Lock Acquisition Studies for Advanced Interferometers

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Abstract. This document describes some results of time domain simulation for a Fabry-Perot cavity with Advanced LIGO parameters. According to this simulation, lock of AdLIGO arm should be acquired with very low power (less than 1 % of full power), and additional hard/software techniques will be needed to establish the first fringe lock. In this paper, possibility of using a suspension point interferometer and a new algorithm called 'Guidelock' are discussed. At the final stage of lock acquisition, more than half MW will be stored in each arm cavity, so that alignment instabilities will happen due to a shift of its beam axis. This simulation predicts that the alignment optical instabilities show up in both pitch and yaw mode, and it can be stabilized by proper alignment controls with 10Hz band-width.

1. Introduction

In Advanced LIGO (AdLIGO) [1, 2], laser power in each arm cavity will be more than half MW, and such high power produces high radiation pressure not only in length but also in alignment. For length sensing and control (LSC), the Caltech 40m which is a prototype for length control of AdLIGO has demonstrated stable operation with optical spring[3]. For alignment sensing and control (ASC), it is known that optical spring and optical instability would happen due to torque of radiation pressure[4]. We should discuss how to establish stable lock acquisition for a long and high finesse cavity with high power laser, and stable ASC with radiation pressure.

A time domain simulation tool called E2E[5] which has been developed to analyze LIGO type interferometer is used here. Using this E2E, we simulated a single Fabry-Perot cavity with AdLIGO parameters including the quadruple suspensions, the radiation pressure on test masses, and control system with proper feedback filters.

2. Simulation setup

The most unknown part for lock acquisition in the next generation interferometer would be arm cavities. It is hard to test experimentally with realistic parameters such as km scale and MW order high power inside cavity. We start the simulation with single Fabry-Perot arm cavity to bridge prototype experiments and real future interferometers. Here we assume to use AdLIGO parameters. The next generation interferometers typically will have values of finesse ∼1000, cavity length ∼few km and input laser power ∼100W. It is not a so bad assumption to use the AdLIGO parameters. Optical parameters used in this simulation are shown in Table 1.

Parameter	Value
Cavity length	3995 m
ITM transmissivity in power	0.5 %
ITM loss in power	50 ppm
ETM transmissivity in power	10 ppm
ETM loss in power	50 ppm
Finesse	1240
Radius of curvature of ITM	2076 m
Radius of curvature of ETM	2076 m
g1	−0.9244
g2	−0.9244
Full power inside cavity	0.71 MW

Table 1. Optical parameters used in this simulation.

The suspension system for each test mass consists of four masses. From the top, they are called a top mass(M0), an upper intermediate mass(M1), a penultimate mass(M2) and a test mass(M3). Local damping for quad-suspensions is applied to only the top mass for 6 degrees of freedom(DOFs) for length, pitch, yaw, side, roll and bounce. Actuators for length control are applied to the M1, M2, and M3 respectively. Maximum dynamic range is limited at the actuators in the unit of force. The maximum force is assumed as 200 mN for M0 and M1, 20 mN for M2 and 450uN for M3.

Several noise sources are implemented in this simulation. Seismic motion is assumed as current Hanford site seismic noise, and it is filtered by proper seismic attenuation which will be used in AdLIGO to make an expected optical table motion. Shot noise is calculated from an incident laser power on photo detectors (PDs). When arm power is full the hitting power is adjusted to be 100 mW total (25mW in each quadrant for ASC PDs) by an attenuator. Radiation pressure and radiation pressure noise are implemented as semi-classically. In other words, there is no coupling between the shot noise and the radiation pressure noise, but it does not make any significant difference on the lock acquisition procedure. Electronic noise is also implemented but it does not make any important role in this paper.

3. Results of time domain simulation

3.1. Lock acquisition with low power laser

In order to investigate the lock acquisition for AdLIGO arm cavity independently from radiation pressure, a very low power input laser is used first. If relative mirror velocity between two test masses is faster than 25 nm/sec, the simulation predicts that it is impossible to acquire lock since oscillations happens on the error signal due to the ringing caused by a long and high finesse cavity. This velocity of 25 nm/sec is too slow compared with the typical mirror speed generated by the nominal seismic motion of AdLIGO site. Even the normalized error signal by transmitted light which is being used in initial LIGO to enhance the linear range is used, the maximum lock velocity does not change because the ringing flips the sign on the normalized signal after passing the resonant point.

Here we tested a new lock acquisition algorithm[6] called 'Guidelock' which predicts relative mirror position and velocity in the computer from the information of first sign and slope of the error signal even the ringing happens then. After the first fringe passed, this algorithm applies maximum force on the actuator to reduce the mirror speed which is slow enough to acquire lock. E2E predicts that this method can enhance the relative mirror velocity up to 500 nm/sec.

Another approach is to reduce the RMS seismic motion. Here, we assumed a typical suspension point interferometer (SPI) performance which reduces seismic motion 10times at low frequency (<10Hz).

Results of these two approaches are summarized in Table 2. The Guidelock or/and SPI can realize the first fringe lock‡ almost/all of the day.

	Lockable speed	Day	Night	SPI/DAY	SPI/Night
Genaral lock	25 nm/s	9.5%	32%	56%	98%
Gudelock	25 nm/s	90%	100%	100%	100%

Table 2. Possibility of lock acquisition for AdLIGO single arm cavity when the cavity passed the resonance. Daytime is estimated from 10% noisiest time at Hanford site and night time is assumed as 1/5 of the daytime.

3.2. Lock acquisition with radiation pressure

In this section, several kinds of power are tested for the Guidelock algorithm to investigate how the radiation pressure affects on the lock acquisition. Lock events are tested with 60 nm/s which is slow enough to acquire lock with no radiation pressure. The test mass has an offset from the resonant point when the simulation has started, and then it passes the resonant point at 0.2 sec. Three typical cases are shown in Fig. 1

‡ Actually the Guidelock reads information at the first fringe and acquire lock at the second fringes.

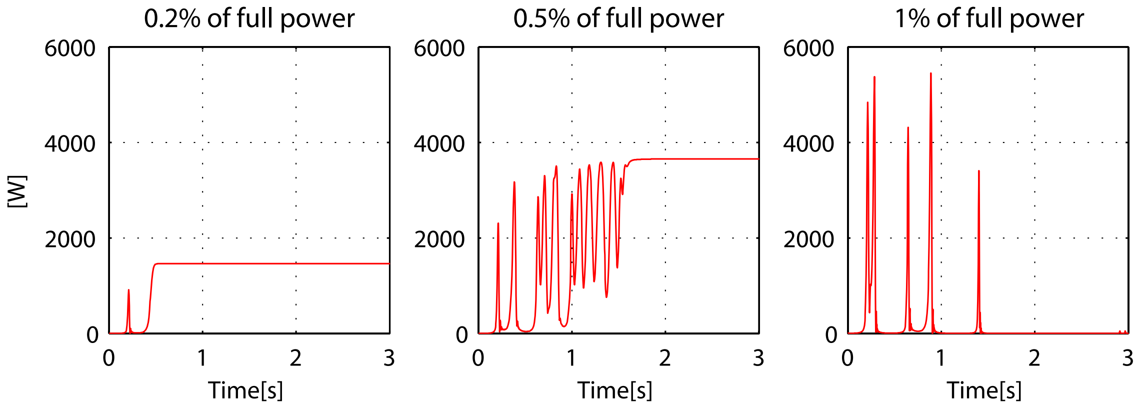

Figure 1. Lock event with 60 nm/s in various power.

with 0.2 % of full power($\sim$1.5 kW inside the arm cavity), 0.5 %($\sim$3.5 kW) and 1 % of full power($\sim$7 kW) respectively. If the power inside cavity reaches several kW, lock acquisition will be disturbed by the radiation pressure. This disturbance is caused by kicking the test masses on length direction by the radiation pressure, but not angle motion. Results tells us that the input power should be provided with such low power somehow, otherwise some special technique, for example an offset lock acquisition on arm common mode which was proposed by the 40 m prototype[3] should be considered.

3.3. Alignment control with radiation pressure

At the final stage of lock acquisition, the power stored inside the cavity is set as the same power as AdLIGO arm cavity (total 0.73 MW with 125 W input, 14.5 of power recycling gain and 770 of round trip time in the arm). During increasing the input power from very low to maximum power, the lock is broken by the huge pitch offset due to the radiation pressure if there is no ASC. Result in Fig. 2 shows that if the cavity inside power reaches 10 %($\sim$70 kW) of full power, the pitch offset breaks the lock.

One of the purpose of this simulation is to make it sure that the ASC works well. We feedback the error signal of WFS to only the penultimate mass in order to control test mass. According to the quad-suspension design, the end test mass(ETM) has an electrostatic drive(ESD) but the input test mass(ITM) does not have, so it is not easy to feedback the signal to the test masses. The f^3 filter is used as feedback servo because the transfer function from the penultimate mass to the test mass has f^{-2} slope so that an open loop gain can be as close as f^{-1} slope to have enough phase margin. Also several boost filters are needed to stabilize DC motion.

Figure 3 shows time series response of the power in the cavity (left) and test mass position (middle) and angle (right) with the ASC. ASC is turned on after length lock is acquired at 0.3 second with low power and then it becomes stable during increasing the power to full between 0.3$-$10 second. E2E can also produce frequency response with excitation of swept sine wave signals from the time series data. We

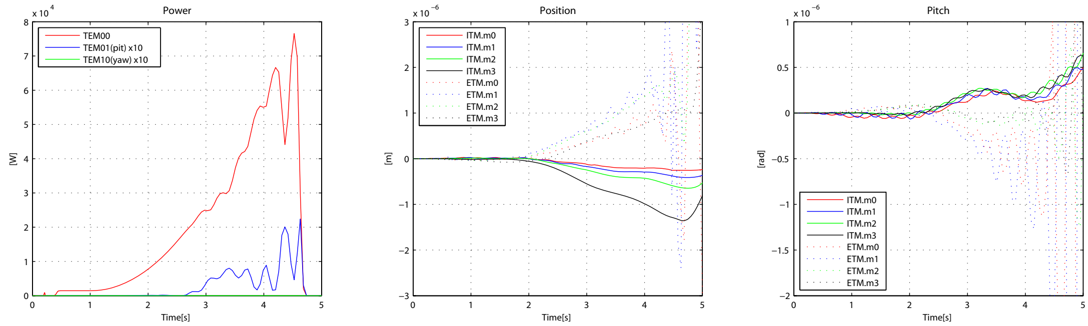

Figure 2. Left graph is power inside the cavity. After lock is acquired with very low power, input power is increased up to full power in 15 seconds. Middle graph shows each mirror position in length direction moved by radiation pressure. Right graph shows pitch angle tilted by wire force due to radiation pressure. Lock is lost due to the pitch offset when cavity inside power reaches about 10 % of full power.

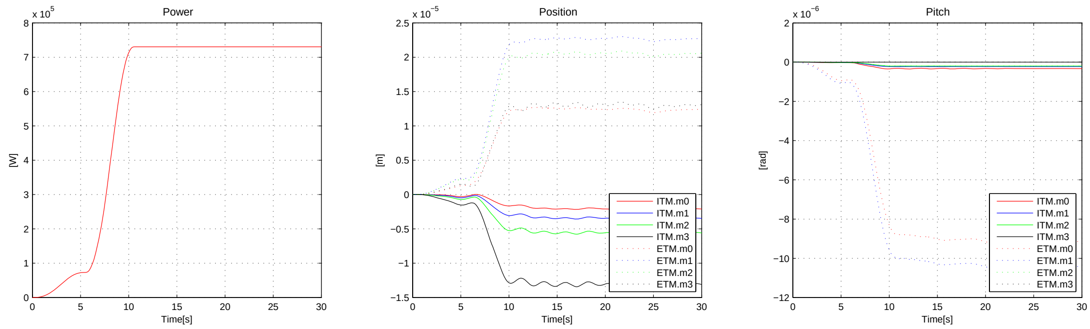

Figure 3. Stable case with full power radiation pressure and higher order mode. 3 graphs show the same things as Fig. 2.

simulate opt-mechanical transfer functions from the actuator input of penultimate mass to the WFS error signal shown in Fig. 4, 5. These transfer functions include original suspension transfer function (red) and optical transfer function with radiation pressure (blue and green). 'Comm' means a common mode excitation that the mirrors are tilted symmetrically and 'Diff' means a differential mode excitation that the mirrors are tilted anti-symmetrically. Beam axis of common mode is shifted to one side of cavity and it pushes the mirrors away, so that the common mode has a negative spring constant, therefore it has no spring peak and it is naturally unstable. On the other hand, beam of differential mode is shifted to cross cavity, and it push the mirrors back, so the differential mode has a positive spring constant and an optical spring at 4.5 Hz for pitch and 4.1 Hz for yaw.

From these results, control band-width is necessary to cover these optical springs at least. In this simulation, it is found that 10 Hz control band-width makes loops stable.

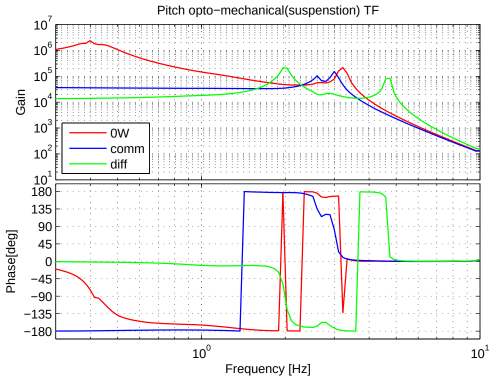

Figure 4. Opt-mechanical transfer function from pitch actuator of penultimate mass to pitch WFS error signal while the FP cavity is locked with no power (red) or full power (blue and green).

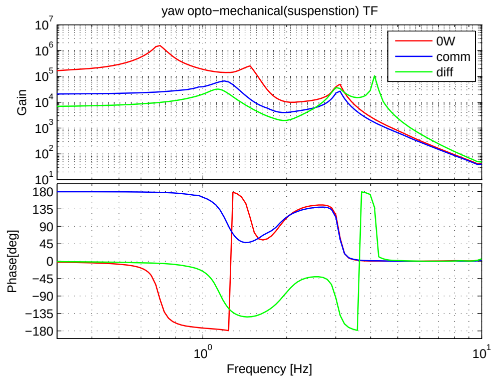

Figure 5. Opt-mechanical transfer function from yaw actuator of penultimate mass to yaw WFS error signal.

4. Summary

Time domain simulation tool E2E is a very useful tool to investigate interferometer with future parameters even if a real interferometer does not exist yet. According to this simulation, optical instability and optical spring show up when the cavity is locked with Advanced LIGO laser power. However these instabilities can be controlled by the proper ASC design which controls the test mass by feedback to the penultimate mass with 10Hz band-width.

Acknowledgments

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