of the laser interferometer is better than that of the laser tracker. When the pyramid prism is used, the stability of the laser tracker is better than that of the laser interferometer. Regardless of whether the pyramid prism is used, the standard deviation of the local velocity of the laser tracker and laser interferometer is the smallest and the stability is optimal when the speed of the sliding table is 100 mm/s compared to the rated speeds of 50 mm/s and 150 mm/s.

(3) When the pyramid prism is used, it can be concluded from the repeatability analysis of the two instruments at equal sampling frequencies that at a low frequency (10 Hz), the standard deviation and repeatability of the local velocities of the laser tracker and laser interferometer are smaller, and the data are more reliable and stable. Regardless of low frequency (10 Hz) or high frequency (25 Hz), the data stability and reliability of the laser tracker are better than those of the laser interferometer.

According to the above conclusions, when the laser tracker is required to measure at equal intervals during the measurement process, the measured equipment or instrument should be at a low speed (50 mm/s) as far as possible, leading the equal interval measurement effect to be optimal. During the equal sampling frequency measurement of the laser tracker or laser interferometer, the measuring instrument should be at a medium speed (100 mm/s) as far as possible, and the velocity stability is relatively better at this time. When the distance is doubled, the laser tracker is preferred for measurement at a low frequency (10 Hz). We cannot explain all phenomena. For example, when the movement speed of the sliding table is set to 100 mm/s, the measured data are divided into two different data clusters, which we did not expect. We did not find a result for this; so, we need to conduct further research. However, this does not mean that there is no dynamic research on laser trackers. On the contrary, this is the basis of our dynamic research on laser trackers. In this experiment, the high-speed measurement of the laser tracker and laser interferometer is achieved for the first time by adding a pyramid prism in the case of a low-speed sliding table, and the applicability of the laser tracker and laser interferometer in different scenarios is analyzed and determined. This experimental scheme has certain universality and broad application prospects.

Author Contributions: F.L. and C.H. designed the experiments, J.L. helped to perform measurements; F.L. wrote the paper, Y.X. revised the paper, C.H. applied for the funding and managed the project. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (62005287).

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pan, T.; Fan, B.; Yi, W.; Yang, Z.; Xi, Q.; Xiao, H. Overview of Large-Scale Dynamic Measurement Metrology. *Geomat. Spat. Inf. Technol.* **2015**, *38*, 70–72+76.
2. Sun, A.; Cao, T.; Wang, J.; Gan, X.; Gao, T. Technological Development Trends of Geometric Dimension Measurements of Large Parts in the High-end Equipment. *Metrol. Meas. Technol.* **2021**, *41*, 41–50.
3. Wang, W.; Duan, M.; Si, M.; Zhang, Y. Visual measurement method for large-space dynamic angles. *Meas. Sci. Technol.* **2020**, *31*, 045011. [CrossRef]
4. Gan, Y.; Duan, C.; Liu, G.; Liu, B.; Chen, F. Dynamic frequency scanning interferometry measurement based on optical frequency synchronous motion measurement and error compensation. *Opt. Commun. A J. Devoted Rapid Publ. Short Contrib. Field Opt. Interact. Light Matter* **2021**, *488*, 126753. [CrossRef]
5. Trevor, J. Investigating dynamic measurement applications through modelling and simulation. *Tm-Tech. Mess.* **2016**, *83*, 557–564.
6. Zhang, Q.; Zhai, Q.; Ding, J.; Zhao, W.; He, X.; Liu, W. An Efficient Method for Dynamic Measurement of Wheelset Geometric Parameters. *IEEE Trans. Instrum. Meas.* **2023**, *72*, 1–11. [CrossRef]
7. Wang, X.; Zheng, S.; Lin, X.; Zhu, F. Improving RGB-D SLAM accuracy in dynamic environments based on semantic and geometric constraints. *Measurement* **2023**, *217*, 113084. [CrossRef]
8. Zhang, H.; Yuan, G.; Liu, X. Precise calibration of dynamic geometric parameters cameras for aerial mapping. *Opt. Lasers Eng.* **2021**, *149*, 106816. [CrossRef]

9. Li, L.; Yu, X.; Liu, Z.; Zhao, Z.; Zhang, K.; Zhou, S. RFID Dynamic Performance Measurement System Embedded in Multiscale Deep Learning. *IEEE Trans. Instrum. Meas.* **2021**, *70*, 1–12. [CrossRef]
10. Li, L.; Yang, H.; Zhang, Y.; Ma, Q. Dynamic positioning error analysis and modeling of CNC machine tool guideway system. *J. Mech. Sci. Technol.* **2021**, *35*, 1955–1967. [CrossRef]
11. Li, G.; Huo, Y.; He, J.; Wang, Y.; Wei, J. Development and implementation of a dynamic force measurement system for automatic tool changer system and drawbar mechanism in machining center. *Int. J. Adv. Manuf. Technol.* **2023**, *124*, 3875–3885. [CrossRef]
12. Yang, J.; Wang, D.; Zhou, W. Precision Laser Tracking Servo Control System for Moving Target Position Measurement. *Optik* **2016**, *131*, 994–1002.
13. Ma, Y.; Fan, B.; Lu, F.; He, C.; Yuan, H. Analysis and Research on Gross Error Detection Technology of Laser Tracker Dynamic Measurement Data. *Geomat. Spat. Inf. Technol.* **2021**, *44*, 23–26.
14. Wang, Z.; Mastrogiacomo, L.; Franceschini, F.; Maropoulos, P. Experimental comparison of dynamic tracking performance of iGPS and laser tracker. *Int. J. Adv. Manuf. Technol.* **2011**, *56*, 205–213. [CrossRef]
15. Lin, J.; Xin, R.; Shi, S.; Huang, Z.; Zhu, J. An accurate 6-DOF dynamic measurement system with laser tracker for large-scale metrology. *Measurement* **2023**, *204*, 112052. [CrossRef]
16. Wang, Z.; Maropoulos, P. Real-time laser tracker compensation of a 3-axis positioning system-dynamic accuracy characterization. *Int. J. Adv. Manuf. Technol.* **2015**, *84*, 1413–1420. [CrossRef]
17. Hoon, H.; Son, J.; Yang, S. Techniques for measuring and compensationg for servo mismatch in machines tools using a laser tracker. *Int. J. Adv. Manuf. Technol.* **2017**, *92*, 2919–2928.
18. Shchelchkov, A.; Fafurin, V.; Korneev, R.; Tukhvatullin, R. Modification of the equation for mass flow rate (mass) measurement of liquid with account of dynamic influencing factors. *Flow Meas. Instrum.* **2022**, *83*, 102117. [CrossRef]
19. Jia, B. Two-dimensional tool tip vibration measurement method with mirror optical fiber bundles in milling machines. *J. Mech. Sci. Technol.* **2022**, *36*, 2189–2200. [CrossRef]
20. Lv, F.; Hu, C.; Sun, H.; Li, W. Study on Dynamic Performance Parameters of Laser Tracker Based on Self-Developed Circular Trajectory Generator System. *Appl. Sci.* **2023**, *13*, 167. [CrossRef]