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Integration of mechanical simulations in the E2E: a white paper

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Contents

1 Introduction and scope **1**

2 Applicable documents **1**

3 Overview of existing simulation packages **2**
3.1 The MSE package 2
3.2 The SEI modeling package 3
3.3 The GEO modeling tools 3

4 Proposed path of integration in the E2E **3**

5 Conclusions **4**

1 Introduction and scope

Several simulation activities have been carried on within the groups involved in the design and realization of the suspensions and the seismic isolation elements of LIGO and Advanced LIGO, and within the E2E (end-to-end) core group. The results of these activities are both sofware packages for mechanical modeling, and models built on top of them.

In turn these models include both the correct physical parameters (masses, stiffnesses ...) and informations desumed by means of experiments. This wealth of knowledge is of paramount importance in order to correctly describe the mechanical subsystems and it is highly desirable to integrate it in the global LIGO simulation, which is provided by the E2E package and models built on top of it.

The E2E is in fact a simulation framework consisting of tools for modeling optics, mechanics and electronics, and allows to connect the resulting models into a global system. It provides therefore a way to predict the behaviour of the LIGO interferometers, in the present and future configurations, and its scope goes beyond the "as is built" approach: the E2E is expected to be the framework for evaluating and comparing also future solutions, envisaged for Advanced LIGO and beyond.

It is important to ensure that an appropriate interface between E2E and the different mechanical modeling activities exists, allowing these studies to be effectively carried out.

Starting from the user's perspective, one can foresee two broad classes of simulation activity, for the LIGO mechanical subsystems:

1. support in the conceptual and design stage, allowing both to test sketchy ideas and mature solutions.

2. Modeling of an existing system at a level of approximation sufficient to predict its interaction with the other LIGO elements.

For studies belonging to the first class it may not be required to integrate the mechanical subsystem with the other LIGO elements, although it is desirable in some circumstances: as an example, it is important to test control loops, including the effect of digitization, dynamic range ... integrating mechanical and electronics models in the E2E framework.

The second class of studies focuses instead primarily on the behaviour of LIGO as a whole and the integration becomes central. It is the purpose of this note to discuss how this issue can be approached and to propose a solution which should allow the integration in a convenient way.

2 Applicable documents

The following material has been consulted when writing this note:

- *Baseline LIGO-II implementation design description of the stiff active seismic isolation system*, J.Giaime, B.Lantz, S.Richman, D.Debra, C.Hardham, J.How and W.Hua, March 8th, 2000, Ver. 1, **LIGO-T000024-00-U**.
- *Computer modeling and simulation in support of the stiff suspension active seismic isolation for LIGO II*, B.Lantz, W.Huw, S.Richman, J.How, Feb. 14th, 2000, Ver. 1.0.1, **LIGO-T000016-01**.
- *LIGO II suspension: reference designs*, The GEO suspension team, January 31st, 2000, **LIGO-T000012-00-D**.
- *Mechanical Simulation Engine: user's manual*, G.Cella, Nov. 1999, **LIGO-T990107-00-E**.
- *Mechanical Simulation Engine: physics*, Nov. 1999, **LIGO-T990106-00-E**.
- *MSE: a mechanical simulation engine for the LIGO E2E model*, Nov. 1999, **LIGO-T010130-00-E**.

In addition, the following web sites have been found useful

- LIGO End to End model: http://www.ligo.caltech.edu/~e2e
- LSC suspensions and seismic isolation working group: http://fiji.nirvana.phys.psu.edu/~swg
- LIGO SAS homepage: http://www.ligo.caltech.edu/~citsas

3 Overview of existing simulation packages

The simulation packages being used inside the LIGO Laboratory and the LSC have been created in order to answer specific questions raised during the conception, design, realization and characterization of the suspensions and the seismic isolation systems. They have been generally driven therefore by specific needs and their scope may be different, altough the similarity of the problems encountered leads in some cases to similar solutions.

3.1 The MSE package

The Mechanical Simulation Engine[1, 2, 3] is a C++ library of functions which is used to model the LIGO suspension[5] and the advanced LIGO configurations[4]; it

- incorporates basic elements for a mechanical simulation, like rigid bodies, beams, wires, springs, blades ...
- Provides a way to specify also black-box elements, in terms of their physical properties, formulated in the time-domain or the frequency-domain.
- Has methods to connect the elements into a mechanical system, and
- to define the way the system is actuated on.
- Allows to search for a working point by minimizing the potential energy, and linearizing the resulting motion equations.
- Provides methods to evolve the system in the time-domain or to compute transfer functions in the frequency domain.

The MSE is sufficiently general, in its present form and with the foreseen extension[3], to allow the modeling of current and foreseeable LIGO suspensions. Its use requires currently a moderate knowledge of C++.

Its scope is limited to the mechanical simulation, and control loops can be simulated in the time-domain or frequency domain using the facilities provided by the E2E.

3.2 The SEI modeling package

This ensemble of tools [7] is being used by the SEI group in order to model the active seismic isolation [6] for Advanced LIGO. It consists actually of three parts, written in MatLab:

- a model constructor, which allows to use masses, springs (wires or blades), sensors and actuators in order to define a mechanical systems.
- A set of routines for searching the working point and obtaining the linearized equations of motion.
- A SimuLink interface which allows to design the control laws and close the loop on the mechanical model.

As for its functionalities, this set of tools allows a complete study of the active suspension system in isolation.

It is not evident to me, on the basis of the documents that I read, if internal modes can also be included, although they are probably not deemed necessary for control studies.

3.3 The GEO modeling tools

The GEO suspension team has developed its own MatLab code for the simulation of the triple pendulum system[8], envisaged for the SUS (suspension) in arvanced LIGO. From the document[7, Sec. 2.1,2.2] I understand that the functionalities and the results of the GEO model have been completely reproduced using the SEI package; I also understand that independent models are being realized for the quadruple pendulum, and that they will be cross-validated by requiring that the results coincide.

As the two approaches share the same physics, and use the same (MatLab) language, they should also easily share the same solution when discussing their integration in the E2E.

4 Proposed path of integration in the E2E

All the modeling tools considered allow to produce a state-space representation (possibly approximate, see below)

$$\frac{dQ\left(t\right)}{dt} = A \cdot Q\left(t\right) + B \cdot U\left(t\right), \qquad Y\left(t\right) = C \cdot Q\left(t\right) + D \cdot U\left(t\right)$$

of the system, where Q is the state vector, Y the vector of observables, U the vector of external actions applied to the system, and the A, B, C, D are (sparse) matrices which completely define the system.

Once such a representation is available, a time domain simulation can be directly implemented, with standard tools for the integration of (linear) differential equations over discrete simulation steps.

In particular, the MSE makes already available for the E2E the Runge-Kutta and Adams integrators, along with methods which allow to compute the state transition (full) matrices A_d, B_d, which allow to evolve the state vectors

$$Q\left[t + dt\right] = A_d \cdot Q\left[t\right] + B_d \cdot U\left[t\right] \qquad Y\left[t\right] = C \cdot Q\left[t\right] + D \cdot U\left[t\right].$$

In this context, a possible path of integration is the following:

- each model, either based on the MSE or on the MatLab codes, provides as output the state space matrices A, B, C, D appropriate for describing the system in the continuum time. A format for exchanging this state space matrices along with the information needed to give a meaning to inputs and outputs should be defined.
- The SEI model control loops can in principle be integrated in the A, B, C, D model, but this might not desirable because it would make impossible to simulate the effects of digitization and of the dynamic range of the actuators. For this reason it is sensible to rewrite the control loop using native E2E objects (filters, digitizers, limiters ...). The needed effort appears limited, given that the E2E GUI is very similar to the SimuLink GUI, and that this work needs to be done only once.

- The time evolution of the mechanical subsystems can be performed inside the E2E by using the integrators already provided by the MSE.

The actions that seem necessary in order to implement this strategy are the following, along with a subjective view of the required manpower: a small task is a one day work, a medium task may require 2-3 days, a large task a couple of weeks.

1. both the MSE library and the SEI matlab code should include a routine for saving the A, B, C, D matrices in a common format. For instance a MatLab ASCII format seems to be appropriate [small task].
2. The E2E library should provide a routine for reading the A, B, C, D matrices into a generic "mechanical system" box, with a variable number of inputs and outputs [small task].
3. The same "mechanical system" box should have methods, built using the MSE library, for computing the time evolution [small/medium task, given that MSE already provides the basic simulation methods].
4. A E2E box should be assembled (composed of native E2E blocks) which reproduces the structure of the control loops adopted in the active isolation systems. This amounts to translate the SimuLink model into a E2E model using the E2E GUI [small/medium task, assuming that it only requires to connect basic E2E blocks, and no new box is needed].
5. The resulting model should be validated by comparing the results of SimuLink and E2E simulations [medium/large task, depending on the complexity of the system and the effort needed to resolve bugs]

The step 4 appears to duplicate the work already done in the SEI group: this is unfortunate, but should be done just once: future updates of the mechanical model would affect only the A, B, C, D matrices, while modifications of the control laws will be probably studied within the SEI MatLab model and only when "final" will need to be updated in the E2E model box.

Notice that the steps 2 and 3 also allow to incorporate models desumed from the experimental data via standard system identification tools, an extra bonus which alone is worth the effort.

We mentioned at the beginning of the section that the A, B, C, D representation can be just an approximation: the reason lies not only in the reduction of degrees of freedom, but also in the difficulty of providing a time-domain model for the structural damping which is both accurate and computationally inexpensive. The experience made in Virgo shows however that for many cases a viscous damping tuned to reproduce the correct quality factor at the resonances can be sufficient for control studies[9], and this is already envisaged for the MSE [G.Cella, private communication].

5 Conclusions

A full integration of the different mechanical models in the E2E, with the purpose of making possible a global simulation of LIGO that includes all the knowledge available in the SEI and SUS groups appears possible, and the required manpower seems to me quite limited in comparison with the return in terms of making lots of important studies possible.

An alternative integration path might be the modeling of the SEI (SEismic Isolation) system using MSE. This is certainly possible, and may start by reproducing the results of the matlab models, and evolve by incorporating (say) also the effect of internal modes. However in my opinion this alternative path might be considered as a second order priority, to be pursued when the need arises.

For the SUS (SUSpension) system there is already an ongoing effort[4] which aims at developing an MSE-based model: this seems to me very well justified, because it will be of great importance to dispose of a simulation which incorporates the internal degrees of freedom, like the violin modes[5].

Hence a situation in which the SEI model is "imported" in E2E as a state-space model, and evolved in the time-domain using MSE and E2E tools, while the SUS is modeled directly using MSE functions appears to me the most appropriate in the immediate future.

The specific actions needed in order to implement this integration will require a careful revision on the side of the E2E and SUS/SEI groups: those suggested in this note should only be taken as a starting point.

References

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