EXPERIMENTAL PERFORMANCE COMPARISONS FOR A HIGH PRECISION POSITION CONTROL SYSTEM WITH DIFFERENT OBSERVER DESIGN METHODS

P.A. Stadler*, S.J. Dodds †, H.G. Wild*

*University of Applied Sciences Bern, Switzerland, CH-3401 Burgdorf, paul.stadler@hti.bfh.ch, harald.wild@hti.bfh.ch
Fax: +41 34 426 43 93

†University of East London, United Kingdom, Stephen.dodds@spacecon.co.uk, s.j.dodds@uel.ac.uk
Tel: +44 208 223 2379 / 2367

Keywords: observers, Kalman filters; nano positioning, pole placement, settling time formula.

Abstract

In this paper, the performance is investigated of an observer-based control system for translational positioning of electronic components, designed to operate with accuracies in the nanometer region, which is the highest attainable with currently available hardware. The original contribution of the paper is the presentation of experimental results at this challenging level of accuracy. Comparisons are made between three observer design methods. The first is based on the Kalman filter. The second is a less well known and based on the LQG control design method [3] and the third is a new alternative method proposed by the authors, based on the observer correction loop settling time. In order to effect a fair comparison, an unusual frequency domain approach is used to ensure that all three observers, treated as dynamic elements in the feedback loop, have similar bandwidths. Simulation results are presented to confirm the correctness of the control system design and the performance comparison is presented by means of experimental results on an air bearing test table actuated by a linear voice-coil motor.

1 Introduction

The possibility of positioning linear machine axes with accuracy in the nanometer region using linear motors is well known [2]. These axes are commonly used for electronic circuit wafer inspection systems. The friction in conventional linear axis mechanisms limits the control accuracy [1], which led to an on-line friction and parameter estimator [4] that can be used for friction compensation. The overall accuracy is limited, of course, by the accuracy of the friction estimation and an alternative, considered here, is friction elimination using an air bearing, as depicted in Figure 1. In the vacuum air bearing, manufactured by the Kunz Precision Company in Switzerland, the moving part of the linear drive is retained in the guide-ways vertically and laterally by a vacuum while direct contact is prevented by an air film. Investigations at the PTB in Braunschweig on a similar test rig showed movements of the bearing in the vertical direction of less than 15nm, which is acceptable for the investigation undertaken.

With such a frictionless mechanism, velocity feedback in the controller is essential for closed-loop stability. An observer is employed for velocity estimation to avoid a) software differentiation of the position measurement signal, which would introduce inaccuracies due to measurement noise and/or encoder quantisation, or b) dedicated velocity measurement instrumentation with the associated increase in cost. This observer is shown as part of the complete control system in Figure 2. The measurement signal was perturbed (amplitude ± 2.5nm) using the standard simulink block ‘Band-Limited White Noise’. This is because a sin/cos-encoder is used on the test rig together with 16-bit ADCs and the measured position signal showed a perturbation of ± 2.5nm amplitude. This permits relatively high observer and controller gains to obtain good disturbance force rejection and high dynamic performance.

It should be noted that the amplifier dynamics is not included in the observer model of Figure 2. The justification for this is...
that for a simple first order model, \( \frac{K_a}{1+sT_a} \), the amplifier time constant is typically \( T_a = 100 \mu s \), which is several orders of magnitude smaller than realistic settling times for the controlled mechanical system.

The position measurement constant in real-time control computer, the position measurement, is:

\[ \text{Position measurement} \]

Figure 2, scaled to be numerically in metres and so, nominally, in metres.

The plant state space model corresponding to Figure 2, with additional plant and measurement noise signals, \( w_p \) and \( w_m \), respectively, is:

\[
\begin{align*}
\dot{x} &= Ax + Bu + w_p, \\
y &= Cx + w_m,
\end{align*}
\]

where \( x = \begin{bmatrix} x \\ v \end{bmatrix}, A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ b \end{bmatrix} \) and \( C = \begin{bmatrix} 1 & 0 \end{bmatrix} \).

The position measurement constant in \( C \) is unity since, in the real-time control computer, the position measurement, \( y \), is scaled to be numerically in metres and so, nominally, in Figure 2, \( x_m = x \). The continuous time observer state differential equation is

\[
\dot{\hat{x}} = A\hat{x} + Bu + K(x_m - \hat{x})
\]

and the observer gain matrix is \( K = \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} \). Here \( \hat{x} = \begin{bmatrix} \hat{x} \\ \hat{v} \end{bmatrix} \) is the estimated state vector. The observer design methods, i.e., methods of arriving at suitable observer gains used ultimately for the experimental comparisons, are presented in the following three subsections.

2.1 Observer 1 Design based on Kalman Filter

The full state observer of Figure 2 has the same structure as a Kalman filter and so its gain matrix, \( K \) can be calculated using this method. The plant and measurement noise co-variances, i.e., the expected values of \( E \{ w_p w_p^T \} = Q \), and \( E \{ w_m w_m^T \} = R \), then determine \( K \) through an algebraic Riccati equation [3]. It should be noted, however, that the optimality of this method relies on the assumptions that the noise sources are white and with Gaussian distributions. Given that this is not the case in many practical applications, it is possible that other design methods will compete and this is the reason for including two more in the following two subsections.

2.2 Observer 2 Design based on Settling Time Formula

Dodds [5] has produced a general formula for the settling time of any continuous, linear, time invariant system whose poles have coincident negative real parts at \( a_{1,2,\ldots,n} = -\sqrt{T_c} \). This formula, which will be referred to briefly as the Dodds formula, refers to any variable of a linear system that converges towards a nominally constant steady-state value. It gives the time, \( T_s \), taken for the difference between the current value and the steady-state value to fall to approximately 5% of its peak magnitude, as follows:

\[
T_s = \frac{3}{2} (n+1) \cdot T_c
\]

where \( n \) is the order of the system. This yields a straightforward deterministic design procedure for calculating the observer gain Matrix, \( K \), based on choosing the observer’s settling time, i.e., the time taken for the correction loop error,
et, in Figure 2, to decay to approximately 5\% of its peak magnitude. For this observer, \( n = 2 \), and the correction loop poles will be made coincident: \( s_{1,2} = -\frac{1}{T_c} = -\frac{9}{(2T_s)} \).

In view of the separation theorem [3], the dynamics of the model correction loop may be considered separately from the remainder of the control system. Therefore applying Mason’s formula to the observer block diagram in Figure 2 yields the following transfer function:

\[
\frac{\hat{x}(s)}{x(s)} = \frac{k_1 s + k_2}{s^2 + \left( \frac{k_1 s + k_2}{s} \right)} = k_1 s + k_2
\]

(5)

The desired characteristic polynomial is therefore:

\[
\left(s + \frac{1}{T_c}\right)^2 = s^2 + \frac{9}{2T_s} s + \frac{81}{4T_s^2}
\]

(6)

Comparing the denominator of transfer function (5) with (6) then yields the following observer gains:

\[
k_1 = \frac{9}{T_s} \quad \text{and} \quad k_2 = \frac{81}{4T_s^2}
\]

(7)

2.4 Observer normalisation in frequency domain

In order to facilitate a fair comparison between the control system performances obtained with the three observer design methods, it is necessary to apply these methods with the constraint that the convergence rate of the state estimation error vector, \( \hat{x}(t) - x(t) \), towards zero should be about the same in each case. This is done by viewing the observer as a dynamic element in the feedback loop and considering it in the frequency domain, as is done for compensators in classical control loop design. The correction loop is notionally broken at the point where the error, \( e \), in Figure 2 is formed. Then the loop gain from this point through the observer and back to the ‘break’ is:

\[
L_f(j\omega) = |C|^{-1} A \quad \text{K}
\]

(8)

Then the parameters, \( Q_N \) and \( R_N \) for observer 1, \( \mu \) for observer 2 and \( T_s \) for observer 3, are adjusted to yield approximately the same Bode magnitude plots. The values arrived at are:

Observer 1: \( Q_N = 10^{-3} \quad [V^2] \quad R_N = 2 \times 10^{-15} \quad [m^2] \)

Observer 2: \( \mu = 10^{-12} \)

Observer 3: \( T_s = 0.004 \quad [s] \)

3 Simulation Results

The nominal constant parameters of the test rig used in the simulations are as follows:

\[
m = 3.25 \quad [kg]; \quad \leq K_d = 0.8 \quad [A/V]; \quad K_n = 11.1 \quad [N/A]
\]

In all three cases, the controller gains have been set to \( K_p = 50; \quad K_r = 650; \quad K = 75 \) which yields an acceptable step response.

The observer gains producing the Bode plots of subsection 2.4 have been used.

In these simulations, the quantisation noise of the encoder has been represented by inserting, in the measurement input to the observer, a quantisation band limited white noise source having a similar magnitude to the quantisation level. Figures 6, 7 and 8 show the results.
4 Experimental Results

The control algorithm is implemented on a dSPACE system. The system parameters are as indicated in section 3. The controlled mass is known to an accuracy of $\pm0.05$ $[\text{Kg}]$.

All three observers estimations of $x$ are all very close to the measurement signal, $x_m$, the errors being within the resolution of the position measurement encoder, i.e. $\pm2.5\text{nm}$. Hence no legend has been included to distinguish them from one another. Figures 9 and 10 show, respectively, the position estimation and the velocity estimation. The noise is due to the position measurement resolution. In Figure 8 the error $e = y - \hat{y}$ between the position measurement and position estimate is shown for all three observer designs. Figure 12 shows the real control variable which is to be compared with the simulation of Figure 8 in section 3.
5 Conclusions and Recommendations for Further Research

This paper experimentally compares the position control performances obtained with three different design strategies for a standard full-state observer which have been implemented on a linear axis test rig using a vacuum-air bearing. It is evident from Figure 11 that accuracies of the order of tens of nm is obtained with all three observer design approaches, but in view of Figure 10, the quality of the velocity estimates from the LQG based observer design is worse than the other two, with the one based on the Dodds settling time formula being marginally the best. It should also be noted that the gain calculation for this observer is much simpler than for the Kalman or LQG based observers.

Further investigations are planned regarding robustness with respect to model parameter uncertainties and external disturbance forces such as caused by gravity due to small misalignments of the rig with respect to the local gravity vector. It is intended to investigate the use of an observer with in built load force estimation [5] as this should yield improved robustness.

It is also planned to investigate the effects introduced by variation of the thickness of the air gap of the vacuum-air bearing. Some conclusions have already been drawn from investigations on a similar test rig at the PTB in Braunschweig and this work will be built upon. The air gap is in the range of a few µm and therefore the boundary layer theory could lead to a better model of the system. As a next step, the PI-P-cascade controller is planned to be replaced by a linear state feedback controller with load force compensation using the aforementioned new observer and the performance with a constant velocity reference input, as used in some wafer inspection processes, will be investigated, where the velocity estimation will be most important.

Acknowledgements

This project is supported by a research grant of the University of Applied Sciences Bern.

References