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Thermal effects and their compensation in Advanced Virgo

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Abstract. Thermal effects in the test masses of the gravitational waves interferometric detectors may result in a strong limitation to their operation and sensitivity. Already in initial LIGO and Virgo, these effects have been observed and required the installation of dedicated compensation systems. Based on CO₂ laser projectors, the thermal compensators heat the peripheral of the input test masses to reduce the lensing effect. In advanced detectors, the power circulating in the interferometer will increase, thus making thermal effects more relevant. In this paper, the concept of the compensation system for Advanced Virgo is described.

1. Introduction

In an interferometric GW detector, the amount of allowable circulating probe power is limited by the nonzero optical absorption in the substrate and coatings of the test masses. The dependence from temperature of the refraction index and the thermal expansion coefficient of optical materials ensure that temperature gradients, induced by the absorption of the Gaussian-profiled probe light, will result in nonuniform optical path length distortions, which will affect both the controllability and length sensitivity of the instrument [1, 2].

Thermal effects have already been observed in Virgo [3] and LIGO [4] and required the installation of Thermal Compensation Systems [5] (TCS). Advanced detectors [6, 7] will be characterized by a higher circulating power (from 20 kW in the initial interferometers to 700 kW in the second generation detectors) and thermal effects will become even more relevant.

Absorption of optical power in the test mass of GW interferometric detectors predominantly occurs in the high reflectivity coating. The absorbed power is converted into heat, producing a gradient of temperature inside the substrate. Two different effects originate from the heating of the test mass:

- nonuniform optical path length distortions (thermo-optic effect, also termed thermal lensing) mainly due to the temperature dependency of the index of refraction.
- change of the profile of the high reflective surface, due to thermal expansion (thermo-elastic deformation) in both input and end test masses.

In the case of first generation detectors, the latter effect is negligible (as shown in figure 2): the main thermal effect is the thermal lensing, affecting the Power Recycling Cavity (PRC). In presence of this effect, which changes the cavity mode, the input laser no longer matches the

PRC and the coupling coefficient between the laser TEM_{00} and the cavity TEM_{00} becomes less than one. This leads to a decrease of the recycling cavity gain and thus in the sidebands power. Since sidebands are used to keep the interferometer locked, thermal lensing affects the possibility to operate the detector at high input powers. The ultimate consequence is a loss of signal-to-noise ratio at high frequencies due to the increase of shot noise. It is possible to compare the amount of thermal effects in Virgo and Advanced Virgo. The computations have been made for 1 ppm coating absorption, that leads to a total absorbed power of about 20 mW and 600 mW for Virgo (25 W input power) and Advanced Virgo (125 W input power) respectively. In figure 1, the comparison between the optical path length increase is shown. We can see that the optical path length increase expected in Advanced Virgo at a distance of 5 cm (one Gaussian beam radius) is about 470 nm, while it is about 30 nm in Virgo, at the same distance. Figure 2 compares the thermo-elastic deformations of the high reflectivity face of the Fabry-Perot cavity mirrors for the two detectors.

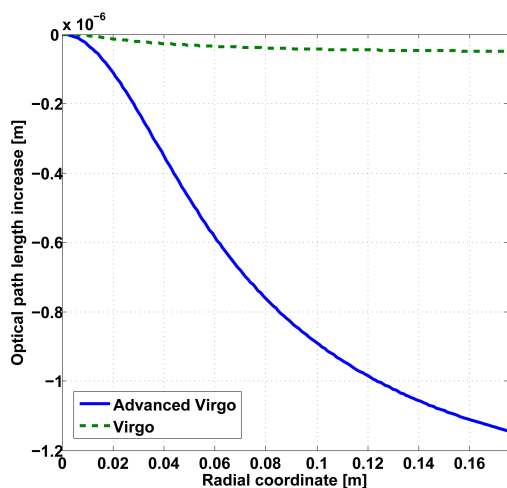


Figure 1. Optical path length increase in Advanced Virgo (blue) and Virgo (green) ITM due to coating absorption.

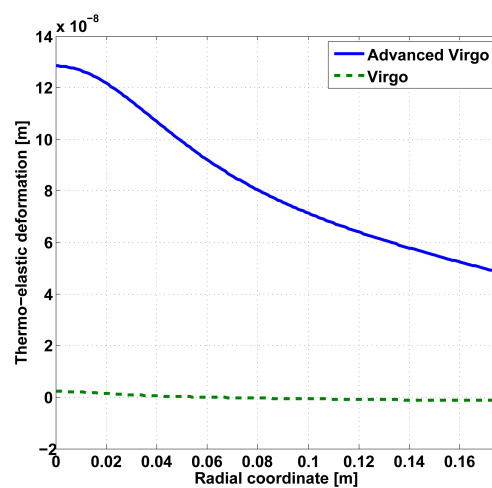


Figure 2. Thermo-elastic deformation of the HR surface in Advanced Virgo (blue) and Virgo (green).

As a consequence, in second generation detectors, besides the thermal lensing, the thermo-elastic deformation will also be relevant, due to the much higher circulating power in the Fabry-Perot cavities. Thermal expansion will change the profile of the high reflectivity surface: a bump will raise in the center of the test mass faces, making their surface profile non-spherical and the Radius of Curvature (RoC) will increase by about 44 m. The cavity will become less concentric, and the spot sizes at the mirrors will shrink. To maintain the arm cavity mode structure, it will be then necessary to control the radii of curvature of all test masses within ± 2 m from the initial RoC.

In advanced detectors, TCS will need to compensate for both effects, acting on both input and end test masses.

2. Thermal compensation in Advanced Virgo

Thermal compensation in Advanced Virgo needs to cope with the increase of circulating power in the optical cavities and with the improvement of the detector sensitivity. The main consequence of the first point is that, as already stated above, TCS will also need to correct the RoC increase in all test masses. The outcome of the sensitivity improvement is that it is no more possible

to shine the input test masses directly with the CO₂ laser, as it is done in initial detectors [5]. The displacement noise introduced by the intensity fluctuations of the CO₂ laser would spoil the detector sensitivity in the frequency band 50 Hz - 100 Hz. To make TCS compliant with Advanced Virgo noise requirement, the relative intensity noise of the CO₂ laser should be reduced to the level of $10^{-8}/\sqrt{\text{Hz}}$ at 50 Hz, one order of magnitude below what it is possible to achieve with the present technology. This implies the need of an additional transmissive optic, named Compensation Plate (CP) to act on with the compensating beam. The CPs are placed in the recycling cavity, where the noise requirements are less stringent by a factor of $\pi/2F$ than in the Fabry-Perot cavity.

The CPs will be shined with the appropriate heating pattern to compensate distortions in the recycling cavity, while to control the radii of curvature of all the test masses, ring-shaped resistive heaters (RH) will be used. This scheme also allows to reduce the coupling between the two degrees of freedom (lensing and RoC), so to have a control matrix as diagonal as possible.

Following the considerations above, the conceptual actuation scheme of the compensation system foreseen for advanced detectors is shown in figure 3. A pictorial view of the input payload, with the ITM, RH and CP, is shown in figure 4.

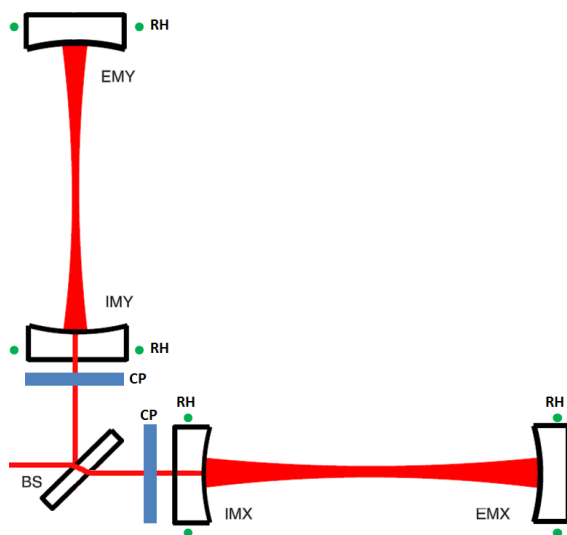


Figure 3. Actuation scheme of the Advanced Virgo TCS: blue rectangles represent the CPs while the green dots around the test masses are the ring heaters.

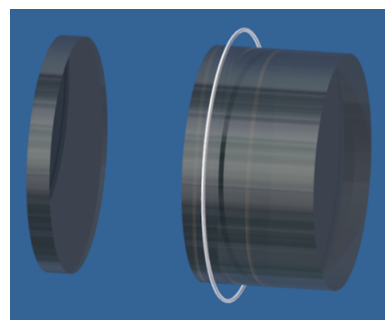


Figure 4. Picture of the input payload, comprising the ITM with the RH and the CP.

The thickness of the CP has been optimized by minimizing the heat escaping from its barrel and taking into account the need to accumulate enough optical path length. The distance between CP and ITM is 20 cm, this allows to minimize the radiative coupling between the two optics. In fact, the heated CP radiates heat towards the test mass. The heating of the TM is uniform, but since the barrel of the input mirror radiates away a part of the heat, a radial temperature gradient is established. This gives rise to an increase of optical path length that adds to the thermal lensing.

The position of the RH along the barrel of the TM is such as to maximize its efficiency (see section 3 for more details).

A useful way to picture the effect of a thermal distortions is the fractional power scattered

out from the TEM₀₀ mode [8], termed "coupling losses" L :

$$L = 1 - A^* A, \quad (1)$$

where

$$A = \frac{\langle E_0 | E \rangle}{\langle E_0 | E_0 \rangle} = \frac{\langle E_0 | e^{i\phi(x,y)} | E_0 \rangle}{\langle E_0 | E_0 \rangle} = 2\pi \int_0^{r_{ITM}} e^{i\phi(r)} |E_0(r)|^2 r dr. \quad (2)$$

E_0 represents the undisturbed cavity field before being subjected to the phase distortion $\phi(x, y) = 2\pi/\lambda \cdot OPL(r)$, E is the distorted field and $OPL(r)$ is the optical path length in the substrate. The last equality in equation 2 holds if cylindrical symmetry is assumed. A phase distortion in a cavity acts to scatter power out of the fundamental mode, and thus out of the cavity, and can be viewed as a simple coupling loss term.

With no thermal compensation, in Advanced Virgo, the coupling losses would amount to approximately $5 \cdot 10^5$ ppm. For a comparison, in Virgo, the losses due to thermal lensing are of the order of 10^4 ppm. The Advanced Virgo TCS needs to reduce to coupling losses at least by a factor of 10^3 (corresponding, roughly speaking, to a maximum peak-to-valley residual optical path length increase of about 8 nm) to allow the correct operation of the detector at design sensitivity.

Current interferometers use axicon-based optical projectors to convert a CO₂ laser Gaussian beam into an annular beam [5]. This heating pattern is not adequate for the advanced detectors, since it can reduce the residual coupling losses only by a factor of 10^2 , while at least a factor of 10^3 is required. Studies on the optimization of the heating pattern, made with Finite Element Model (FEM), have shown that it is possible to reduce the residual coupling losses to about 6 ppm, thus leading to a reduction factor of about 10^5 , with about 18 W of CO₂ power shined on the compensation plate.

Different methods for the generation of the optimal heating pattern are being investigated.

3. Test masses RoCs tuning

The need to control the radius of curvature of the test mass in GW interferometric detectors has already been faced in the past: the GEO detector [9] used a ring heater to change the RoC of one of the two test masses [10]. The GEO RH is placed on the back of the mirror, radiatively coupled with the optic.

Compensation and control of the test mass high reflectivity (HR) surfaces will be accomplished in Advanced Virgo with the same technique. The TCS baseline design considers four ring heaters, one around each test mass. The input mirror RH also provides limited compensation of thermo-optic effect in the recycling cavities. Unlike the GEO heater, the Advanced Virgo RH will be equipped with a reflecting shield to maximize the amount of power reaching the test mass.

The efficiency of the ring heater to change the RoC also depends on the position of the RH along the barrel of the test mass. In order to study the RH dynamics, an ANSYS coupled thermal-structural FEM has been developed, modeling a radiating ring placed around the barrel of the TM at different distances from the HR surface. At each position, the model calculates the RoC of the TM as a function of the RH power. It is found that, for a 20 cm thick test mass, the power required to recover the cold state RoC (1420 m) is minimized when the position of the RH is at about 18 cm from the TM HR surface.

The engineered design of the ring heater for Advanced Virgo is in progress, taking also into account two important constraints: high temperature operation and UHV compatibility. Moreover, since the last stage of the suspension system will use coil-magnet actuators for the control of the mirrors, it is necessary to avoid any stray magnetic field generated by the ring heater. In fact, the coupling of the RH magnetic field to the actuators would introduce displacement noise in the detector, limiting its sensitivity.

4. Measurement of thermal effects

The aberrations induced by absorptions will be sensed by several complementary techniques. The amplitude of the lensing will appear in some ITF channels, such as the power stored in the radio frequency sidebands. These are scalar quantities that can only give a measurement of the amount of power scattered into higher order modes. Phase cameras [11] will sense the intensity distribution and phase of the fields in the recycling cavity. However, control of thermal effects using error signals coming from such detectors has not been demonstrated yet.

Therefore, each optic with a significant thermal load will be independently monitored. The HR face of each test mass will be monitored in reflection for deformation. The input test mass/compensation plate phase profile will be monitored on reflection on-axis from the recycling cavity side. The TCS control loop will then use a blend of all the signals from the different channels, as shown in figure 5.

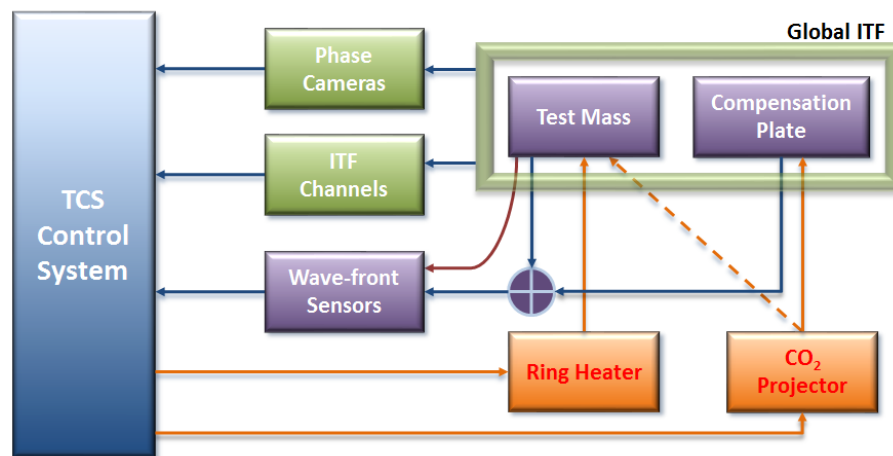


Figure 5. Conceptual scheme of the TCS control loop.

The ITM-CP phase profile dedicated sensors consist of a Hartmann Wavefront Sensor (HWS), and a probe beam whose wavefront contains the thermal aberration information to be sensed. The working principle of the device is shown in figure 6.

The Hartmann sensor selected for Advanced Virgo is that already developed and characterized on test bench experiments and in the Gingin High Optical Power Test Facility for the measurement of wavefront distortion [12].

This sensor [13] has been demonstrated to have a shot-to-shot reproducibility of $\lambda/1450$ at 820 nm, which can be improved to $\lambda/15500$ with averaging, and with an overall accuracy of $\lambda/6800$.

Due to the requirement on the maximum residual optical path length peak-to-valley of 8 nm, the precision of the wavefront sensing must be of the order of 0.8 nm, corresponding to $\lambda/1000$ @ 800 nm (to be compared with the measured noise level of $\lambda/15500$). This indicates that the selected Hartmann sensor is both sufficiently sensitive and accurate for the measurements of absorption-induced wavefront distortions in advanced GW interferometers. A prototype of the sensor is in the Tor Vergata Laboratories for further characterization and integration into the test facility for the development of the Advanced Virgo Thermal Compensation System.

5. Conclusions

Advanced Virgo aims to achieve a factor of 10 sensitivity improvement over Virgo and requires pushing the limits of technology on several frontiers. Thermal Compensation System will play a

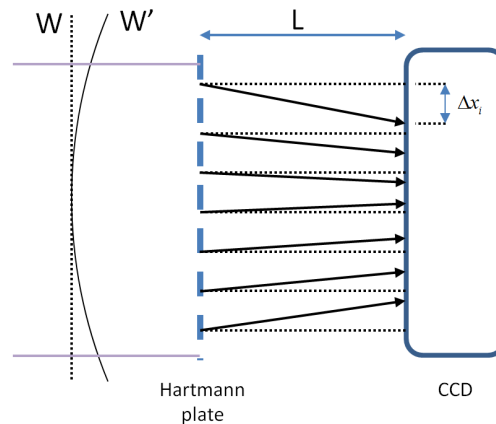


Figure 6. Working principle of the Hartmann Wavefront Sensor: an aberrated wavefront W' is incident on a Hartmann plate. The resulting rays propagate a distance L , normal to the wavefront, and are incident on a CCD. The new spot position, x'_i , is measured and compared to a reference spot positions, x_i , determined using a non-aberrated wavefront W . The wavefront gradient in the i^{th} position is given by $\frac{\partial \Delta W}{\partial x} = \frac{\Delta x_i}{L}$.

crucial role in correcting optical path length distortions in the recycling cavities and in allowing the detector to reach its design sensitivity. High precision beam shaping of the CO₂ laser beam and high sensitivity wavefront sensors will be implemented to face this challenge, moving TCS towards adaptive optical systems.

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