euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

System for directly driven Hexapods for highly dynamic 6 DoF applications

Christian Muellerleile[1], Reinhard Kotter[2], Dr. Thomas Haase[1], Dr. Christian Rudolf[1]
[1]Physik Instrumente (PI) GmbH & Co.KG, 76228 Karlsruhe, Germany
[2]Physik Instrumente (PI) GmbH & Co.KG, 83026 Rosenheim, Germany
c.muellerleile@pi.ws

Abstract

Hexapod systems are well known for positioning applications in six degree of freedom (6 DoF). PI (Physik Instrumente) provides extremely accurate hexapod systems in the field of micro- and nanopositioning [1]. Such parallel-kinematic designs are used in many different fields, from handling systems in electronics production and tool control in precision tool machines to medical technology and optical systems such as space telescopes and satellite receiving systems [2]. The demand for transferable dynamics and maximum resolution is on the increase and can no longer be met using traditional drive concepts. In addition to free and highly dynamic motion in six degrees of freedom - to calibrate and measure mechatronic components and sensors, for example - precision positioning of the mounting platform right down to the nanometer is required. We have previously shown the principal mechatronic design of a directly driven Hexapod [3], Fig. 1. This paper describes some new features for closed-loop control with highly dynamic applications.

Keywords: voice coil hexapod, high precision, direct drive, highly dynamic, control theory, parameter tuning

1. Introduction

The hexapod consists of six completely passive, flexure joint guided, and light-weight carbon-fiber-composite (CFC) struts. The individual lower base points are each connected to an electromagnetic linear direct drive. Each drive is designed as a voice coil actuator (VCA) with a stroke of +/- 8.5 mm at a sensor resolution of 5 nm.

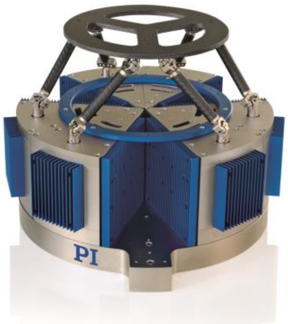

Figure 1. 6 DoF H-860KMAG driven hexapod for dynamic shaker applications

When designing a robust shaker control system, the most important characteristics are tracking performance and stability. By decreasing the moving mass, a significant improvement of efficiency is possible. In [3], the entire hexapod structure is described. It was shown that any nonlinear behaviours of each magnetic actuator have an impact on the tracking quality and linearity of the whole system.
For testing, there are sinusoidal input, random input, and deterministic waveforms, which are employed to emulate the characteristics of actual field conditions. Trajectory generation and coordinate transformation is done in the controller. Polynomial splines are used to produce smooth, resonance-reducing motions with continuously higher deviations.

2. Controller Design

The position control function is done with a single axis PID control structure. The PID controller is based on the tracking error without full information of the model or the transfer functions. As the hexapod shows non-linear effects a standard position PID control loop does not provide optimal control.

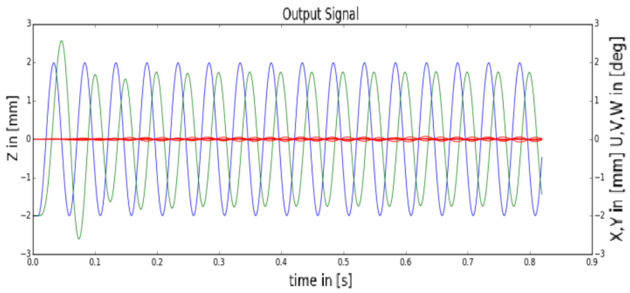

Figure 2. Sinusoidal response with high phase shift of the position PID controlled system

So the mathematical model was derived and various design techniques, as feedforward and state-feedback control, were verified for determining the control structure and the parameters.

The voice coil actuator is separated into three parts:
The electrical, the mechanical, and the electro-mechanical block.
The actuator can be modelled by three elements in series – a resistance, an inductance, and a voltage source. For a simple approximation, a first-order system is used, resulting in the transfer function

$$G_E(s) = \frac{I(s)}{U(s)} = \frac{1}{L_0 s + R}$$

Dominated by the Lorentz Force Principle, a force will act on a current-carrying conductor placed in a magnetic field. Because the magnetic field and the conductor length are nearly constant, the generated force F_M is directly proportional to the input current I. The relation between force and current was measured with a force sensor and can be described as

$$\boldsymbol{G_M(s)} = \frac{\boldsymbol{F_M(s)}}{\boldsymbol{I(s)}} = \frac{\boldsymbol{k}}{\boldsymbol{T_M s+1}} \text{ with } \boldsymbol{T_M} = \frac{\boldsymbol{1}}{\boldsymbol{2\pi f_m}}$$

There is a rigid mass m_S installed on the platform. Additionally the mass m_H of the moved Halbach array assembly has to be considered. The guiding of the moving magnet assembly is realized by leaf springs with spring constant c_F, resulting in the transfer function

$$G_L(s) = \frac{X(s)}{F_m(s)} = \frac{1}{(m_H + m_S)s^2 + c_F}$$

Assuming nonlinear effects are reduced to a minimum, the voice coil actuator can be described according to the following La Place formula

$$G_{sys}(s) = G_E G_M G_L = \frac{k}{(L_0 s + R)(T_M s + 1)(ms^2 + c_F)}$$

3. Results

For a stable closed-loop system the relative dominance of closed-loop poles has to be considered. Because the electrical pole dominates, a digital PI current controller was implemented.
The actuator must process low inertia, which together with the low stiffness and the absence of the gear reduction mechanism makes the system more sensitive to forces. The mechanical pole has a dominant effect on the transient response. Therefore it is necessary to feedback the velocity and acceleration error with a proportional gain. Since only the position signal is supplied by the high-resolution optical sensor, a numerical method is used to estimate the velocity and acceleration. At the moment there is a lowpass and notch filter implemented. A polynomial fit is used for offline simulation. It allows calculating derivatives of the smoothed signal that show much better frequency characteristics.
Acceleration feedforward reduces the tracking error and allows the system to work with a wider bandwidth. The feedforward parameters can be simulated offline and configured by simulating the actuator's load and the 6dof motion. However, it is necessary to tune the control parameters, as feedforward offers faster response and may cause an overshoot.

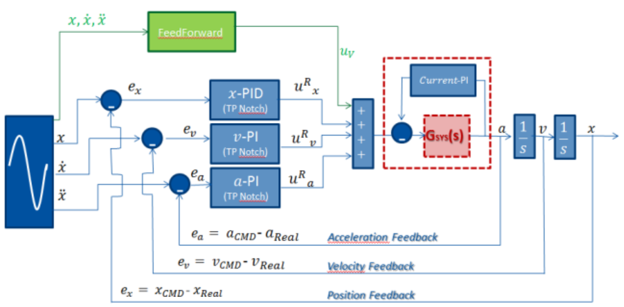

Figure 4. Control structure of a single hexapod leg that is decoupled from the other legs by design

At PI bode plots as well as derived transfer functions are used to characterize stages in the frequency domain. In a second paper "Motion control parameter identification using genetic algorithms" PI shows an approach to define task specific control parameters. Figure 5 shows the resulting bandwidth and phase margin for a tuned system for a 100Hz frequency range. The tracking error and phase shift of the hexapod platform is significantly decreased.

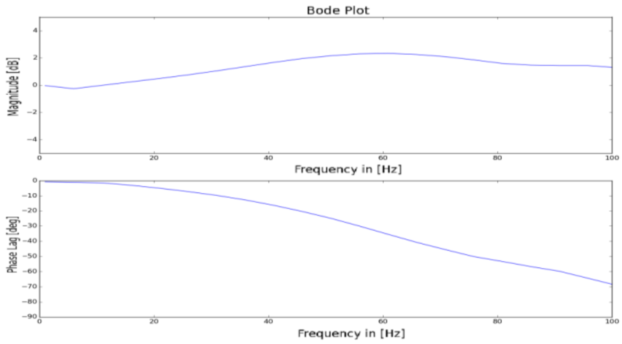

Figure 5. Resulting closed Loop Bode plot

Typically, the output of interest is the platform acceleration as a result of given acceleration motion profiles, see Fig. 6. The power-spectral-density integration analysis is used for identifying and quantifying instabilities.

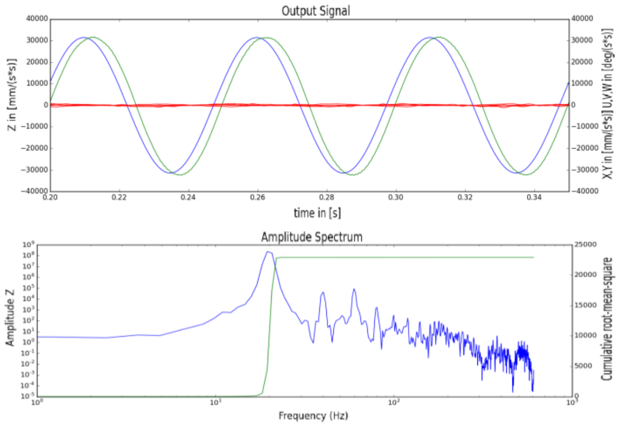

Figure 6. Acceleration response and amplitude spectrum with no significant noise, tested with a 20Hz motion profile

4. Summary

For a stable closed-loop system, the relative dominance of closed-loop poles have been considered. As a result, a digital current controller and a velocity and acceleration feedback were added.
Tracking the reference signals with feedforward allows the desired response with a higher bandwidth and lowers the phase shift between the target and the current position while the feedback handles uncertainties and disturbances.
Based on PI's standard digital controller C-887, the accelerations up to 750 mm/s and 6 g could be reached. Also, for fast shaker function of 20 Hz with 2 mm amplitude, a tracking performance of less than 15µm is shown.

Editor
Any questions about the abstract process, or about a specific abstract, should be directed to the author, Christian Muellerleile at c.muellerleile@pi.ws.

References

[1] Gloess, R. : Hexapod Strukturen mit Mikrometer Genauigkeit. Chemnitzer Parallelstruktur – Seminar April 1998.

[2] Gloess, R.& Lula, B.: Challenges of extreme load hexapod design and modularization for large ground-based telescopes, Proc. SPIE 7739, Modern Technologies in Space- and Ground-based Telescopes and Instrumentation, 77391U (July 21, 2010);

[3] Rudolf, C. et.al.: Directly Driven Hexapods for Highly Dynamic Applications, Proceedings of the 15th Int. Conf. of the EUSPEN, June 2015, Leuven, Belgium