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Characterization of 3-D Cartesian Co-ordinate Laser Interferometer Tracking System

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Abstract

This paper presents the tracking system of 3D-Laser Interferometer Tracking System (3D-LITS). The transfer functions of the whole system which consist of Laser Tracking System (LTS), X-Y stage tracking mechanism and PID controller are determined by using Identification Technique. This technique is done by stimulating the input of system and then measuring the response of the output of system. The input and output signals are collected and analyzed by software, i.e., the System Identification Toolbox, MATLAB. In the present work, the whole transfer functions are created in Simulink then verified with the real system on close-loop situation.

1. Introduction

As shown in Fig. 1, the Laser Tracking System (LTS) detects the two-dimensional movements of a target by using a two-dimension position sensor, a Four-Quadrant Detector (4QD). The 4QD provides a tracking error signal to the Proportional-Integral Derivative (PID) controller, then the PID controller drives the tracking mirrors, which are fixed on each axis of an X-Y stage mechanism, to follow the target. The three parameters (proportional gain, integral time, and derivative time) of the control need to be adjusted to stabilize the controlled system. The performance of overall system depends on the character of the driving system and the tuning of controller's parameters. In this paper, a simulation technique is used to approach this adjustment and to determine the character of each sub-system in the control loop. Typically, the character of any systems can be described by its transfer function which can be found by physical model method or by identification method. The transfer function is a mathematical description that shows a relationship between inputs and outputs of a system.

The physical model method formulates transfer function by breaking down the properties of the system into sub-systems whose behaviors are known. Then the relationships among sub-systems are used to form the transfer function of the system.

The identification method is based on experiments. With this method, the input signals (stimulating signal) and output signal (response signal) of a system is observed. By applying the mathematical technique, the relation between the input and output of the system can be formulated. The System Identification toolbox, which runs on MATLAB [1, 2], can be used to formulate transfer function in this report.

When all transfer functions of a system are found, the simulation technique can be applied to verify the system's characteristics. A simulation package, Simulink, which also runs on MATLAB, is used to verify the tracking system. This technique is an inexpensive and safe way to experiment with the system. Parameters in the system such as controller parameters and driving system parameters can be changed. The system response at any points can be monitored on screen until the optimum parameters are found. Then, the optimum parameters can be applied to the real system. However, the accuracy of the simulation results depends completely on the quality of the system model.

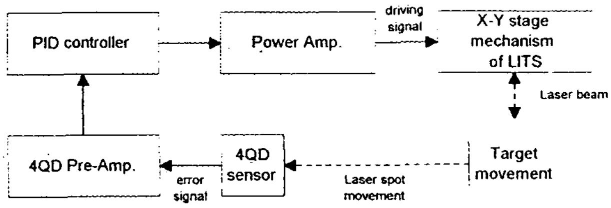


Fig. 1 Configuration of LITS

The system model of LITS in Fig.1 can be divided into 3 sub-systems, which are:

- Sensor system which consists of a position sensor and its pre-amplifier;
- PID controller which has three control modes and a low pass filter;
- Driving system which contains the power amplifier and the driving mechanism of Co-ordinate Measuring Machine (CMM).

The transfer function of a driving system is formed by an analytic method and an identification method. In the experiment for system modeling, a Linear Variable Differential Transformers (LVDT) was used to measure the movement of the driving system as a response signal. The transfer function of the PID controller is only formed by the identification method. The other two transducers, 4QD and LVDT, are calibrated for use within the simulation program. When the overall transfer functions of the system are assembled into the simulation program, the system responses from the simulation technique are verified with the experiment again. The simulation system is also used to optimize the three parameters of the PID controller. The method of Quarter-Decay-

Response (QDR) [3] is used to tune the PID controller. Then the optimum value was set on the controller. Finally, the step response of the closed-loop control and the stability of tracking system are tested.

2. Characterization of Tracking System

A moving bridge type CMM is used as the tracking mechanism in this proposed 3-D LITS. It has a base table of 450x560 mm and three moving carriages supported by air bearings. Each axis is driven by a DC motor with a timing-belt mechanism and a tachometer. The Y-axis of CMM is disabled by clamping the outer-leg of the bridge. The performance of the CMM affects directly the tractability of the system. The static behavior of a CMM can be found by calibration and are generally given in its specifications. However, the dynamic characteristic of CMM is usually not known. Here we report an approach to test the dynamic behavior of the CMM used for this 3-D LITS.

2.1. Frequency Response

The frequency response of the CMM is obtained by applying a driving signal to each arm and measuring the corresponding movement. In the experiments, a random signal was selected with a frequency range from 2 to 200 Hz. The response of the CMM was monitored by a piezoelectric accelerometer (type 4370). A spectrum analyzer (AD3225) was used to analyze frequency response and results are shown in Figs. 2 and 3. The results show that the natural frequency of X-axis is some where between 8 and 9 Hz. For Z-axis, the phase response graph shows a high damping effect, as the slope of this curve is small. From the magnitude plot, it is difficult to tell the resonant frequency. Looking at the phase plot, the approximate frequency at a phase shift from +90° to -90° is about 40 Hz.

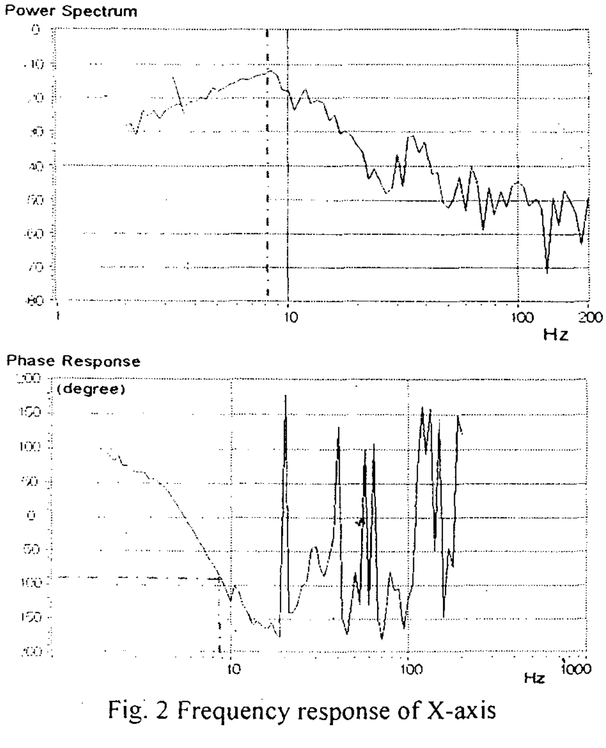


Fig. 2 Frequency response of X-axis

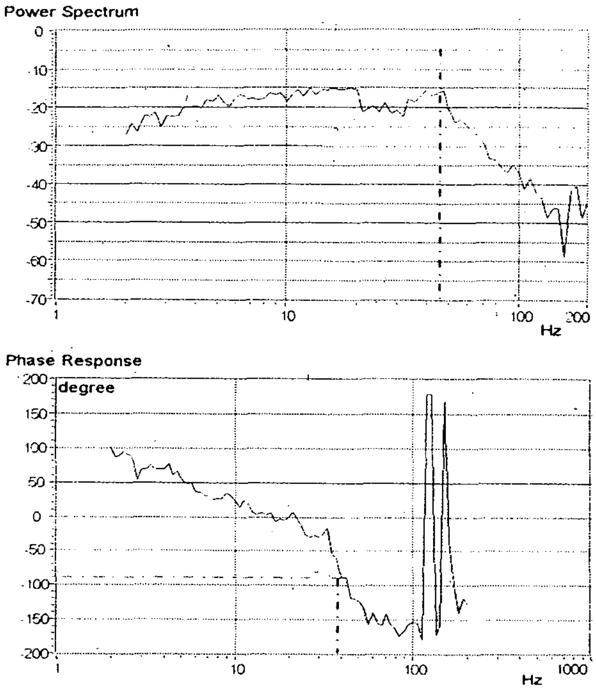


Fig. 3 Frequency response of Z-axis

2.2. System Modeling

System identification technique based on experiments has been applied to model the tracking and control units. As shown in Fig. 4, a stimulating signal is fed into the input of a system and the response signal of the system is observed.

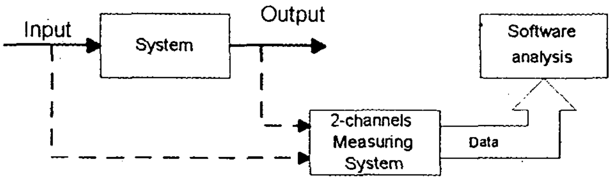


Fig.4 Set-up experiment for System Identification

Both signals are recorded at the same time. By establishing a transfer function to each unit, the relationship between input and output of the system can be formed. The testing results from the system were then modeled by an ARX-model in MATLAB System-Identification-Toolbox. The driving mechanism consists of a power amplifier and a moving carriage. The transfer function is modeled by two parts: one from the power amplifier to the tachometer of the driving motor, and another from the tachometer to the carriage position. The position of the carriage is measured by a long-range linear variable differential transformer (LVDT).

Figures. 5 and 6 show the detailed transfer functions of the X-axis and Z-axis control loops. The modeled system was then constructed in MATLAB/Simulink and a sinusoidal signal with a frequency of 0.5, 1, 2 and 5 Hz was applied, respectively. The same signal was applied to the real system and the response from the 4QD was monitored. The simulated output was then compared with the experiment result.

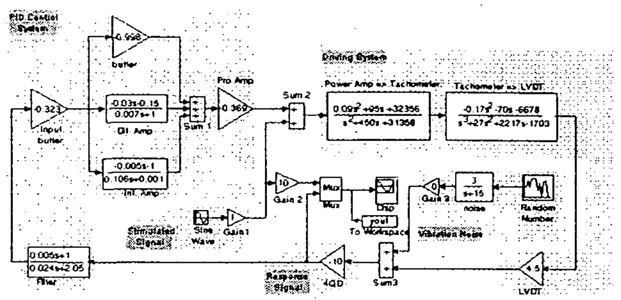


Fig. 5 Closed-loop diagram for X-axis system

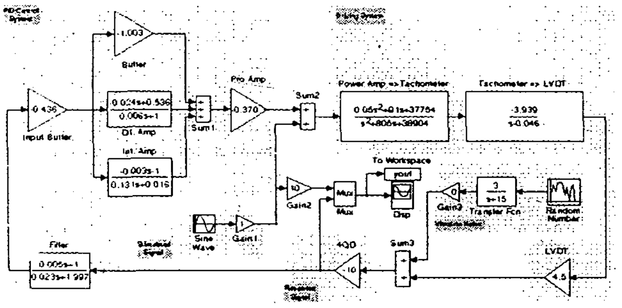
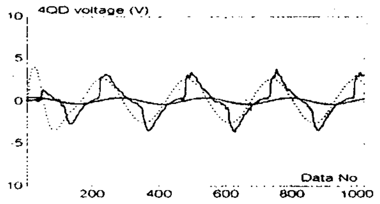
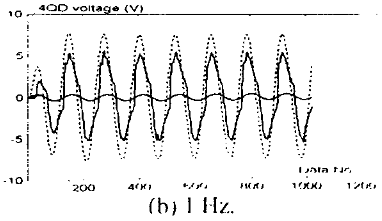


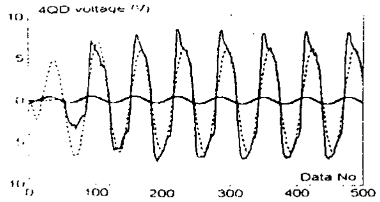
Fig. 6 Closed-loop diagram for Z-axis system



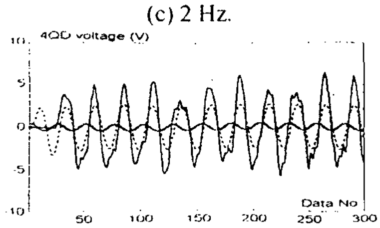
(a) 0.5 Hz.



(b) 1 Hz.



(c) 2 Hz.

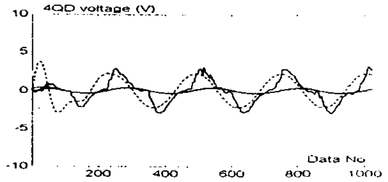


(d) 5 Hz.

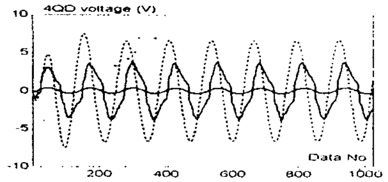
- - - - - Simulation response
———— Experimental response
———— Input-driving signal

Fig. 7 Comparison results of simulation and experiment in X-axis.

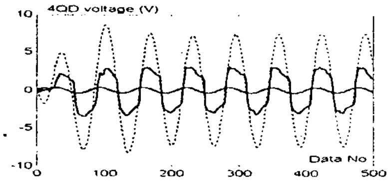
Figures 7 and 8 show the comparison results between the simulations and experiments for X and Z-axis at the frequency of 0.5, 1, 2, and 5 Hz. The input-driving signal is the small amplitude sinusoidal signal, the experiment response is in solid line and the simulation response is in dashed line. Both axes can follow the input at a lower frequency up to 1 Hz and then show a phase delay at higher frequencies.



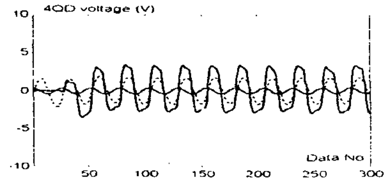
(a) 0.5 Hz



(b) 1 Hz



(c) 2 Hz



(d) 5 Hz

- - - - - Simulation response
———— Experimental response
———— Input-driving signal

Fig. 8 Comparison results of simulation and experiment in Z-axis.

At the lowest frequency, 0.5 Hz, the simulation result is close to the experiment in amplitude but there is a slight phase shift. The experiment curve is not very smooth, which might be caused by the inertia in the sliding system because both carriages are quite heavy. At a higher frequency, the phase shift between experiment and simulation is small, but there is a large difference in amplitude, especially in Z-axis. The reason for this is possibly due to the fact that the Z-carriage has a pneumatic cylinder. The force for moving this cylinder has a non-linear characteristic, which is complicated to model. Therefore, it causes a larger difference between experiment and simulation in Z-axis. The structures of moving carriages are complex. Some higher frequencies may activate the vibration of sub-structure in the carriage and this will affect the response of the system. Therefore, the experiment have been were pre-treated by a low-pass filter with a cut-off frequency of 10 Hz before the calculation process. Thus the transfer function obtained is only close to the real system in a certain bandwidth. In general, the method of Quarter-Decay-Response (QDR) is used to tune the PID controller. The Z-axis has a wider dynamic range than the X-axis because of different resonance (9 Hz for X-axis and 40 Hz for Z-axis). However, due to the complexity in Z-axis, it is not recommended to drive the both axes at a frequency higher than 5 Hz.

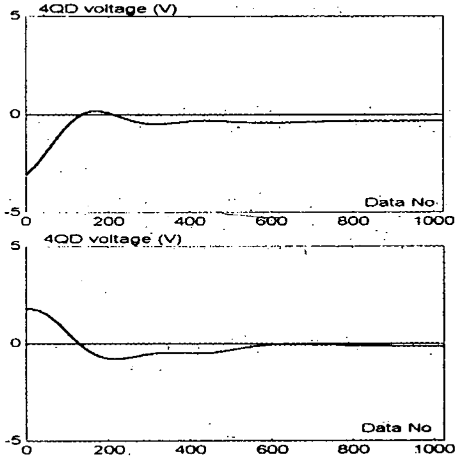


Fig. 9 Step response of tracking in X-axis.

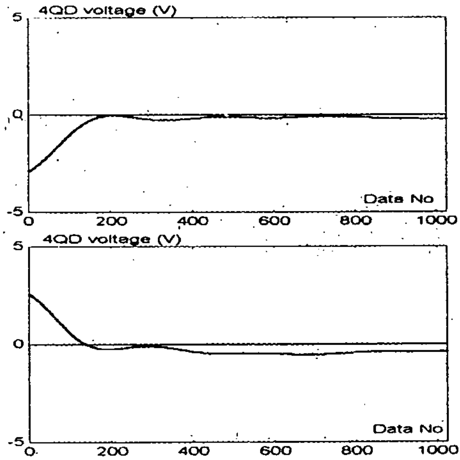


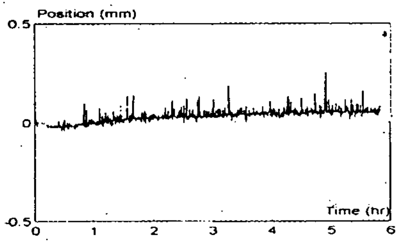
Fig. 10 Step response of tracking in Z-axis.

2.3. Tuning PID Controller

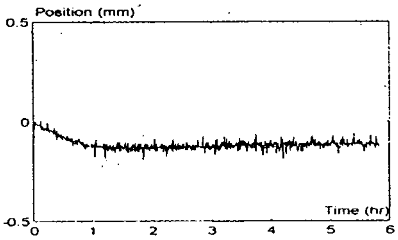
The method of Quarter-Decay-Response (QDR) is used to tune the PID controller. The system control loops for X and Z-axis as shown in Figs. 5 and 6 have been simulated in MATLAB/Simulink. The response output at 4QD is monitored while the PID parameter is adjusted until the amplitude of the response signal is equal to a quarter of the previous cycle. By doing this, the optimum parameters of PID have been obtained. As mentioned earier, the system transfer function is only simplified version of the real system, hence the PID parameters obtained need to be tuned in real time. The parameters are then set into the real system and a step response was carried out to test the system. In this particular tracking system, the step input is given by a disturbance by moving the X or Z carriage to a certain position. This is done by moving the target to a position where the output of 4QD is about 3 V which is equivalent to 0.3 mm, then switching on the PID control and monitoring the variation of the 4QD signal. The results of such step responses of X and Z-axes are shown in Fig. 9 and 10. The step is given from two directions; positive step and negative step. The horizontal axis is shown in sample number, which can be converted into time by multiplying the sampling time interval of 7.8 ms.

2.4. Stability of Tracking System

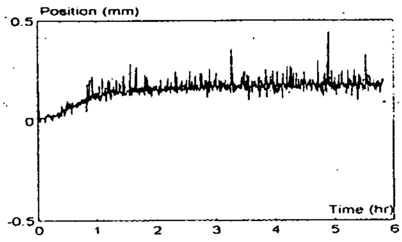
Long term stability of the system is important for applications in calibrating machine tools and robots. To minimize the effect of vibration on the tracking system, the target retro-reflector is fixed on the CMM table. When the controller is switched on, the positions of X-axis, Z-axis, the accumulated distance of LIS and the output of 4QD are measured. The stability test is run for six hours. Over this period, 1000 data-points have been collected by the host computer where each data point is an average of 80 readings sampled in 21 seconds. The results of position stability show that during the first hour there is a high drift in the position control, seen in Fig. 11.



X position



Z position



LIS system

Fig.11 Stability tests on position and measurement systems.

Generally, the drift is higher in Z-axis than X-axis. This may be due to the fact that more parts attached to the Z-axis, which requires a longer time to reach the thermal equilibrium. The drift on the LIS is probably caused by the housing of the 4QD. This warm-up period sometimes can be less than one hour. There are nine stability tests carried out over a month and each one was under slightly different parameters of the PID-controller. It is noted that the position control depends on the variation of 4QD signal, which directly affects by the characteristic of the tracking mechanism and the performance of PID controller. In general, an average of standard deviation in position controls better than 20 μm can be obtained with the existing system. All the experiments have been performed in a temperature and humidity controlled metrology laboratory, normally at 20 ± 1°C and 40 ± 5% RH.

3. Conclusions

A 3-D Cartesian co-ordinate laser interferometer tracking system has been designed and built. It consists of a laser interferometer for displacement measurement as well as a reference datum to perform the automatic tracking of a moving object, a Co-ordinate Measuring Machine as a tracking mechanism and an analogue PID controller to control the tracking system. The performance of the prototype system has been tested and characterized. System identification techniques have been used to model the system transfer function. The model thus obtained can be used to predict the response of tracking system and tune the PID parameters. The system can track a target in space with ease of measurement and set-up of the origin of co-ordinates. No pre-calibration is needed. Potentially it can be use to calibrate a machine tool or a robot both statically and dynamically. The use of CMM as the tracking mechanism gives linear scales and a large working volume but the tracking speed is limited due to the low resonance in the moving parts of CMM. This problem causes an oscillation in the tracking system and generates noise in measuring system. The tracking system can be improved by using a compact two-axis stage for dynamic performance but at the cost of working volume. The stability of the system has been tested over a long time period, and the repeatability is better than 20 μm. To reduce the drift effect, a warming up period of one hour is recommended before any measurement is taken and the environment temperature should be controlled.

4. Acknowledgement

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References

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[2] MATLAB Reference Guide', The MathWorks Inc., 1992.
[3] A.B. Corripio, 'Tuning of Industrial Control Systems', Industrial Society of America, 1990.