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Redesign of an auto-levelling base for submarine seismic sensor

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Abstract

The OBS (acronym of Ocean Bottom Seismometer) is a system to monitor the submarine seismic activity. To properly work, an OBS system needs a suitable auto-levelling base to maintain a fixed (horizontal) position during the measurement phases.
In this work a new auto-levelling base for submarine seismic sensors has been designed. During the redesign process a preliminary phase of analysis of the state of art has been made. Afterwards, the technological solutions chosen by different manufactures have been critically analysed, and a full description of their functionalities, working principles and system performances has been carried out. Later, some innovative concepts have been proposed. Among these ones, the most interesting are the auto-levelling bases with spherical joint, based on: air bearings, ball bearings and magnetic levitation systems.
The concept scoring method has been used to identify. as best concept, the auto-levelling base with spherical joint and air bearings system.
Successively, the chosen concept has been implemented: the technical working principles have been studied to choose the best solutions in terms of dimensions, shapes, materials of all base components. A full parametric CAD model of the auto-levelling base has been also created.
The new designed base, by using a very innovative auto-levelling system, allows to obtain very good results as regards the accuracy of positioning, so ensuring a remarkable improvement of the performances of the ocean bottom seismometers.

1 Introduction

It is well known that in countries surrounded by seas, like Italy, the observation of seismic and volcanic processes is necessarily restricted without measurement stations placed under the sea.

Many of the earthquakes recorded by the land seismic networks, in fact, are from the sea but only few of them, whose magnitude is very high, are properly located using exclusively the seismic data coming from the land stations.

In this way, a great part of seismic events generated on the submarine earth crust cannot be correctly measured, so important data for the study of the seismic activity and the geodynamics cannot be acquired.

OBS/H (Ocean Bottom Seismometer *with Hydrophone*) stations are submarine systems used to detect the earthquakes in proximity of submarine faults and volcanoes.

OBS/H stations allow to collect seismic data that are very useful for the localization of events, the study of the seismic activity and the geodynamics of the crust in the offshore areas. These stations, moreover, could be effectively connected to a global real-time system able to warn about the risk of tsunami events.

For all this reasons, the OBS/H stations represent, nowadays, ones of the most important seismic data measurement tools.

Also basing on these observations, the so-called "OBS/H project" was planned and developed at the *National Institute of Geophysics and Volcanology* (INGV) of Gibilmanna (Cefalù-Italy) in 2005. In this context, moreover, a laboratory specialized in the design, production and management of OBS/H stations (the OBS LAB), has been founded at the INGV of Gibilmanna [1].

The purpose of the presented work is the conceptual redesign of a self-levelling base to be used in an OBS station prototype made at the OBS LAB. In particular, a new self-levelling base, suitable for the most innovative seismic sensor nowadays on the market (e.g. *Nanometrics Trillium Compact*), has been redesigned, starting from an OBS/H prototype by INGV.

2 The OBS/H prototype by INGV

The OBS/H prototype (fig.1) developed at the OBS Laboratory consists of the following main components:

- a seismometer Nanometrics Trillium 120p [9];
- a Differential Pressure Gauge (DPG), a differential pressure sensor with a 500 seconds bandwidth at 2 Hz frequency, suitable to detect the propagation of tsunami waves;
- a digitizer SEND Geolon-MLS with 4 channels and maximum sampling frequency equal to 200 Hz;
- the self-levelling base.


Figure 1 OBS/H station.

The seismic sensor is fixed on the self-levelling base that is fastened to a "bentosphere" (a floating housing) in glass of which diameter is 17 inches. The self-levelling base is used to impose and to keep the correct positioning of the sensor along the horizontal direction; this represents a necessary geometric condition for its correct working and accurate measurement of the seismic signals [2] [3].

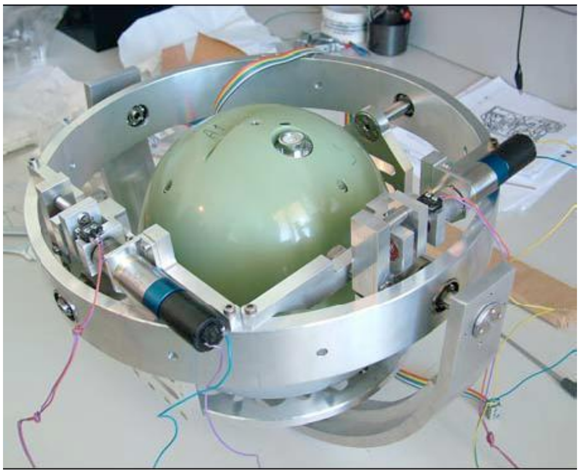
Figure 2 INGV self-levelling base

The digitizer and the battery packs are placed in the lower part of the OBS/H, inside a canister in ERGAL.

The measurement of the seismic and acoustic signals, performed by the seismometer and the DPG, starts as soon as the OBS station reaches the sea floor by free fall. This data acquisition phase goes on for a time depending on the used sensors and the range of the battery packs.

At the end of the measurement phase, the acquired data (stored in the data logger) can be downloaded and post-processed for further analyses.

Recent research activities are related to the real time monitoring of the measured seismic signals, in order to get, as soon as possible, any information on possible earthquake or tsunami events.

2.1 The INGV self-levelling base

The working principle of the INGV self-levelling base (fig. 2-3) is based on the passive gimbal (universal) joint. It has a locking system that through two radial clamps, activated by electric motors, blocks the rotation axes when the right position is reached (fig. 4).

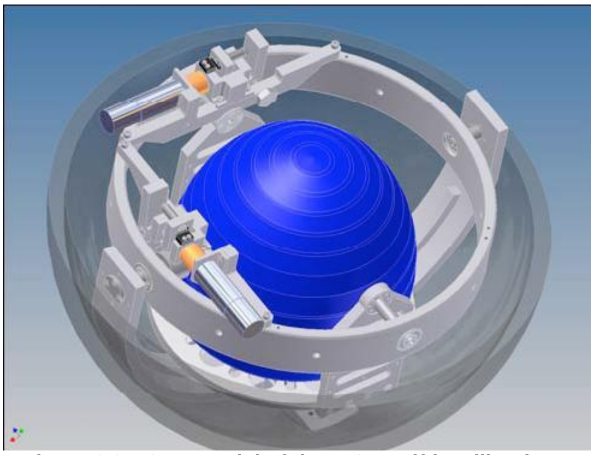
Figure 3 3D CAD model of the INGV self-levelling base

The self-levelling base is welded to the bottom of the glass "bentosphere" using a resin having a high stiffness value.

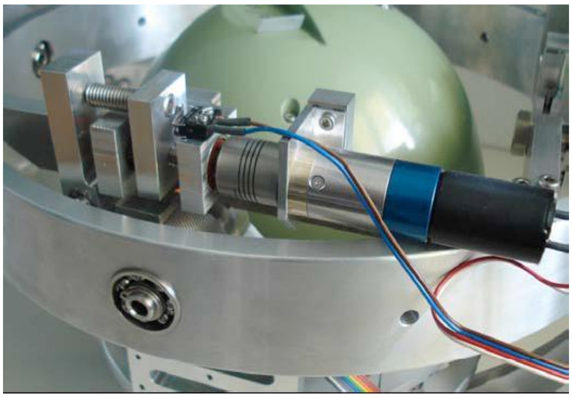
Figure 4 INGV self-levelling base: blocking system details

As pointed out during the first long-time OBS campaign in the Ionian sea, carried out by INGV [2], different open issues must be solved to improve the performances of the INGV auto-levelling prototype. In particular, the main problems are related to the levelling accuracy and the natural frequencies of the structure. As regards the first problem, the measured data showed that all the sensors have worked for a long time period (more than one week) with an about ± 0.1° misalignment (inclination value referred to the horizontal plane). Even if the maximum acceptable value is ± 0.2°, because out of this range the sensor could not record any earthquake signal, more is the misalignment more energy is absorbed by the seismic sensor. The necessary energy can even raise from 600 mW up to 2.5 W, depending on the misalignment value, so making the batteries flat very soon and reducing the measurement time. Concerning the problem of the natural frequencies, it has been also noted, through experimental tests performed in laboratory, that the structure containing the seismometer filters many signal frequencies lower than 50 Hz, moreover its natural frequency is around 8 Hz. All these characteristics alter the level and the spectrum of the recorded signals. A solution to that problem could be, almost certainly, to reduce the size of the whole structure. Such a solution could allow, moreover, to use smaller seismic sensors with reduced power consumption (lower than 160mW).

It has been also noted that the frame of the INGV base is extremely weak and causes distortion and/or damping of seismic signals. That is mainly due to the used joining solutions. The base, in fact, is welded to the bentosphere only through its bottom part; that generates a tuning fork effect that, because of the structure resonance, does not allow to detect very important (low frequency) signals.

3 State of the art

The first research activities addressed to the setting up of OBS prototypes were developed in the early 60's. One of the first OBS station prototypes was designed and built at the Columbia University [4].

In that case, the problem of the seismic sensor levelling was, for the first time, solved using the gimbal joint. The rotations of the two axes were managed by an electronic card equipped with a level feedback sensor (horizontal pendulum).

Still nowadays, the gimbal is the most diffused working principle used in the self-levelling bases, both for active and passive-based levelling systems. The first ones reach the working (horizontal) position through actuators (little electric motors), the second, instead, level the base exploiting the gravitational forces, through the use of masses positioned on the bottom part of the seismometer base. Even if they have low energy consumptions, the passive levelling systems amplify the problems concerning the influence of the stiffness of the cables (connected to the seismometer) that can affect the right positioning of the base. The cables stiffness of the cables, in fact, could generate a tangential force that does not allow the correct levelling of the base. For this reason, to obtain good alignment values of the base it needs materials and technical solutions minimizing the stiffness of the cables.

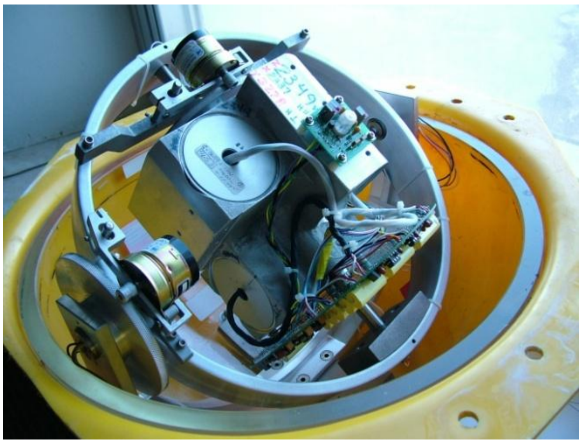

Figure 5 Active self-levelling base developed at the Columbia University

An update model of the previous OBS prototype, also developed at the Columbia University [4], is shown in figure 5. It uses an active levelling system whose rotations are applied by means of two electric motors connected to the moving parts of the gimbal joint. Each motor has a rotating pin mated with a knurled disk (Fig. 5) that is linked to the fixed parts of base; that allows the right positioning of the levelling system.

In 1993 Timothy et al. [5] designed, at the University of Cambridge, a new OBS station. In this case, the levelling base, even if based on the (well-known) passive gimbal working principle, uses a new technical solution for the locking of the system. The self-levelling base, in fact, is immersed in a viscous fluid, properly designed, so as to ensure the locking but also the detection of seismic signals in useful frequency ranges.

In 2005, Thwaites and al. [6], using the principle of the gimbal, designed and developed an OBS prototype (fig. 6) based on a passive levelling base. An innovative aspect of this prototype is the locking system. This OBS, in fact, uses a new locking system (Fig. 6) composed of two disks. These ones are made of frictional material and are linked to the moving parts. Through a screw-based mechanism (fig.7), driven by an electric motor, the two disks are pressed each other so ensuring the locking of the system [6].

Figure 6 Thwaites self-levelling base with disks locking system

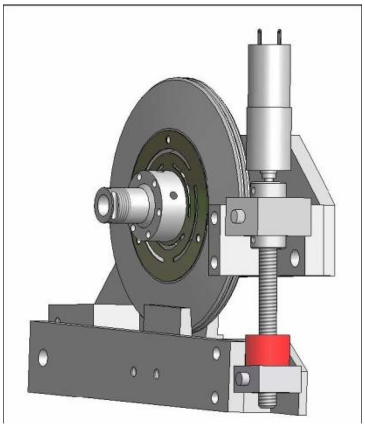

Figure 7 Particular of the CAD model of the Thwaites locking system

The Nautilus (Fig. 8) is, nowadays, one of the most common self-levelling bases in the market. It uses the passive gimbal levelling principle but, unlike other products, it has a particular locking system working in the following way: when the right levelling is obtained, the base is moved down, by two electric motors, until its lower part comes into contact with the bentosfere. In particular, the base is pressed against the internal surface of the bentosfere so to ensure its rigid locking; to allow a correct mating between the surfaces, the contact occurs only in (four) restricted areas.

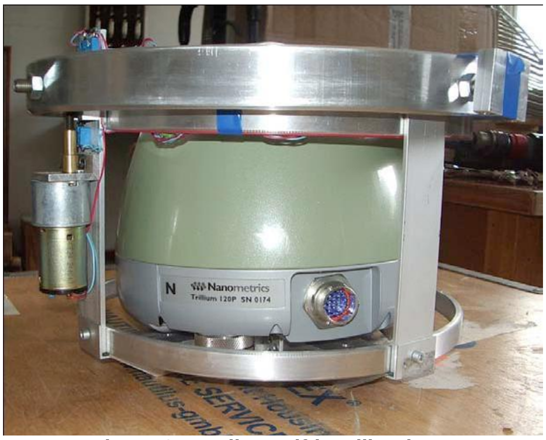

Figure 8 Nautilus self-levelling base

The Guralp self-levelling base, is also based on the principle of passive gimbal but, unlike the previous presented systems, it allows larger values of the tilt levelling angle, that can vary in the +/-120° range [7]. Figure 9 shows a CGM-40TOBS Guralp base.

Figure 9 CGM-40TOBS Guralp self-levelling base

To block the rotation axes, two electric motors act on two strips, made in flexible material that, pressed against the end (cylindrical) parts of the shaft, allow the locking of the system. However, from laboratory tests, it was noted that this locking system is not much accurate because it causes a remarkable rotation of the base around the two axes, due to the sliding of the strips on the rotating axles.

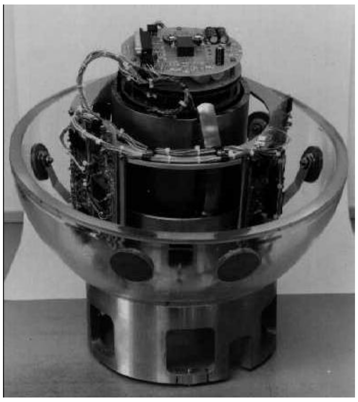

Figure 10 OBS Guralp Triaxial Broadband

The Guralp company also produces another kind of active self-levelling system (Fig. 10), called Triaxial Broadband Ocean Bottom [8].

This base uses the spherical joint working principle. In particular, it is composed (fig. 11) of a sensor seat and a sensor package (containing the seismometer), linked to a rotating disk through a mobile joint.

Through the rotation of the disk and the radial movement of the mobile joint, it is possible to obtain a correct levelling of the base. Both the disk rotation and the mobile joint translation are imposed, independently, by two electric motors.

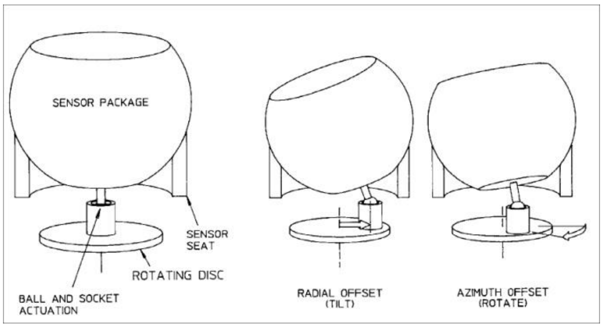

Figure 11 Guralp levelling system Triaxial Broadband

This levelling system, unfortunately, allows very low misalignment (tilt) angles (about +/- 30°), if compared with other auto-levelling bases, but its very stiff structure allows a better acquisition of the seismic signal.

4 Redesign of a new auto-levelling base

The aim of the redesign activity was to overcome the limitations of the INGV prototype. This redesign process has been organized in:

- a preliminary phase during which analysing the state of the art, identifying the goals and defining the product specifications;
- a following stage in which different alternative concepts have been proposed and evaluated, and the best solution has been identified;
- a final step where the analysis and the conceptual set up of the best solution were carried out.

4.1 Guidelines of the redesign process

The first phase of the redesign process (reverse engineering [9]) has been initially addressed to the study of the state of art of different self-levelling bases, included the ING prototype. The results of this analysis have been described in section 3. From the study emerged that some of the most important characteristics of an OBS self-levelling base are related to the levelling and signals measurement accuracies. The self-levelling base, in fact, must be able to automatically reach and maintain the horizontal position (with a very reduced error; e.g. lower than ± 0.2°) but, also, to ensure the transmission of seismic waves without any damping effect and interference.

After the state of art analysis, the functional specifications of the levelling base have been identified. That has been made through both the study of the technical documents and the identification of the main users' requirements.

The most important specifications/requirements that the new system should respect, are related to the:

- kind of the seismometer; in particular, the new base must be suitable for containing the Nanometrics-Trillium compact [10-11], available at the INGV OBS laboratory;
- environmental working conditions, with particular reference to pressure and temperature values;
- geometric constraints; the new self-levelling base, in fact, must be placed inside the frame of the existing INGV OBS station;
- duration of the measurement period that could be also one year long;
- low-energy consumption requirements;
- constraints on the costs that should be minimized.

So, basing on the most important functionalities of an OBS base, with the aim of overcoming the actual limitations of the INGV prototype, it was decided to redesign this base in order to:

- modify the base structure, to avoid any noise during the signal acquisition due to the filtering effects of the low frequencies and to the structure resonance;
- increase the accuracy of the base levelling;
- increase the levelling tilt, to allow a high value of misalignment of the base;
- reduce the energy consumption;
- improve the structure reliability;
- minimize the production and maintenance costs.

4.2 New self-levelling base concepts

The phase of new concepts generation has been conducted basing on the brainstorming approach [12]. During this phase, several concepts have been proposed and their working principles, components and possible technological solutions have been analysed.

Even if many possible solutions have been proposed, only the following three, selected using the concept screening method, have been considered:

- auto-levelling base with spherical joint and air bearings system [13];
- Auto-levelling base with spherical joint and ball bearings system [14];
- auto-levelling base with spherical joint and magnetic levitation system [15] [16].

CONCEPT SCORING MATRIX					
Criteria	Weights	Concepts			
		INGV Prototype	Base with *air bearings*	Base with ball bearings	Base with magnetic bearings
Production costs	5	5	2	2	1
Maintenance costs	5	4	3	3	4
Levelling accuracy	15	2	5	4	5
Reliability	10	4	5	3	4
Levelling tilt	5	4	3	2	3
Energy consumption	20	4	4	3	2
Signal acquisition quality	40	2	4	4	4
Total	100	295	**405**	345	355

Table1 – Concept scoring matrix

After, these three concepts have been carefully evaluated through an objective method based on the concept scoring approach [12]. The selection criteria used during the concept scoring phase are the:

- production costs,
- maintenance costs,
- levelling accuracy,
- reliability of the system,
- levelling tilt,
- energy consumption,
- signal acquisition quality.

The obtained results, summarized in the concept scoring matrix in table 1, have shown the best solution is the auto-levelling base with spherical joint and the air bearings system. By comparing the scores of the INGV prototype and the auto-levelling base with spherical joint with the air bearings system, it can be noted that, even if this last is slightly worse than the INGV system as regards the costs and levelling tilt, it is much better as regards very important functional characteristics like the levelling accuracy, the reliability of the system and the signal acquisition quality. The air bearing system, in fact, is able to drastically reduce the friction between the two spherical mating surfaces so allowing a higher accuracy during the levelling phases. Of course, the simpleness of the auto-levelling base with spherical joint with the air bearings assures high levels of system reliability, whereas the rigid and compact structure allows to reduce the noise during the transmission of seismic waves and to eliminate any damping effect and interference.

5 The new self-levelling base concept

The last phase of the redesign process has been addressed to the analysis and modelling of all the base components. In particular the functional principles have been studied, the components materials have been defined, a full parametric 3D solid model and the detailed 2D drawings of every component have been carried out.

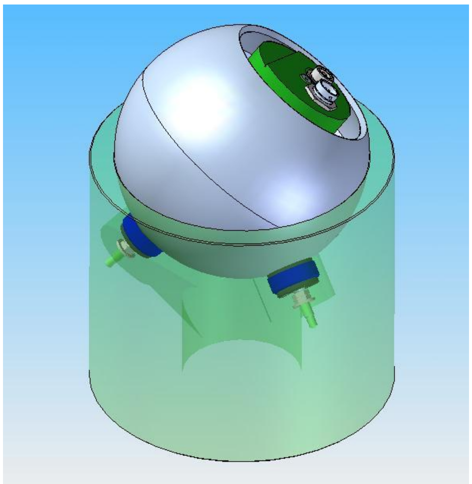

Figure 12 The new self-levelling base

The functional principles that characterize the new system (fig. 12) are mainly two: the spherical joint, thank to which it is possible correctly positioning the seismometer, and the passive levelling, which ensures the self-levelling of the seismic sensor without the use of electric motors.

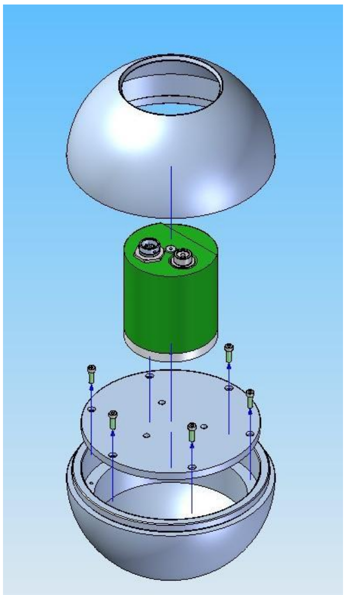

Figure 13 Exploded model of the spherical cage

The main components of the base are the spherical joint, composed of a spherical cage (fig. 13) and a support, and the pneumatic system.

The spherical cage (fig. 13) is a thin-walled sphere, with a hole in its top part, containing the seismic sensor; the cage is coupled with its support, whose mating surface has a concave hemispherical shape.

The support has, in its inner surface, three holes, placed at 120° each other, made to contain the air bearings (fig.14).

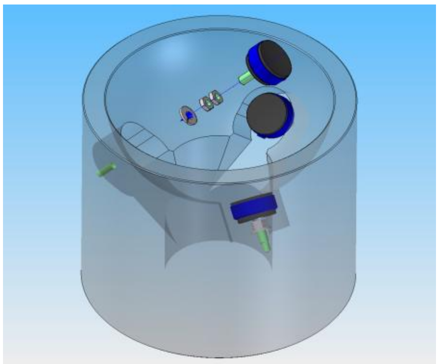

Figure 14 Exploded CAD model of the air-bearings system

The pneumatic system consists of three air bearings, a compressed air container in composite material [17], a differential valve [18] and an electrovalve.

In particular, innovative spherical air bearings (fig. 15), made by the New Way Air Bearings [19][20][21], were chosen. They are able to assure the relative movement of the two components of the spherical joint with very low friction levels.

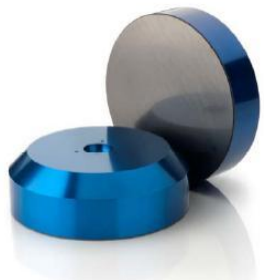

Figure 15 New Way Air Bearings

This kind of air bearings are made in a high performances porous carbon [22][23], which allows the distribution of the airflow and, consequently, of the pressure, uniformly over the whole contact surfaces. The air bearings in porous carbon have a negligible friction level (about 2 orders of magnitude lower than classical bearings), and are very suitable for high accuracy applications [20] [23].

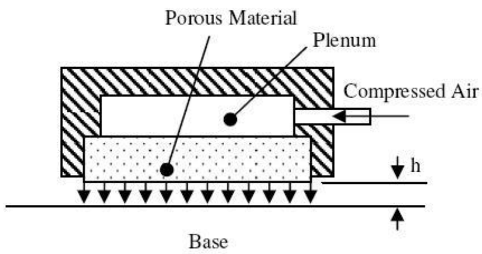

Figure 16 Air bearing scheme

The carbon porous air bearings to properly work, must be fed by a pneumatic system able to provide a constant flow of air (fig.16).

In the new designed base, the constant air flow is assured by a high pressure cylinder controlled by two valves, a two-stage differential one, which is necessary to make constant pressure gradient between the two environments (inside and outside the air container cylinder), and an electrovalve, controlled directly by the datalogger of the station, that manages the activation of the levelling phases.

The working principle of the base is the following: when the seismic sensor must be aligned, the pneumatic system is activated and, by means of the high-pressure air passing through the bearings, the spherical cage is lifted and so can float on an air cushion.

The weight of some masses placed and the bottom of the cage allows, thanks to the gravitational force effect, to correctly align the seismometer base. When the right levelling is obtained, the pneumatic system is stopped and the cage sets down on the support; the base locking is assured by the friction between the two mating surfaces. Thanks to this working principle, the new designed base allows do not use any additional locking system that can require energy consumption.

The new base, if compared to the gimbal-based ones, allows a better levelling accuracy, it has, in fact, three degrees of freedom (instead of two) and can be also rotated around the vertical axis z. Moreover, its compact structure assures very high accuracy in seismic data measurements, without any bad filtering or damping effects.

Finally, the new designed base, in comparison with other existing self-levelling bases (e.g. the Triaxial Broadband [8]) also allows a larger tilt angle (about ± 60°).

6 Conclusions

In this work, the re-designing of a self-levelling base for an OBS submarine seismic sensor, designed and developed for the first time in 2005 at the Gibilmanna Geophysical Observatory of INGV (OBS Lab), has been carried out.

Different concepts were analysed, through the description of the operating principles, components and technological solution. To evaluate the different concepts, an objective, structured and methodical approach was used. The concept screening and the scoring concept matrices were used to select the better solutions and to identify the best one. The best concept has been identified as the self-levelling base with spherical joint and air bearings.

The new proposed concept meets all the product requirements and uses innovative technical solutions.

It allows very accurate base levelling (thanks to the air bearings system) and data measurements, and has very low energy consumptions, so allowing long-time acquisition phases. The compact structure of the new self-levelling base allows to avoid any noise (e.g. due to interference or structural damping effects) during the signal acquisition phase.

Desirable future developments involve the construction of a physical prototype of the new self-levelling base in order to assess its performances through real tests.

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