Enhanced Feed-Forward Control for Advanced LIGO
LIGO-T

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1 Introduction

This document will introduce the enhanced feed-forward controller that is currently used at the Standford Engineering Test Facility for aLIGO. Included within this document are the feed-forward theoretical derivations, the implementations to the system, and the testing performance results of a single degree of freedom.

2 Calculations

With traditional feed-forward control, disturbances must be measured and accounted for before they affect the output of the system. The difficulty behind this type of control is that the designer must be able to accurately predict the system's response and compensate for it, which can become extremely complex. The theory behind the simple feed-foward implemented here at the Stanford ETF is that a decent FF control can be constructed with only knowing the spring rate of the system without knowing any of the plant dynamics. This however requires the designer to assume a few generalities about the system and its surroundings.

The first simplification assumes the stage that the actuator is pushing against (stage 0) doesn't move. This assumption by itself has caused a few problems to the control system. It is known that stage 0 at 10 Hz does in fact have a significant amount of seismic motion that cannot be completely neglected. The resulting problem that was encountered due to this assumption was an unstable system with the isolation feed-back loops turned on in the Z translational degree of freedom. This was due to a 37 Hz resonance mode in the ETF structure at stage 0. The first attempt at solving this problem was through passive damping which involved placing viton pads at the base of the structure. This slightly improved some lower frequency modes but was unsuccessful in damping the unstable 37 Hz mode. The next step then required us to embed a notch filter into our Z-dof controller to actively stabilize our system. Using the notch filter, a little performance was lost in the targeted 10 Hz region, but overall the process was successful because both the isolation loops and the enhanced feed-forward controllers could run simultaneously without making the system unstable.

Another assumption required the actual calculation of the system to be modeled as a mass (stage 1), spring, and damper (MSD).

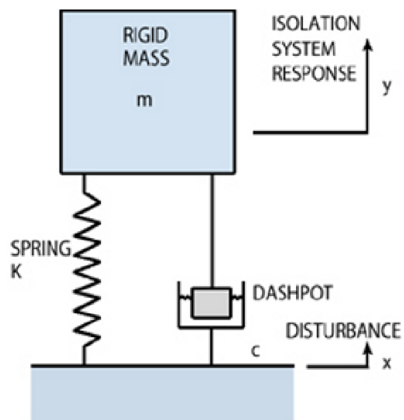

Figure 1: Stage 0-1 MSD model

$$ms^2 Z_1 = -k \cdot (Z_1 - Z_0) - bs \cdot (Z_1 - Z_0) + F(s)$$
$$Z_1 \cdot (ms^2 + bs + k) = Z_0 \cdot (k + sb) + F(s)$$

Ideally with feed-forward control implemented, the stage 1 motion would equal zero ($Z_1 = 0$). Assuming this is true with our designed controller as well, the calculated ideal force of the actuator is:

$$F(s) = -Z_0 \cdot (k + sb)$$

i.e. Force of actuator = - Force ground, which in turn, makes the total force of the system equal to zero. Assuming the designer can calculate Z_0 (calibrated stage 0 sensor measurement) and that the drive motion $>>$ ground motion, we can derive our ideal FF transfer function (K_{ff}) to be

$$TF_{stg1-drive} = \frac{Z_1}{\text{drive} - \text{counts}} \qquad TF_{stg1-gnd} = \frac{Z_1}{Z_0}$$

$$K_{ff} = \frac{TF_{stg1-gnd}}{TF_{stg1-drive}} = \frac{\frac{Z_1}{Z_0}}{\frac{Z_1}{\text{drive} - \text{counts}}}$$

$$K_{ff} = \frac{\text{drive} - \text{counts}}{Z_0}$$

Using the DC of an ideal feed-forward $Z_1 = -Z_0$, the transfer function can be finalized as:

$$\boxed{K_{ff} = \frac{-1}{\frac{Z_1}{\text{drive} - \text{counts}}}}$$

3 Data

3.1 Implementation

Real time data was then gathered from the corresponding L4C channels for each dof during a period of reduced noise. With this data and the experimental calculations aforementioned, we then created the ideal feed-forward enhancements unique to the Stanford ETF. Using Matlab, we plotted the frequency response of the theoretical feed-forward transfer function to illustrate the optimal design for our controller . An iteration method was then used to match this transfer function with a design that yielded the best expected performance for each individual dof. The ideal measurement and the matching function for the X dof are shown below superimposed in Figure 2 about the targeted 10 Hz frequency range. Once matched with the "correct" TF, a functionality check was used to see if the discrete time zpk filter of each controller could be converted to a usable foton file. Lastly, these controllers were saved to a data structure and built into the Stanford ETF for performance testing.

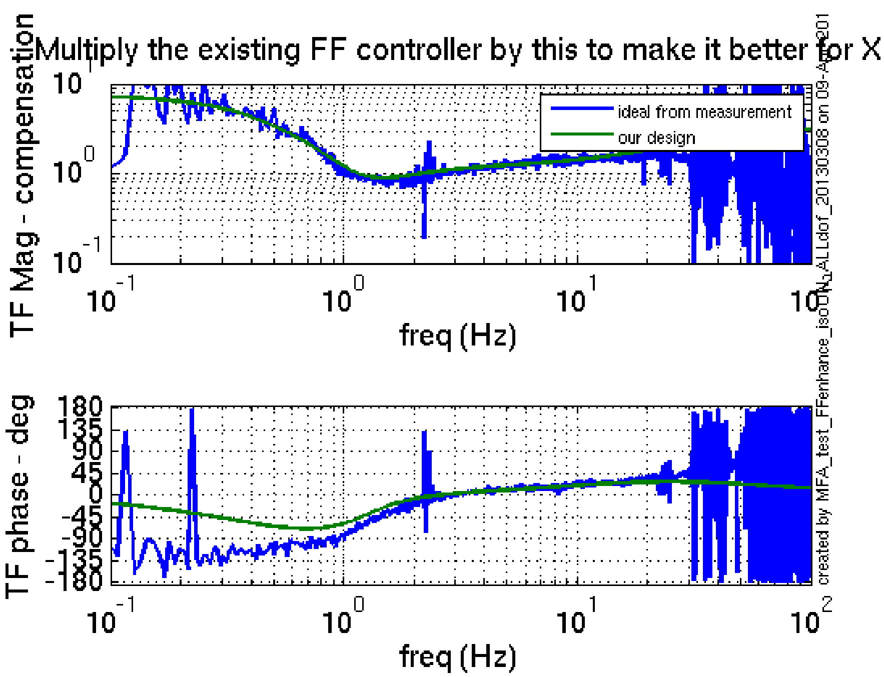

Figure 2: Ideal Feed-forward TF design

3.2 Performance Results

The feed-forward performance was measured with a variety of conditions: i.e. ETF system status, time of day, isolation loop controllers on/off, etc, were all factors in different performance scenarios. However, the final performance measurement was taken with the system in vacuum, a time period with reduced noise, the 12 dof damping loops on, the HAMish isolation loops on, and the designed feed-forward enhancement on. The feed-forward comparison data between stage 1 with the basic FF off, and with the basic/enhancement on, illustrates a performance improvement by about a factor of 50, and in some cases about a factor of 100 at the targeted 10 Hz frequency range. The feed-forward transfer function measurement improvement is shown in Figure 3 below for the X dof.

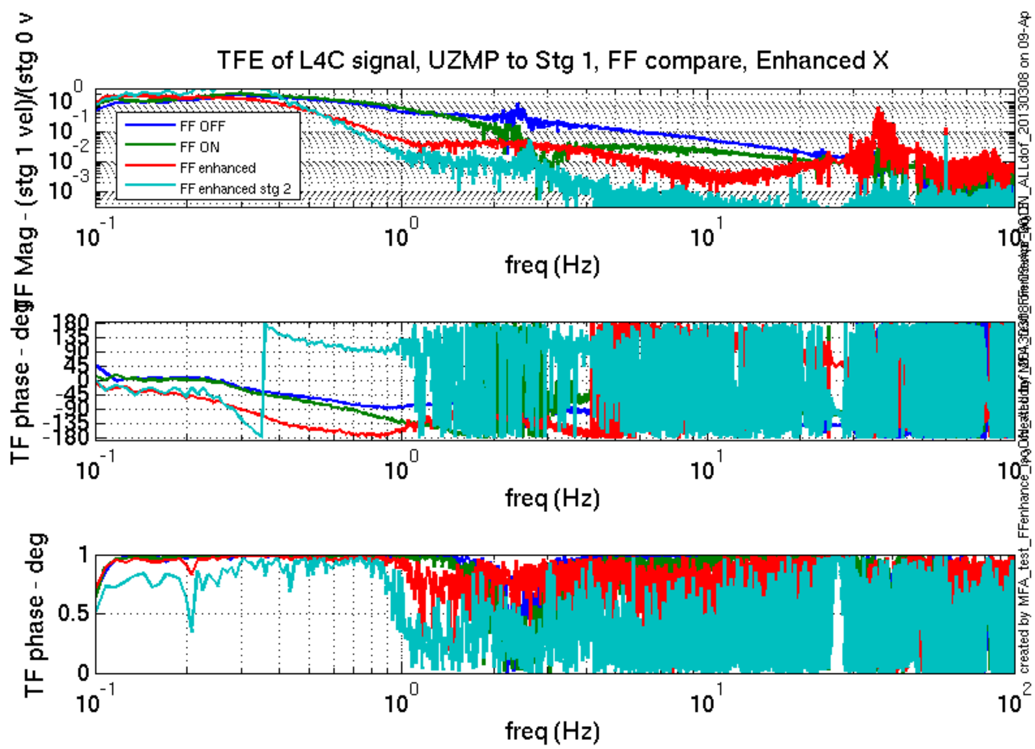

Figure 3: TFE Performance

In addition, the Amplitude Spectral Density (ASD) plot as seen in Figure 4, is a good indicator of the total displacement in m/rtHz.

4 Conclusion

It is known that feed-forward control is a great tool to significantly improve disturbance rejection of a given control system. However, since traditional feed-forward control requires you to understand the system dynamics and accurately predict the output of a disturbance, the control design can become complicated. The enhanced feed-forward controller that we are experimenting with here at the Stanford ETF for the aLIGO HAM chambers, as seen, only require the measurement of the spring stiffness of the system. Taking general assumptions about the system, the derivation complexity of feed-forward controller is drastically simplified while still maintaining high performance improvements.

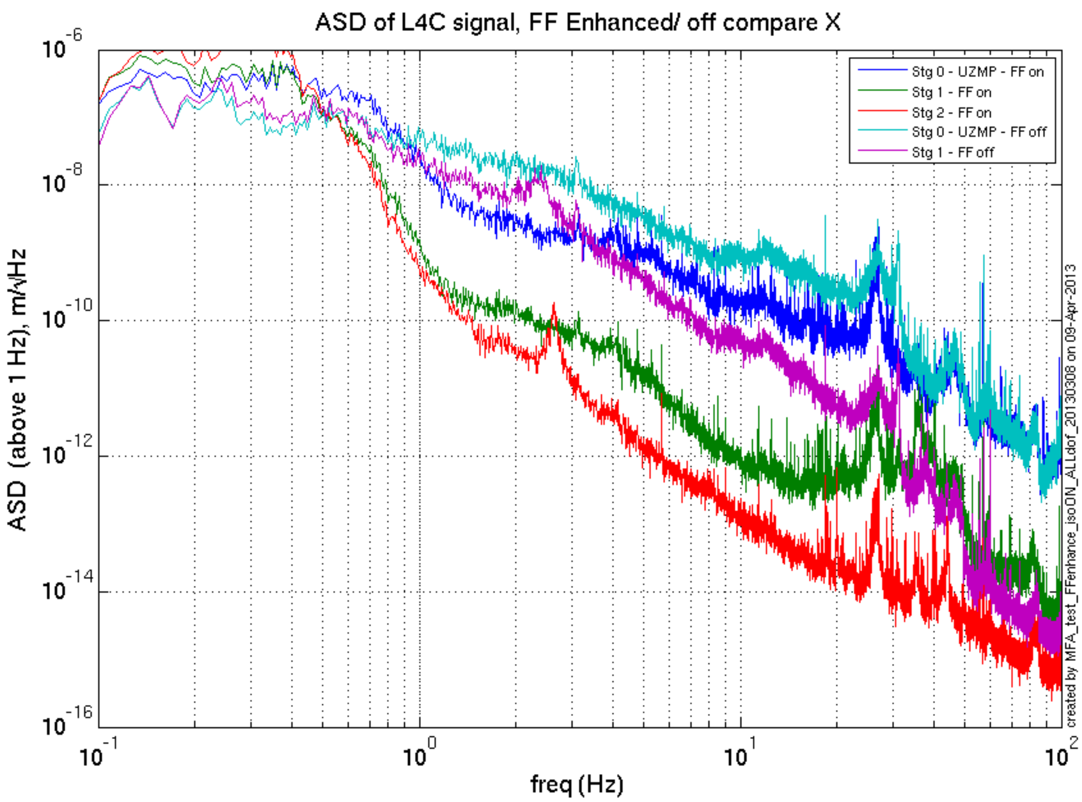

Figure 4: ASD Displacement Performance