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OSCAR: A MATLAB based package to simulate realistic optical cavities

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ABSTRACT

OSCAR is a MATLAB toolbox to simulate optical resonators such as Fabry–Perot cavities in presence of imperfect optics. It can handle any wavefront distortions as deviation of radius of curvature or 2D profile height of the surface of the mirrors. The package also natively supports arbitrary laser beam shapes from higher order optical modes (in Hermite or Laguerre Gauss basis) or from exotic flat beams. One of the most suitable application of OSCAR is designing and commissioning the long arm cavities of laser gravitational wave detectors.

Code Metadata

Current code version	3.2
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX_2020_116
Code Ocean compute capsule	none
Legal Code License	BSD-3-Clause
Code versioning system used	git https://github.com/Jerome-LMA/oscar
Software code languages, tools, and services used	MATLAB
Compilation requirements, operating environments & dependencies	Same as MATLAB
If available Link to developer documentation/manual	documentation is inside the package
Support email for questions	j.degallaix@lma.in2p3.fr

1. Motivation and significance

Optical resonators are regularly used to amplify signals through the interaction with light. The most simple of such resonators is the Fabry–Perot cavity, two high reflectivity mirrors facing each other and separated by a distance. The length of the cavity could range from millimeter to probe optomechanical interaction [1], to meters (for magnetic birefringence measurement of vacuum [2]) and up to a kilometer scale for laser gravitation wave detectors [3].

To achieve the maximal signal amplification, optical losses must be restrained, setting hard specifications on the surface or coating of the mirrors. In particular, the quality of the polished substrate is crucial as surface defects scatter light and are usually the major source of optical losses [4]. Unfortunately, no simple analytical model exists linking the low spatial frequency surface defects (called flatness) and the losses in the cavity. Such a study could easily be performed in OSCAR as we will see later in this article in Section 3.

OSCAR stands for Optical Simulation Containing Ansys Results since this software was first designed to simulate optical cavities in presence of thermal distortions due to the heating from the laser beam. The non-spherical distortions (themoelastic deformations of the surfaces or thermal lensing effect in the substrates) was at that time derived from the FEM software ANSYS.

Later OSCAR was expanded to simulate any kind of planar optical cavities, linear or ring shapes with an arbitrary number of mirrors (2, 3 or 4 mirrors being the most common). In recent years, to fully simulate gravitational wave detectors, systems of coupled cavities were also implemented. The most complex configuration tested so far is Advanced Virgo, a dual recycled Michelson interferometer with Fabry–Perot arm cavities, however the code is not public as not yet fully documented. The code is always under-development to answer the needs of physicists and to take advantages of the latest computing development.

OSCAR was used extensively during the optical design and commissioning of the Advanced Virgo gravitational wave detector. In particular, it helped to define the geometry of the long arm cavities and setting the mirror polishing specifications. It also contributed to define the optical wavefront distortion budget

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in order to not degrade the interferometer performances setting constraints on the quality of the correction of the Thermal Compensation System (TCS) [5]. More details on this topic could be find in the chapter 2 of the Advanced Virgo technical design report [6]. During the commissioning of Advanced Virgo, OSCAR is used to understand the behavior of the interferometer and in particular explaining the power and optical mode contents at the different port of the detector, for the carrier and sidebands fields.

2. Software description

The core of the program is a set of routines written in MATLAB to gain the full benefits from multicore CPU or user friendly interfaces [7]. The code takes advantage of the oriented object programming with classes (for example: electric field or cavity) and associated methods (for example: propagate the field or display the field intensity).

The goal of the simulations is to calculate the laser beams at the different positions inside and outside the optical cavity. For example for a given input laser beam, we are interested in the steady state power and shape of the laser beam circulating inside the cavity but also being reflected or transmitted. Those results depend also on the geometry of the cavity as well as the transmission/reflection of the different optics. In OSCAR, the laser beams are represented as 2D arrays of complex numbers corresponding to the 2D spatial distribution of the electric fields. For example, a complex fundamental Gaussian beam E could be discretized on a 2D Cartesian grid (x,y) as:

$$E(x,y) = Ae^{i\phi}e^{-\frac{(x^2+y^2)}{\omega^2}}e^{-i\frac{2\pi}{\lambda}\frac{(x^2+y^2)}{2R}} \tag{1}$$

with A the amplitude of the electric field, ϕ a possible phase shift (including the Gouy phase), ω the beam Gaussian beam radius, λ is the wavelength and R the complex radius of curvature of the wavefront. Of course, as the beam propagates or is reflected the parameters A, ϕ, ω and R will change accordingly.

2.1. Principle of the simulations

The code is built around a beam propagation method based on the FFT (Fast Fourier Transform) algorithm under the paraxial approximation [8]. Such approach is extremely powerful as the propagation over a distance of any arbitrary 2D electric fields is possible and with always the same computational effort. In more details the propagation is done in 3 steps:

1. the decomposition of the electric field on a sum of plane waves, done with a 2D FFT
2. propagation of each plane waves, done with a multiplication point by point of a complex 2D array
3. recomposition of the planes waves into the electric field with a 2D inverse FFT.

The second ingredient of the simulation is the handling of wavefront distortions encountered by the laser beam. Such distortions could come from the transmission through a lens, a reflection from a spherical mirror or an aberrated surface. A distortion is characterized by a 2D non uniform phase shift quantified by the optical path difference *OPL*. An electric field E_1 passing through the distortions *OPL* will thus get the additional phase shift and becomes E_2 according to:

$$E_2(x,y) = E_1(x,y)e^{-i\frac{2\pi}{\lambda}OPL(x,y)} \tag{2}$$

As an example, *OPL* from a mirror is simply twice the surface height (also called sagitta), for a spherical mirror of radius of curvature R_C, the *OPL* is given by:

$$OPL(x,y) = 2\left(R_C - \sqrt{R_C^2 - (x^2+y^2)}\right) \tag{3}$$

Once we are able to simulate the propagation of laser beams as well as reflections over surfaces, everything is in place to simulate optical cavities. In the Fabry–Perot cavity, the laser beam is propagating back and forth between the two mirrors and then all the propagating fields are summed at the same plane to calculate the total circulating beam. From there, the reflected and transmitted beams could be calculated.

2.2. Typical simulations

OSCAR is provided with a set of examples to demonstrate the simulation possibilities. As mentioned before, the code is particularly suited to simulate the steady state circulating, transmitted and reflected laser beams from optical cavities with any numbers of mirrors (example file: `Example_Pcirc.m`). It can include arbitrary input beams as well as imperfect optics (example file: `Example_HOM_with_maps.m`).

Once the cavity is defined, it is also possible to perform a scan over one free spectral range and display the result (example file: `Example_cavity_FSR_scan.m`). Theoretical 2D eigenmodes and eigenvalues of the cavity fields could also be calculated to check the round trip loss and resonance positions of the different higher order modes of the cavity (example file: `Example_cavity_eigenmodes.m`).

To simulate length control signals, radio-frequency sidebands can be added on the input field to derive error signals using the Pound Drever Hall technique [9] (example file: `Example_PDH_signal.m`).

OSCAR provides also a set of functions to read directly the 2D surface height files taken by wavefront measurement interferometers [10] from the brand Zygo [11] used in the mirror's characterization. It is possible to remove the tilt and curvature over a certain diameter and calculate the RMS of the surface (example file: `Example_Display_Create_maps.m`). That is particularly useful to validate the polishing work.

3. Illustrative example

One of the most emblematic example is the simulation of cavity round trip optical loss in presence of realistic polishing 2D surface maps. The round trip loss represents the fraction of light power falling outside the clear aperture of the mirror due to the imperfect flatness of the mirrors. That is a critical number for high finesse (i.e. very low loss) cavity and give some strong constraint on the surface quality of the mirrors.

To achieve this simulation, one must first define the mirrors: that includes, at minima, the diameter or clear aperture, the curvature and the reflectivity (or transmission) of the coating. Then a file, representing the 2D surface height of the mirror surface is loaded and added to the curved mirror surfaces. Such files could come from wavefront measurement of real mirrors [12] and are essential to confirm that mirrors meet their specifications.

Once the two (or more) mirrors are defined, the length of the cavity and the input beam are specified. That is all the information required to launch the simulation as output quantity could be selected later. A first function will calculate the round trip phase shift to guarantee that the circulating field is on resonance, maximizing the circulating power and a second function calculates the 2D steady state permanent fields in the cavity (circulating) as well as outside (reflected and transmitted fields). From there the conservation of energy (or power) can tell us how much light is lost due to the finite aperture of the mirrors.

An example of the result of such simulation is shown in the right part of Fig. 1. As the RMS of the flatness over the central part of the mirror is increased, the cavity round trip

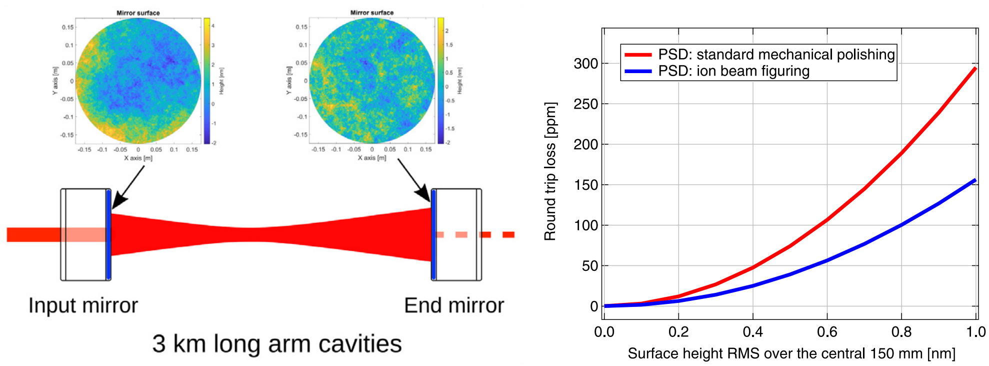

Fig. 1. Principle of the simulation (left): a Fabry–Perot cavity is simulated with realistic surface of the mirrors. The surface of the mirrors, excluding the curvature, is shown as 2D color plot of the surface height above the cavity sketch. Result of the simulation (right): Round Trip Loss (RTL) as a function of the surface flatness over the central part.

loss is also increased.[1] That is expected as the mirror surface defects are larger, more light is scattered and so lost. For this plot, two different kind of surfaces are tested, manufactured with two different techniques: standard mechanical polishing and ion beam figuring [13]. The two different techniques result in surface defects with different spatial frequencies (different PSD of the surface [14]), and hence different amount of light scattered even if the flatness in RMS is the same.

It can be remarked that, the round trip loss in the cavity is independent of the input beam shape for a high finesse cavity when there is no resonance degeneracy between the fundamental mode of interest and higher order optical modes. Also to be complete, the flatness is not the only source of light losses, as the surface (high spatial frequency) roughness or coating optical absorption must also be included in the light loss budget.

4. Impact

OSCAR was essential during the design and commissioning of the Advanced Virgo gravitational wave detector. Several points where this software made an impact could be highlighted:

- OSCAR was used to defined the flatness requirement for the most critical optics, in particular the mirrors of the long arm cavities. Similar to the example shown in Section 3, the cavity round trip loss was calculated for different levels of surface defects and it was demonstrated that to achieve a total round trip loss of less than 75 ppm, the RMS of the flatness must be less than 0.5 nm, on the central diameter of 150 mm.
- Still in the design phase of Advanced Virgo, OSCAR simulation of the full interferometer demonstrated the absolute necessity to be able to correct in situ the distortions in the power recycling cavity. It was shown that the errors of radii of curvature of the mirrors due to polishing tolerances have disastrous consequences on the light used to control the interferometer (the sideband fields). So stringent specifications were set for the thermal compensation system which must be able to correct such distortions.
- During the large optics production for Advanced Virgo, all the results from the optical characterization were progressively incorporated in the simulation. It was shown that an optic used in transmission (a compensation plate) was presenting a very large wavefront distortion impacting the performance of the detector. It was then decided to use a spare of better quality, which is now installed on the site.

[1] This is an academic example, as mechanical polishing cannot reach flatness below 2 nm RMS over a large diameter.

OSCAR is still currently used for the commissioning and monitoring of Advanced Virgo optical properties. As the input laser power is progressively increased, the uniform and non-uniform thermal effects are included and the simulations help to find the best operating point.

In the gravitational wave community but beyond Advanced Virgo, OSCAR was also essential to simulate:

- the losses inside long filtering cavities used to manipulate the quantum properties of light [4,15]
- the damping of parametric instabilities using tuning of the radius curvature of the mirrors [16,17]
- for the next generation of detectors, how the implementation of higher order modes could be impacted by mirror surface imperfections [18,19]

Outside the field of very large laser interferometers, OSCAR has also been proven to be useful to simulate mm-scale Fabry–Perot cavities and the degeneracy with higher optical modes [20,21].

5. Conclusions

OSCAR is a reliable and versatile MATLAB package to simulate realistic Fabry–Perot optical cavities. The main driver for its development was the design and commissioning of the laser gravitational wave detector Advanced Virgo and it has since been extensively used within this collaboration. OSCAR has also served other research area working with high finesse cavities. Since its first public release in 2008, the software has been downloaded more than 4000 times.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.softx.2020.100587.

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