Workplan for the mechanical simulation module.

Giancarlo Cella.

Here we describe the working plan for the implementation of the mechanical simulation module and for its integration in the LIGO end-to-end model.

1.0 Schematic view

In this section I list the points which in my opinion should be implemented in the model. The tasks in the first three subsections are somewhat mandatory, and also there are standard methods and a well established literature about them (apart, to my knowledge, for some point in the third subsection). The tasks in the last two subsections are really (more or less) research problems.

1.1 Low frequency mechanical simulation

1.1.1 The first stage is a finite element module with capabilities of dynamical and spectral analysis. It can get external forces and return measured movements or positions, in the time or in the frequency domain.

1.1.2 Limited capabilities of integration with the optical module are ready from the start. For example, it will be possible to get an output force from the optical module and put it as an input in the mechanical one.

1.1.3 In the initial stage the problem must be described in a completely linear way. This means that all constraint must be linearized by hand and the working point also must be given.

1.2 Internal modes

1.2.1 A linear finite elements model can be “compiled”, in the sense that can be always reduced to a representation in term of transfer functions between an input and an output.

1.2.2 When we get a big enough detail a coupling could not be point-like. Also in this case we can “compile” this feature transforming into the space of the strength of coupling functions.

1.2.3 The informations about reduced transfer functions are not always available in a simple analytical form. So we must implement efficient and precise techniques for storing in a numerical way these informations. The standard choice is to use a rational approximation, which can be easily translated in a ARMA filter representation. However in some particular cases other solutions could be more efficient.

1.3 Nonlinearities 1: setting the working point

1.3.1 The determination of the working point for a mechanical system is typically a non linear problem. In the later stage of the model development the simulation module will provide an optional facility for the search of the static equilibrium position and for the automatic calculation of the linear model parameters.

1.4 Integration with the optical simulation

1.4.1 The point-like approximation is no longer true (or is a crude one). See Section 1.2.2.

1.4.2 A mirror coupled to mechanics and optics can be crudely implemented as a composite object with an “optical” mirror and a “mechanical” mirror coupled. This could be inefficient if we want to refine the model, and we could need to construct fundamental objects with both optical and mechanical capabilities.

1.5 Nonlinearities 2: correction to linear regime

1.5.1 Some interesting nonlinear mechanical effects (for example, up conversion effects) can be implemented in a perturbative way.

1.5.2 A dynamic non linear simulation can also be implemented, but if the model is very refined it can become very heavy from a computational point of view.

1.5.3 Probably the relevant nonlinear effects are confined to some critical subsystems, so it will be relevant the implementation of fundamentally linear simulation with some well-defined non linearities.

2.0 Priorities

Here I give a list of task priorities, with a tentative estimate of the time needed to complete them (when this is reasonably predictable).

2.1 A support for new mechanical subsystems design

At this stage the system has the capabilities described in Section 1.1. To obtain this result we must implement some additions to the syntax description file and a first simulation engine which contains methods for mechanical systems composed of simple finite elements.

2.1.1 A first task is the construction of a “system builder”, which is called in the initialization phase. It construct the data structures which provide the mathematic description of the mechanical system starting from

1. The list of fundamental building blocks
2. The connections bewtween them
3. The list of input connections from non mechanical subsystems
4. The list of output connections from non mechanical subsystems

The total time required for this depends on how much easily the existing code will be integrated in the end to end model.
Estimated time: 2-3 months.

2.1.2 A second task is the specification of the algorithmic implementation of each mechanical blocks. A consistent fraction of the code written so far will be adapted and re-used. This task is mixed, in its temporal evolution, with the first..
Estimated time: 1 month.

2.1.3 A third task is the optimization of the algorithms. This means search about strategies to reduce computational requests and to speed up calculations. Finally there is a validation phase, which will consist in the construction of some non-trivial examples and in the analisys of the relative results.
Extimated time: 1 month.

2.1.4 A fouth task is to add to the sistem the capability of generate in the time domain the termal noise appropriate for a given equilibrium temperature.
Extimated time: 1 month.

Total estimated time: 6 months.

2.2 A support for the study of mechanical imperfections

At this stage the system has additional capabilities which can be used to construct the system in a fully modular way. The simulation engine is capable to compile the information of complex linear submodules and use them in the global time or frequency domain in an efficient way. It is so possible to include internal modes in the model at the desired refinement level. **Estimated time: 6 months.**

2.3 An integrated optical and mechanical simulation

At this stage the optical and mechanical module are integrated, including the modelization of complex couplings (radiation pressure, mirror heating, termal transport effects).
Estimated time: It is difficult to say, probably 6-8 months.

2.4 A debugging tools for the locked interferometer

At this stage the optical and mechanical system integration is well validated. It is possible to include effects like limited nonlinearities and complex sources of noise (say, the creep of the wires). **Estimated time: 6 months.**

2.5 Working point automatic search.

At this stage the system will have the capability for of an automatical search for the working point, starting from an initial specification of (possibly non linear) constraints. Some limited capabilities are already implemented, but we lacks a general tool.
Estimated time: 3 months.

2.6 A tool for locking

At this final stage the model can be used to study the system in a completely nonlinear regime, and we expect the model to be very detailed. This is a very ambitious task, and probably it does not make sense to set a final target.
Estimated time: I don't know.

3.0 Modelization

Here I list the physical and mathematical tools which should be studied and developed in order to build a refined, usable and efficient mechanical simulation tool.

3.1 Approximation methods for transfer functions

This point is connected first of all with the computational cost of the simulation, and next with its precision. In some limited cases a transfer function can be obtained in a closed analytical form. In other cases (say, a mirror with complex shape and/or complex boundary conditions) this is not possible. The information about transfer function is generally requested in a limited frequency band, but here the description must be quite precise (say, to describe a narrow resonance). Also the information must be available in a form which can be easily used for the time or frequency domain simulation.

3.2 Automated constraint reduction

This problem is generally equivalent to the minimization of a nonlinear function of many variable. Often this function is known only in a implicit way. In any case there is a big literature on this subject and the main task is to find the best approach in our context.

3.3 Termal noise

The modelization of the termal noise is connected to the modelization of the dissipative mechanism. It could also be connected with the modelization of transport, non-equilibrium phenomena.

3.4 Other internal noises

This the modelization of complex mechanism of energy relaxation. For example creep noise, electromagnetic couplings, eddy currents, magnetic ordering effects, hysteresis phenomena.

3.5 Non equilibrium effects

The approximation of termal equilibrium could not be accurate enough beyond some refinement level. This is a problem which must be modeled with a complete integration between optics and mechanics.

3.6 Non linear effects

This is first of all the study of methods to include in the simulation nonlinear phenomena in an efficient way.

Workplan for the mechanical simulation module.

Giancarlo Cella.

Here we describe the working plan for the implementation of the mechanical simulation module and for its integration in the LIGO end-to-end model.

1.0 Schematic view

In this section I list the points which in my opinion should be implemented in the model. The tasks in the first three subsections are somewhat mandatory, and also there are standard methods and a well established literature about them (apart, to my knowledge, for some point in the third subsection). The tasks in the last two subsections are really (more or less) research problems.

1.1 Low frequency mechanical simulation

1.1.1 The first stage is a finite element module with capabilities of dynamical and spectral analysis. It can get external forces and return measured movements or positions, in the time or in the frequency domain.

1.1.2 Limited capabilities of integration with the optical module are ready from the start. For example, it will be possible to get an output force from the optical module and put it as an input in the mechanical one.

1.1.3 In the initial stage the problem must be described in a completely linear way. This means that all constraint must be linearized by hand and the working point also must be given.

1.2 Internal modes

1.2.1 A linear finite elements model can be “compiled”, in the sense that can be always reduced to a representation in term of transfer functions between an input and an output.

1.2.2 When we get a big enough detail a coupling could not be point-like. Also in this case we can “compile” this feature transforming into the space of the strength of coupling functions.

1.2.3 The informations about reduced transfer functions are not always available in a simple analytical form. So we must implement efficient and precise techniques for storing in a numerical way these informations. The standard choice is to use a rational approximation, which can be easily translated in a ARMA filter representation. However in some particular cases other solutions could be more efficient.

1.3 Nonlinearities 1: setting the working point

1.3.1 The determination of the working point for a mechanical system is typically a non linear problem. In the later stage of the model development the simulation module will provide an optional facility for the search of the static equilibrium position and for the automatic calculation of the linear model parameters.

1.4 Integration with the optical simulation

1.4.1 The point-like approximation is no longer true (or is a crude one). See Section 1.2.2.

1.4.2 A mirror coupled to mechanics and optics can be crudely implemented as a composite object with an “optical” mirror and a “mechanical” mirror coupled. This could be inefficient if we want to refine the model, and we could need to construct fundamental objects with both optical and mechanical capabilities.

1.5 Nonlinearities 2: correction to linear regime

1.5.1 Some interesting nonlinear mechanical effects (for example, up conversion effects) can be implemented in a perturbative way.

1.5.2 A dynamic non linear simulation can also be implemented, but if the model is very refined it can become very heavy from a computational point of view.

1.5.3 Probably the relevant nonlinear effects are confined to some critical subsystems, so it will be relevant the implementation of fundamentally linear simulation with some well-defined non linearities.

2.0 Priorities

Here I give a list of task priorities, with a tentative estimate of the time needed to complete them (when this is reasonably predictable).

2.1 A support for new mechanical subsystems design

At this stage the system has the capabilities described in Section 1.1. To obtain this result we must implement some additions to the syntax description file and a first simulation engine which contains methods for mechanical systems composed of simple finite elements.

2.1.1 A first task is the construction of a “system builder”, which is called in the initialization phase. It construct the data structures which provide the mathematic description of the mechanical system starting from

1. The list of fundamental building blocks
2. The connections bewtween them
3. The list of input connections from non mechanical subsystems
4. The list of output connections from non mechanical subsystems

The total time required for this depends on how much easily the existing code will be integrated in the end to end model.
Estimated time: 2-3 months.

2.1.2 A second task is the specification of the algorithmic implementation of each mechanical blocks. A consistent fraction of the code written so far will be adapted and re-used. This task is mixed, in its temporal evolution, with the first..
Estimated time: 1 month.

2.1.3 A third task is the optimization of the algorithms. This means search about strategies to reduce computational requests and to speed up calculations. Finally there is a validation phase, which will consist in the construction of some non-trivial examples and in the analisys of the relative results.
Extimated time: 1 month.

2.1.4 A fouth task is to add to the sistem the capability of generate in the time domain the termal noise appropriate for a given equilibrium temperature.
Extimated time: 1 month.

Total estimated time: 6 months.

2.2 A support for the study of mechanical imperfections

At this stage the system has additional capabilities which can be used to construct the system in a fully modular way. The simulation engine is capable to compile the information of complex linear submodules and use them in the global time or frequency domain in an efficient way. It is so possible to include internal modes in the model at the desired refinement level. **Estimated time: 6 months.**

2.3 An integrated optical and mechanical simulation

At this stage the optical and mechanical module are integrated, including the modelization of complex couplings (radiation pressure, mirror heating, termal transport effects). **Estimated time: It is difficult to say, probably 6-8 months.**

2.4 A debugging tools for the locked interferometer

At this stage the optical and mechanical system integration is well validated. It is possible to include effects like limited nonlinearities and complex sources of noise (say, the creep of the wires). **Estimated time: 6 months.**

2.5 Working point automatic search.

At this stage the system will have the capability for of an automatical search for the working point, starting from an initial specification of (possibly non linear) constraints. Some limited capabilities are already implemented, but we lacks a general tool.
Estimated time: 3 months.

2.6 A tool for locking

At this final stage the model can be used to study the system in a completely nonlinear regime, and we expect the model to be very detailed. This is a very ambitious task, and probably it does not make sense to set a final target.
Estimated time: I don't know.

3.0 Modelization

Here I list the physical and mathematical tools which should be studied and developed in order to build a refined, usable and efficient mechanical simulation tool.

3.1 Approximation methods for transfer functions

This point is connected first of all with the computational cost of the simulation, and next with its precision. In some limited cases a transfer function can be obtained in a closed analytical form. In other cases (say, a mirror with complex shape and/or complex boundary conditions) this is not possible. The information about transfer function is generally requested in a limited frequency band, but here the description must be quite precise (say, to describe a narrow resonance). Also the information must be available in a form which can be easily used for the time or frequency domain simulation.

3.2 Automated constraint reduction

This problem is generally equivalent to the minimization of a nonlinear function of many variable. Often this function is known only in a implicit way. In any case there is a big literature on this subject and the main task is to find the best approach in our context.

3.3 Termal noise

The modelization of the termal noise is connected to the modelization of the dissipative mechanism. It could also be connected with the modelization of transport, non-equilibrium phenomena.

3.4 Other internal noises

This the modelization of complex mechanism of energy relaxation. For example creep noise, electromagnetic couplings, eddy currents, magnetic ordering effects, hysteresis phenomena.

3.5 Non equilibrium effects

The approximation of termal equilibrium could not be accurate enough beyond some refinement level. This is a problem which must be modeled with a complete integration between optics and mechanics.

3.6 Non linear effects

This is first of all the study of methods to include in the simulation nonlinear phenomena in an efficient way.