Institute of Physics Publishing Journal of Physics: Conference Series **32** (2006) 398–403
doi:10.1088/1742-6596/32/1/061 Sixth Edoardo Amaldi Conference on Gravitational Waves

Simulation tools for future interferometers

H. Yamamoto[1,*], M. Barton[1], B. Bhawal[1], M. Evans[1], S.Yoshida[3]

1. LIGO laboratory, California Institute of Technology, Pasadena, CA 91125, (USA)

2. Southeastern Louisiana University, Hammond, Louisiana, 70402 (USA)

Corresponding Author: hiro@ligo.caltech.edu Tel +1.626.395.8467

LIGO document LIGO-P050042-01-E

Abstract. For the design and commissioning of the LIGO interferometer, simulation tools have been used explicitly and implicitly. The requirement of the advanced LIGO interferometer is much more demanding than the first generation interferometer. Development of revised simulation tools for future interferometers are underway in the LIGO Laboratory. The outline of those simulation tools and applications are discussed.

1. Introduction

The commissioning phase of the current LIGO (called Initial LIGO hereafter) interferometers [1] is almost over and operations to acquire data for scientific research have already begun [2]. Several significant upper limits have been obtained and published [3]. A long data taking run with sensitivity close to the design value is scheduled this fall.

The interferometer was designed using best tools available at the time. But, not all necessary tools with sufficient resolution were ready to be used. The lock acquisition design [4] was done after basic hardware and electronics installation were completed. During the commissioning phase, it was found that various control systems needed to be redesigned. The effect of the thermal deformation of the input test mass had been studied with reasonable considerations, but the actual effect observed was much larger than expected and a thermal compensation system under development for advanced LIGO was adopted to solve this problem.

Some of these issues could have been avoided or could have been prepared for if adequate simulation tools were available. The system of Advanced LIGO [5] is much more demanding, and it will be crucial to design the system using appropriate tools in the design phase, not in the commissioning phase, to minimize the extra time and cost to address problems after the hardware is completed.

Three kinds of simulation tools are found to be useful for designing interferometers. One is a time domain simulation, which can address nonstationary and nonlinear processes, including the lock acquisition process. Second is a code to calculate details of field profiles in the interferometer with details of optics, like mirror surface aberration. It is desirable that these two tools are combined in a single simulation tool, but the computation speed prohibits building a time domain model that can trace details of beam profiles. The time domain model uses fields expressed using the modal model with a limited number of modes, and the detailed spatial profiles of fields are studied separately using a static model based on the FFT method.

The third tool is a frequency domain model, which has been actively used to identify details of the detector noise budget. Again, computational limits demand that this be implemented separately from the other two models, this one in the frequency domain. Compared to the time domain model, the frequency domain model can describe only stationary and linear systems. In these systems, couplings among different frequency components are simple. For example, a carrier field reflected by a moving mirror can have only one pair of upper and lower audio sidebands. Because of this simplicity, one can usually calculate an explicit solution of fields in a given system. With this explicit solution, one can understand the effect of the underlying physics and can calculate fields and signals quickly. When an interferometer acquires lock and becomes stationary, the entire system can be viewed as a linear system for most purposes and the frequency domain model is a very powerful and handy tool.

A time domain model [6] (called e2e model hereafter) has been developed by Caltech and a FFT-based static simulation model has been customized and improved for LIGO by MIT [7] (called the FFT model hereafter), which is based on the work in the Virgo group [8].

The proposal for advanced LIGO was submitted in 2003, and has been approved by the National Science Board this year. National Science Foundation funding is scheduled to start in 2008 together with international collaborator funding from the United Kingdom, Germany and possibly Australia. The design and testing of subsystem proptotypes is well underway. It is a crucial time to have the simulation tools ready so that these designs can be developed with proper tests in realistic conditions.

In this paper, e2e and FFT models are discussed. First, the use of the simulation tools for the current LIGO is reviewed to understand how the simulation could be used for the interferometer development. Then, the status of the revised version of these models for advanced LIGO is discussed.

2. Use of simulation tools for Initial LIGO

Simulation tools are useful in various ways. One is to design a system before the actual hardware is built. Various trade studies can be examined. The design and testing of control systems are one of the major tasks. The robustness of the control system in a realistically nonstationary and noisy environment with various physics effects, like radiation pressure, can be studied. Another use is to understand the process going on in the as-built hardware. Various quantities can be calculated quantitatively based on the simulation of the integrated system consisted of mutually interacting subsystems, like mechanical structures, optical cavities and control systems. Various unmeasurable quantities by installed devices can be easily studied, and the study may identify devices to be added to gain better control of the system.

The simulation tools have been used explicitly and implicitly. An example of explicit use is the design of the lock acquisition system. The simulation of the optical system implements the necessary characteristics of field evolutions, linear and nonlinear behavior. The locking code was developed using the simulated interferometer and the resultant code was used in the actual LIGO lock acquisition system. An example of the implicit use is the study of the alignment control. The setup of the in-lock state LIGO simulation does not have the up-to-date control systems installed at the site and does not have all hardware imperfections, and the control code designed using simulation cannot be used as is. Instead, the simulation environment was used to develop an algorithm, which is robust in a realistic environment with time dependent gains and modest noises. After the concept was developed, the improvement of the actual control system was implemented with this knowledge gain by using simulations.

2.1. Applications of e2e [6, 9, 10, 11]

The following are examples of the use of e2e for the Initial LIGO commissioning.

The lock acquisition design was the first and the most important application of e2e. After the completion of the locking design, improvement of overall alignment and length control design were further studied using the simulation. During this study, the mistake of the Schnupp asymmetry setup of 4km interferometers was identified.

When the wave front sensor was implemented and tested in the simulation, it was found that the contribution of the sideband on sideband (interference of resonant sideband and non resonant sideband) is larger than naively expected. When the alignment control was designed, this interference was assumed to be small and neglected. This resolved one discrepancy between the measurement and the original design.

The thermal deformation of the input test masses is implemented as a thin lens in e2e. Temperature dependence of various signals was calculated to assist the commissioning. The waist position of the beam going to a photo detector is dependent on the thermal state of the core optics system. A systematic study was done to find a position in the propagation path of the beam where the beam profile does not depend much on the thermal state. Design work derived from this study was used to re-arrange the optics to make the wave front sensor signal stable and the alignment control robust.

The imbalance of two arms, especially the difference of cavity eigenmodes, can induce signals in the in-phase demodulated asymmetric port output (ASI). This was studied, including the differentially heated input test masses, to quantify the ASI signal as well as the effect of the addition of an output mode cleaner to clean the signal.

The effect of the radiation pressure in the long arm and the role of the alignment control were studied, and it was shown that the radiation pressure effect is not negligible but that the alignment control design is good enough to keep the arm stable.

The sensitivity curve of Initial LIGO was calculated from the time series of error signals using the same procedure as the real data processing, and compares well with the measured sensitivity. This demonstrates that the simulation includes all essential ingredients of the interferometer, and further details can be studied when properly used.

2.2. Application of FFT [9, 10, 14]

The original FFT program was used to define the specifications for Initial LIGO, including the requirements on the optics quantities. After Initial LIGO mirrors were delivered, the program was used to calculate the effect of the as-built mirror surface aberration on the sensitivity.

The program was used to study the thermal effect during the design stage to decide the optimal choice of the mirror curvatures. During the commissioning phase, this study was developed further, including the research for advanced LIGO [12] and evaluating measurements during commissioning [13]. The effect of the mode matching and the overlapping of the carrier and sideband fields were calculated to give valuable insight into the observed Initial LIGO performance.

When the thermal effect in the input test mass is approximated by a thin lens, the net effect is that the curvature of the incoming field changes when the field is reflected or transmitted. The actual thermal effect is more complicated, and the resonating sideband in the Michelson cavity shows deviation from a simple Gaussian shape. This simulation result initiated a revised design of a pattern of the thermal compensation system to improve the shape of the sideband to match better with the carrier field.

The effect of the beam splitter curvature was studied. Beam splitter curvature, at the as-manufactured level, induces an effect similar to two input test masses heated unevenly, which causes imbalance of upper and lower sidebands. Quantitative calculations and estimations on various signals due to imbalance of upper and lower sidebands were carried out.

The optical gain is expected to be proportional to the sideband amplitude in the Michelson cavity, but the measured data showed a small, but significant deviation. The FFT simulation reproduced this deviation . This kind of calculation can be used to make the future design more realistic.

3. Simulations for advanced LIGO

The Simulation tools will play a more crucial role for the advanced LIGO development. The existing tools are now being updated to have enough capability to provide necessary information in the design time scale.

The time domain model can be used to develop the lock acquisition strategy and to estimate quantitatively the magnitude of the force needed to actuate the test mass. It can also be used to test the robustness of the control systems in a realistic environment with radiation pressure and relevant noise sources.

The static model based on FFT can be used to study various design requirements, including the tolerance on the test mass curvature and the aberration of mirrors. Now with a better understanding of the thermal deformation through research and experience in Initial LIGO commissioning, realistic beam profiles in a complicated interferometer can be simulated with good confidence. By combining this information with the time domain simulation, the control system design can be made more realistic and useful.

3.1. Time domain model

The time domain simulation consists of two parts. One part is the simulation engine, like matlab program itself, which is capable of simulating a wide variety of opto-mechanical system with control systems. When enough supplementary information is provided, phenomena like the parametric instability can be studied. The other part is configuration files defining the system to be simulated, analogous to the code written to be run in matlab.

The simulation environment is ready to study the lock acquisition design [15]using the plane wave approximation [16] and to study the angular instability due to radiation pressures with alignment control systems [17]. The framework package, called SimAdvLIGO, has been build with all necessary ingredients, including dual recycled Michelson cavity (DRM), suspensions, seismic isolation and control systems with analog to digital conversion (ADC) and digital to analog conversion (DAC) elements. In order to test the integrity of the framework, the simulation was used to simulate a 40m interferometer-like configuration. The simulation can reproduce the characteristic features of the real 40m experiment [18]. A locking process was demonstrated to guide the interferometer to the locked point. A simulation of a simplified Fabry-Perot system demonstrated that the angular instability caused by the radiation pressure can be reduced with a simple alignment control [9]. This study needs to be extended to set actual requirements on the optics parameters and control systems.

Several improvements are needed for the advanced LIGO simulation. One is a fast simulation of fields in a DRM. A code has been developed to calculate the field evolution in DRM using a linear approximation, i.e., mass motions and field evolutions are approximated by linear forms for the duration of the field propagating one way in the long arm (~10 microseconds). The code is based on a plane wave approximation of fields. This will serve to study the length degree of freedom, including the lock acquisition. An improved code based on the time domain modal model is under development, which is needed to study details of the interferometer, including the stability of the lock state.

The suspension simulations, both quadruple and triple pendulums, are based on the model developed in the LIGO suspension group [19]. Each arm of the interferometer is formed by two test masses, each supported by quadruple pendulums (with main and reaction chains), whereas all other cavity optics are supported by single chain, triple pendulums. The seismic isolation part is based on the model developed by the LIGO seismic isolation group [20]. These mechanical parts of the simulation are still under development by collaborating with subsystem design groups.

Because of the complexity of the mechanical and optical systems, the simulation is much slower than the one for Initial LIGO. Because of the tight interdependence of all parts of a gravitational wave detector, simulations in the time-domain are difficult to parallelize. In order to overcome this limitation and to utilize threads as efficiently as possible, dependencies among actions are analyzed taking the overhead of using threads into account, and relatively independent actions are arranged to be executed in parallel using threads. This analysis and arrangement are done automatically at runtime. For example, mechanical simulations in different chambers are done in parallel.

In order to make it easy to develop and test the control system code, the compilation and linking of the code are transparently integrated with the simulation environment. When one develops the control system code written in C or C++ for a specific part of interest, the codes are automatically compiled and dynamically linked with the main execution code when the simulation is executed. This way, the user of the simulation does not need to know how to use or how to customize the time domain simulation.

3.2. FFT model

The optical configuration of the advanced LIGO interferometer is more complicated than the current detectors. In front of the input test mass is placed a compensation plate, which will be used to suppress the thermal effect. There is an asymmetry between inline and offline directions due to the beam splitter. There is a proposal under study to make the cavity formed by the power recycling mirror and input test masses and the cavity formed by the signal recycling mirror and input test masses to be non degenerate.

In order to simulate these various possibilities, it is necessary to make the code structure modular for easier customization, in addition to understanding well various physics approximations and equations used in the simulation. It is also necessary to understand the relationship between the simulated state of the FFT model and the locked state of the actual interferometer. For this purpose, it is necessary to implement some kind of locking mechanism and alignment control in the FFT model using error signals in a similar way to the real experiment.

The development of a revised FFT model has started. The basic concept is based on the original FFT model. The FFT propagation uses the adaptive grid size method [21], because the design of the advanced LIGO arm is concentric where the beam size at the waist and that on the mirror is different by factor 6. By using this adaptive method, the error induced through propagation can be reduced. This error is more and more problematic for fields with energy distributed towards the outer radius, like higher order Hermite Gaussian modes. [22] The code is written in C++, reusing codes developed for the time domain simulation.

4. Summary

The simulation tools used in Initial LIGO, and the development status of tools for Advanced LIGO, have been summarized. The simulation tools lagged the design effort in Initial LIGO, and, in part as a consequence, some significant changes were needed after the commissioning started. LIGO laboratory is preparing the necessary simulation tools for the Advanced LIGO project to enable a more robust design and to minimize post-installation changes (i.e. minimize schedule, funds and risk).

There are several problems anticipated in the simulation code development. Because of the complexity of the system to be simulated, the computation speed could be a problem, as had been an issue of using FFT for Initial LIGO design. Another issue is the coverage of the dynamic range necessary in the time domain simulation. The dynamic range is from the micro seismic motion to the minimum mass motion, which is a little bit beyond the precision of 64 bit floating value. Another challenge could be that the FFT model style beam profile tracing might be needed to be used in the time domain simulation, instead of a simplified modal model approximation.

5. Acknowledgement

The LIGO Observatories were constructed by the California Institute of Technology and Massachusetts Institute of Technology with funding from the National Science Foundation under Cooperative Agreement PHY-0107417.

References

[1] B. Abbott, et al., "Detector description and performance of the first coincidence observations between LIGO and GEO", Nuclear Instruments and Methods in Physics Research A 517, p. 154-179. (2004)

[2] D. Sigg "Status of the LIGO Detectors"; R.Adhikari "Recent Noise Reductions in LIGO"; talks in this conference.

[3] Publications and latest public results are available at http://www.ligo.org/results/.

[4] M. Evans, et al., "Lock acquisition of a gravitational-wave interferometer," Opt.Lett. 27 p598-600. (2002)

[5] D. Shoemaker, "Advanced LIGO: Context and Overview (Proposal to NSF)", LIGO Document M030023-M (2003)

[6] H. Yamamoto. "Simulations as crucial tools for GW experiments" in Proc. IEEE NSS, Rome, Oct.2004, LIGO-P040046-E (2004)

[7] B. Bochner and Y.Hefetz, "Grid-based simulation program for gravitational wave interferometers with realistically imperfect optics," Phys.Rev.D, 68 (8) p082001-082019 (2003)

[8] J.-Y. Vinet, P.Hello, C.N.Man and A. Brillet, "A high accuracy method for the simulation of non-ideal optical cavities," J.Phys. I (Parisa) 2, No.7 p1287-1303 (1992)

[9] H. Yamamoto, "Recent LIGO I Simualtion Results", LIGO Document G030417-E, (2003)

[10] H. Yamamoto, "Next to lowerst order approximation of LIGO I", LIGO Document G040514-E (2004)

[11] B. Bhawal, "The Effect of Thermal Lensing on Wave-Front Sensor signals", LIGO Document T040066-E, (2004).

[12] R. C. Laawrence, "Active Wavefront Correction in Laser Interferometric Graviational Wave Detector", Ph.D. desertation (Massachusetts Institute of Technology) (2003)

[13] D. Ottaway, "TCS and IFO Properties", LIGO Document G050188-Z (2005)

[14] H. Yamamoto, "FFT Study of Mode Matching at LHO and LLO", LIGO Document G050229, (2005)

[15] M. Evans, "Simulation of Advanced LIGO and the 40m", LIGO Document G050490-E, (2005)

[16] H. Yamamoto, "Calcualtion of fields in a Dual Recycled Michelson Cavity using linear approximation", LIGO Document T040062-E, (2004).

[17] H. Yamamoto, et. al., "Advanced LIGO simulation using e2e", LIGO Document G050491-E (2005).

[18] O. Miyagawa, "Progress Report from 40m Team for the Advanced LIGO Optical Configuration", LIGO Document G050437-R, (2005).

[19] M. Barton, "Models of theAdvanced LIGO Suspensions in Mathematica", LIGO Document T020205-D (2002).

[20] B. Lantz, "Snapshot of the SEI Model for e2e", LIGO Document T050141-R, (2005).

[21] The Virgo Collaboration, "The VIRGO Physics Book, Vol.II : OPTICS and related TOPCIS", (2003).

[22] B. Bhawal, private communication. Y. Pan, "FFT Simulation Note 1 : Formulation", LIGO document, T050218-E (2005).