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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. Future interferometer will employ a high power laser and high finesse cavities. Lock acquisition of arm cavity will be more difficult due to the optical instabilities which are caused by very high power inside the cavity. According to this simulation, the arm cavity should be locked with very low power, and additional hard/software techniques will be needed to establish the first fringe lock. In this paper, possibility of using a new algorithm called 'Guidelock' and a suspension point interferometer are discussed. After lock is acquired, alignment controls must be engaged before increasing the power. This simulation predicts that alignment optical instabilities show up due to a shift of high power beam axis, and they can be stabilized by proper alignment controls.

1. Introduction

In Advanced LIGO (AdLIGO) [1, 2], the 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 a stable lock acquisition for a long and high finesse cavity with high power laser, and stable ASC with radiation pressure.

Even considering low power operation of the detector (no radiation pressure), it it the fact that the lock acquisition is difficult since complicated quadruple suspensions and the electro static drives (ESD) which actuate mirror with much weaker force compared with nominal coil-magnet actuator are used.

A time domain simulation tool called E2E[5] which has been developed to analyze LIGO type interferometer is used here to analyze a lock acquisition strategy. 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.

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2. Simulation setup

The most difficult part of lock acquisition in gravitational wave interferometers both experimentally and in simulation involves the locking of the arm cavities. It is impossible to test experimentally with realistic parameters without a full size interferometer with kilometers long arms and supporting hundreds of kW of circulating power. Therefore we focused our simulation work on Fabry-Perot arm cavities like those expected to be used in the next generation interferometers whose parameters are shown in Table 1.

Parameter	Value
Cavity length	3995 m
Transmissivity of ITM in power	0.5 %
Transmissivity of ETM in power	10 ppm
Loss of ITM/ETM in power	50 ppm
Finesse	1240
Radius of curvature of ITM/ETM	2076 m
Full power inside a cavity	0.71 MW
Mass of ITM/ETM	40 kg

Table 1. Parameters used in this simulation.

The Fabry-Perot mirrors are suspended from multiple pendulum suspensions to isolate them from ground motion. The suspension system for each test mass consists of four masses. From the top, they are called the top mass(M0), an upper intermediate mass(M1), a penultimate mass(M2) and the test mass(M3). Details of the suspension system are contained in [6, 7] Local damping for quad-suspensions is applied to the top mass for length, pitch, yaw, side, roll and bounce. Force actuators for length control are applied to the M1, M2, and M3 respectively. Maximum actuator force is limited to 200 mN for M0 and M1, 20 mN for M2 and 450uN for M3.

Several noise sources are included in the simulation. The seismic motion is assumed to be that measured at the Hanford facility is filtered by the transfer function of the proposed advanced LIGO active isolation system [7, 8]. The shot noise is calculated from an incident laser power on the photo detectors (PDs). The radiation pressure and radiation pressure noise are implemented semi-classically [9].

3. Results of time domain simulation

3.1. Lock acquisition with low power laser

We begin by investigating the lock acquisition at very low input laser power where radiation pressure is unimportant. If the relative mirror velocity between the two test masses is greater than 25 nm/sec, the simulation predicts that it is impossible to acquire lock because the error signal oscillates. Nominal seismic motion both LIGO sites are

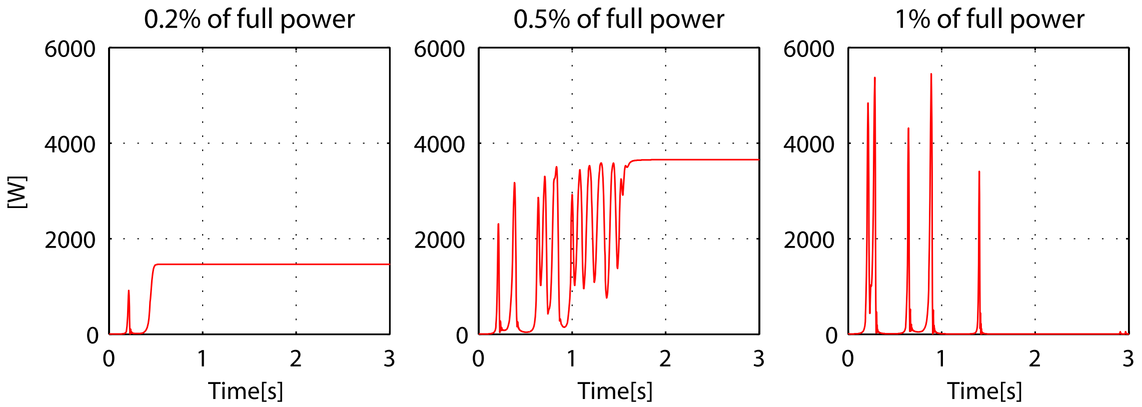

Figure 1. Lock event with 60 nm/s in various power.

greater than this and even if the error signal is divided by the transmitted light as in initial LIGO to enhance the linear range it is still impossible to acquire lock.

Here we tested a new lock acquisition algorithm[10] called 'Guidelock' which predicts the relative mirror position and velocity from the information of first sign and slope of the error signal before the ringing begins. After the first fringe passes this algorithm applies the maximum allowed force to the test mass to reduce the mirror speed which can reduce the mirror speed sufficient to acquire lock. E2E predicts that this method can allow relative mirror velocity as high as 500 nm/sec and still acquire lock.

Another second approach is to reduce the RMS seismic motion using a typical suspension point interferometer (SPI) [11] which can reduces seismic motion by an order of magnitude at low frequency (<10Hz).

Results of these two approaches are summarized in Table 2. This table shows that possibilities of lock acquisition for AdLIGO single arm cavity for day/night time with/without SPI when the cavity passed the resonance. Either the Guidelock or the SPI can allow acquisition of lock for most 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

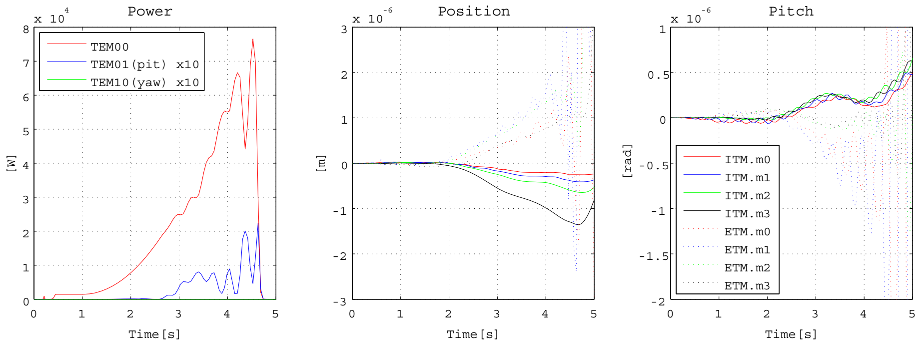

Figure 2. Radiation pressure effects on angle motion without alignment control. Left graph is power inside the cavity. After lock is acquired with very low power, input power is increased up to full power in 15 seconds. Middle graph shows each mirror position in length direction moved by radiation pressure. 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.

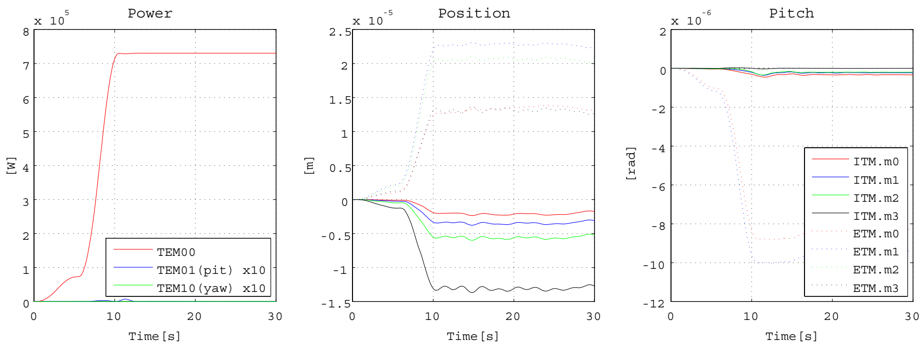

Figure 3. Stable case with full power radiation pressure. ASC is turned on with very low power (0.2 sec). 3 graphs show the same things as Fig. 2.

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 with 0.2 % of full power(∼1.5 kW inside the arm cavity), 0.5 %(∼3.5 kW) and 1 % of full power(∼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 tell 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). While the input power is increasing from

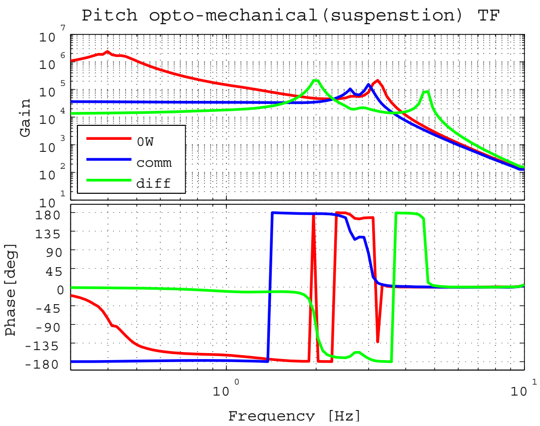

Figure 4. Opt-mechanical transfer function from pitch actuator of penultimate mass to pitch WFS error signal while the FP cavity is locked with no power (red) or full power (blue and green).

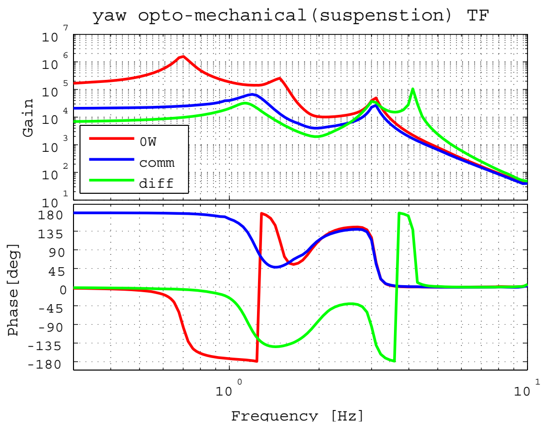

Figure 5. Opt-mechanical transfer function from yaw actuator of penultimate mass to yaw WFS error signal while the FP cavity is locked with no power (red) or full power (blue and green).

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 %(∼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 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.

4. Summary

Time domain simulation tool E2E is a very useful tool to investigate interferometer with future parameters to deal with radiation pressure even if a real interferometer does not exist yet. According to this simulation, it is necessary to acquire the lock first with a low input power, and then engage the alignment control while increasing the power to keep the interferometer locked, and optical instabilities and optical springs 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.

Acknowledgments

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