Status of the Monolithic Suspensions for Advanced Virgo

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Abstract.
Successfully implemented in GEO and Virgo+, the monolithic suspensions are one of the most important upgrades in the second generation of gravitational wave interferometric detectors, including Advanced LIGO (aLIGO) and Advanced Virgo (AdV). Characterized by a very low thermal noise, monolithic suspensions are essential for improving the interferometers sensitivity at low frequencies (10-100Hz). In Advanced Virgo their installation was delayed because of a contamination problem in the vacuum system: dust produced by scroll pumps was injected in the main vacuum chambers during the venting processes, damaging the fibers and ultimately causing their repeated failure. The effort to explain and resolve this issue was useful to further confirm the suspensions’ reliability and our control on the production process. Moreover, we developed and implemented new tools and procedures to certify each part of the monolithic suspensions. In the meanwhile, in order to join aLIGO during its second Observation Run (O2), a temporary steel suspension was implemented, based on the initial Virgo design. That solution allowed us to contribute to the first three-detector observation of a gravitational wave (GW)\textsuperscript{(1)}, and to the first observation of a coalescing neutron star binary (\textsuperscript{2}). In the near future the monolithic suspensions will be reinstalled along with additional upgrades of Virgo.

1. Introduction
In AdV, the input and end mirrors are all suspended from a steel marionette which, in turn, is suspended to the last filter of the superattenuator, called \textit{filter7}. The marionette and the mirror form a double-pendulum system, surrounded by a rigid structure called \textit{cage}, attached to the \textit{filter7} \textsuperscript{3}. The assembly of the marionette-mirror pendulum system with the cage and associated auxiliary optics and actuators is referred to as the \textit{payload}. The payload is conceived for the compensation of residual seismic motion and for acting on the test masses working point in the interferometer. A schematic view of AdV payload is shown in Fig\textsuperscript{4}, whereas a full description is available in the paper \textsuperscript{4}. In this final stage two silica interface pieces (ears) are bonded to the mirror using the silicate bonding technique \textsuperscript{5}. Four silica fibers are glued under those ears and on the top of the marionette with the same technique (Fig\textsuperscript{1}), providing better seismic isolation and lower thermal noise \textsuperscript{6, 7}. In the following, we shall deal mainly with the development and implementation of our monolithic suspensions in AdV.
2. Advanced Virgo Monolithic suspensions

The monolithic suspensions were developed keeping into account the mechanical constrains of the whole payload, with the aim of reducing the suspension thermal noise and increasing the reliability of the suspensions themselves [6, 3]. The installation procedure was defined by performing dozens of simulations and tests on each part of the suspension system [3]. Moreover, a recovery strategy was developed and tested using dummy parts: a brief description is available in the Recovery strategy paragraph of present paper.

2.1. Fibers design and production

The test masses, having a mass of 42 kg, are suspended from the marionette with the monolithic suspension system. The design of the monolithic suspensions is optimised taking into account the issues related to the thermal noise reduction, the mechanical frequencies and the stresses in the silica elements as well as the mounting, handling and recovery procedures. An extensive finite element simulation was used for this purpose (see [8] for the anchors and ears).
The fiber profile is shown in figure 2. This dumbbell shaped geometry strongly reduces the thermoelastic contribution to the thermal noise [9]. Fibers are produced starting from a rod, welded to fused silica anchors (Fig. 5), using a CO$_2$ laser pulling machine [3, 10]. All the fiber parameters are carefully measured during this process, such as the fiber length under nominal load, in order to meet the requirements on mirror positioning and the bending length [11, 12]. Statistics on about 100 fiber samples measured a breaking load of about 40 kg (~ 3 GPa), i.e. four times the working load. Validation of each fiber is done applying briefly a load of 20 kg (~ 1.5 GPa) load.

**Figure 5.** Dissipation and stress simulation to optimize the silica parts and to reduce their thermal noise [8].

**Figure 6.** AdV sensitivity curve.

3. Monolithic issue
Successfully implemented in Virgo+ [10], the monolithic suspensions failed in AdV during the installation phase. A summary of the breakages is shown in Tab. 1.

| Mirror failed | Failure date     | Time in air | Time in vacuum |
|---------------|-----------------|-------------|----------------|
| WI            | 18 November 2015| 5 months    | 7 days         |
| NI            | 18 December 2015| 4.5 months  | 5 days         |
| NI dummy      | 1 March 2016    | 1 week      | 5 days         |
| WI dummy      | 26 April 2016   | 1 week      | 11 days        |
| WI            | 25 June 2016    | 1 month     | 1 month        |
| WE            | 28 June 2016    | 7 months    | 18 days        |
| NE            | 13 October 2016 | 6 months    | 4 months       |

**Table 1.** Advanced Virgo monolithic suspensions failures summary

After the first failure, several possible reasons were analysed in laboratories of Virgo and of the LIGO Scientific Collaboration [13]. All the analyses didn’t show any significant evidence of a problem, however there were few indications that the breakages of the fibers were not the first cause of the suspension failures but just the result of something else.

On October 13th, 2016, the NE payload failed during a venting operation. It had been in air for 6 months and in vacuum for 4 months (Tab. 1). Starting from this event it was finally realized that there was a contamination problem in the pumping system. This hypothesis was confirmed by the fact that the failures always started from the fibers closer to the venting side. Moreover, a report by an external company (SSV laboratory), issued just at the time of the NE event, confirmed that all the failures had started from the thin part of the fibers: it became evident that something from the venting pipe was hitting the fibers.
4. Vacuum issue

After the failure of the NE payload, clearly related to a venting operation, two facilities were developed to test both a single fiber and an entire payload. The two setups replicated as much as possible the standard vacuum system of a Virgo vacuum chamber (the *tower*) and were used to test the venting procedure. With the single fiber setup was possible to reproduce, for the first time, a failure a few seconds after the venting of the chamber. The test was repeated three times with the same result, but with different failure times. The dust collected from these tests and from the towers after the failures was analyzed by optical microscope, SEM, IR and Raman spectroscopy. All these tests confirmed that the contamination was due to particles coming out from the scroll pumps. Indeed, in the standard vacuum configuration the scroll pumps and the venting system shared the same pipe: the failures were due to the dust produced by the scroll pumps, stored in the pipe and then injected in the main vacuum chamber during the venting process, hitting the fibers.

An analytical model developed by the collaboration [14] shows that, during a venting, air shock waves can accelerate 50 - 100 micron particles to speeds up to 20-50 m/s for a 2 m travel (Fig.7). The kinetic energy of these particles is well in the range necessary to cause the breaking of a fiber.

![Figure 7. Analytical model of the speed of the dust in vacuum.](image1)

![Figure 8. Velocimeter optical scheme](image2)

To verify this hypothesis, an interferometric velocimeter was developed and used to measure the velocities of particles coming out of a scroll pump (Fig.8): velocities of the order of 1 m/s were observed. An interesting addendum was proposed by the study of the effects of an electrostatic field: it increases the effective cross section of the fibers for incoming particles; on charged surfaces the dust is 5 times more w.r.t. the not charged ones.

It is worth to remark that during the Virgo+ runs, the vacuum contamination problems were probably avoided because pots were in place that covered about half of the section of the tubes used for venting and pumping. Moreover, in Virgo+ scroll pumps were used with a reduced duty cycle.

After the identification of this problem, new features were discussed with external experts of clean vacuum applications from CERN, LASA and DESY. The main upgrades that will be implemented concern the use of new *clean* pumps with longer pipes and particle filters; the design of a separated venting circuit; the installation of an inner shield in front of the venting pipe to stop any residual contaminants; the use of fiber guards on the payload itself [4]. Moreover, we shall perform a special cleaning procedures of all tower chambers to remove any residuals from the past ventings with scroll pumps and from the explosion of the silica fibers, before each new integration of a monolithic payload.
5. Temporary solution for O2: steel suspensions

To proceed with the commissioning of the detector, the Virgo Collaboration asked for a temporary solution that allowed to test the different sub-systems in order to join O2 in coincidence with LIGO. The faster and more reliable solution was the implementation of steel suspensions such as those installed during the first Virgo setup [15]. To suspend the main optics, two steel wires were used, forming a cradle on which the mirror was to be housed. The wires, with a diameter of 0.3 mm, were thermally treated for one week at 150 °C with their nominal load, to release their internal stress and to reduce the creep noise. To connect the wires to the steering system, four steel clamps were screwed on the marionette while four silica stand-offs were glued on the lateral flats of the mirrors, in order to reduce the friction between the wires and the mirror barrel.

The expected sensitivity curve in this configuration is shown in Fig.6 [16]. This solution made possible the first three-detectors observation of gravitational waves from a binary black hole coalescence (GW170814) [1] and the first multi-messenger observation of a binary neutron star merger (GW170817) [2].

6. Monolithic suspensions upgrades

To improve the AdV sensitivity, the monolithic suspensions will be reinstalled for the O3 observation run in coincidence with LIGO interferometers (Fig.6). Although all the analyses have shown that there was nothing wrong with the current design of monolithic suspensions, the knowledge acquired during the revision process was useful to confirm the suspensions reliability. In addition, an optimized procedure for fiber production was developed, a new anchor design was devised, new tools to certify each part of the suspensions were implemented, a better recovery and reinstallation strategy was defined.

6.1. Fiber upgrades

Even though there was no evidence of any weakness in the fiber production process, the whole procedure has been revised and optimized. The welding is now obtained with a longer laser exposure time, at lower power according to Glasgow group suggestion. A digital camera ensures a good control of the welding process, and an optical scan system with a digital microscope is used to search for any defect. Furthermore, a new drawing for the anchors was implemented using a thicker T-shape design with a smoother groove around the cone. The anchors were treated with a flame polishing and successive annealing to reduce the cracks induced by the machining. With this new design and procedures, two breaking stress tests were performed and the fiber/anchors system reached respectively 160kg and 130kg before breaking, 10 times greater than the nominal load. The tests were recorded by a high speed camera (about 15000 fps) to identify the origin and the dynamics of the breakages.

Furthermore, in the test payload facility at the Virgo site some studies are in progress, in order to reduce the suspension thermal noise. In particular the use of a new generation shadow-meter [17] will be very useful to study the dynamics of the fibers thermal peaks and the possibility to damp them.

6.2. Recovery strategy

The payload will be removed from the tower, placed in a clean room and dismounted, and the mirror will be put in its transportation box and stored under a class 1 clean hood. According to the past experiences, to clean the mirror it is sufficient to apply the first contact; as usual, it will be peeled away just before closing the flange of the tower for pumping down its vacuum chamber. After the application of the first contact, it will be possible to remove safely the spacers, used for the steel wire suspensions, and to clean the ears from any residual of the anchors, left from the suspension failures. Holes and scratches due to the failures will not be cured: indeed our FEM
simulations show that if the thickness of the silicate bonding is greater than 8.5 µm, its thermal noise starts to dominate on the overall thermal noise of the mirrors. Hence, the recommendation is to clean the ear from any residuals and to avoid any glue in the holes.

At the end of this procedure, the mirror will be ready to be suspended in the payload. The complete reinstallation procedure will last three weeks per payload. Before starting the real reassembling of the monolithic payloads, a full scale test will be performed by integrating the test payload, with real fibers and a dummy mirror, inside the NE tower. The dummy payload will be equipped with the new fiber guards and with supports holding wafers for contamination control [4]: a dedicated optical scan for wafer analysis was developed to certify the vacuum quality. A full description of all the procedures is available in [18].

7. Conclusion
Successfully implemented in Virgo+, the installation of our monolithic suspensions in Advanced Virgo was delayed because of a series of failures that happened under vacuum after days or months from the integration of the payloads. These problems forced us to suspend the test mass mirrors with steel wires, so to be able to run in coincidence with aLIGO in O2, while, at the same time, performing tests and studies on the failures. After about one year of investigations, finally we found that some particles, coming from the pumping system, were injected into the towers during the venting cycles, and projected onto the fibers. The amount, size and kind of particles varied in an unpredictable way over time and from one tower to the other, resulting in different kinds of damages to the fibers and, consequently, in different times of failure. This scenario is confirmed by all tests, analysis and simulations carried out up to now.

The main message coming from these results is that there was nothing wrong with the current design of our monolithic suspensions. In any case, the many investigations carried out since the first suspension failure in November 2015 resulted in a careful revision of all our procedures and in further refinements of the design and testing procedures, confirming the reliability of our monolithic suspensions and improving our control on the production process.

A positive results of this long quest for finding a solution to the monolithic suspensions failures was the development of closer collaborations with other monolithic suspensions group in the LIGO Scientific Collaboration. In particular, we have strengthened our collaboration with the Glasgow Group, whose help has been precious during these investigations.

By the end of this year (2017), we shall start to integrate again monolithic suspension in Advanced Virgo so to join aLIGO with an enhanced sensitivity in O3.

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