LASER INTERFEROMETER
GRAVITATIONAL WAVE OBSERVATORY
- LIGO –
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Applying the SAS Know-How to produce remedial solutions to the LIGO seismic isolation shortfall
2: Passive External Isolation and Stack Damping

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Introduction

Due to intermittent low frequency seismic activity[1] the LIGO interferometer experiences difficulties in achieving or maintaining lock for long periods. Occasional seismic bursts, with velocities up to 5 μm/sec in the 1-3 Hz frequency band, excite resonant modes of the stacks to the point of overwhelming the mirror control authority. Therefore an urgent remedial action is needed[2].

The SAS group has looked into the possibility of using the SAS know how and capabilities for this remedial action. Two solutions have been considered, one is discussed in a separate paper[3].

The ideal solution to eliminate the problem of the LIGO stack resonances being seismically excited would be to eliminate the seismic excitation and then, if still necessary, to sense the residual stack resonances and damp them using external actuation (inertial damping). This is the essence of both the hydraulic end the electromagnetic linear motor proposed solutions and it is the base of this second SAS-based proposal.

We believe that we can take advantage of the SAS know-how to satisfy most or all the isolation requirements using passive techniques and, at the same time, to suspend the stacks on an almost inertial platform on which to apply any active attenuation that would still be necessary with negligible force and power requirements.

The idea is to directly apply the proven and well-known SAS pre-attenuation technology on the four piers to passively negate the stacks' seismic excitation. The whole scheme is external and do not require opening of the LIGO vacuum chambers.

An unstable (negative stiffness) Inverted Pendulum (IP) and GAS Filter 0 (F0) would be used to neutralize the stiffness of the bellows in all six degrees of freedom and tune the resonant frequencies of the pre-attenuator below 100 mHz. In the TAMA design IP and F0 have been measured to produce 60 dB of passive attenuation factors starting at low frequency. Because of the differences between the topologies of the TAMA and the BSC/HAM chambers (seismic energy is fed in by the bellow's stiffness and inertia) the TAMA performance will be degraded. Happily for remedial solutions, the required attenuation is only 30dB above1Hz and it should still be possible to achieve the requirements with the purely passive behavior of the proposed pre-attenuator.

This system naturally offers an ideal platform for tidal corrections and limited (up to 10 mm) earthquake protection.

Additionally, LVDTs, constant force actuators and accelerometers would be installed, also externally, to damp the residual stack excitation. This will be possible from the outside because the sensors will operate on an already pre-attenuated platform and therefore well sensitive to the stacks modes.

The option described below is designed to be as simple as possible while trying to fulfill the basic isolation requirements. The complexity of a six degree active attenuation can be added later, in staged steps, to boost performance and only if necessary. The system can be completely made out of existing and tested components. Furthermore, the simplicity of the mechanics makes the construction and installation fast and easy.

Step one: External attenuation

The main problem in external attenuation comes from the relatively stiff coupling of the cross pipe structure to the ground through the four vacuum bellows. To achieve a suspension at sufficiently low frequency to passively satisfy the requirements (30 dB of seismic attenuation at 1 Hz or above) we first need to neutralize the spring stiffness of the bellows with the help of negative stiffness supports. This can be done passively if the pier and the vacuum tanks can be considered a rigid body up to well above the 3 Hz target frequency. This seems to be the case already[4]. If necessary sufficient cross rigidity can be added with two simple straps between the top of each pier and one of the BSC chamber flanges. Some limitations could come, especially in the HAMs, due to the flimsiness of the cross-beam structures.

The LIGO bellows have been measured[5] to be high quality springs with transversal stiffness.

$K_x = K_z = 4.4\ 10^4$ N / m

and longitudinal stiffness

$K_y = 0.6\ 10^4$ N / m

The crossbeam, support tube, bellows, spherical mount, mount cap, mount base add up to 2080 Kg. If we were to float the payload freely in space and keep it only connected to ground through the bellows, the stiffness of the bellows would still cause the suspended structure to oscillate at a frequency F where:

$F = \sqrt{(K/M)} / (2\pi) = \sqrt{(4.4\ 10^4 / 2080)} / (2\pi) = \sqrt{21.7} / (2\pi) = 4.66 / 2\pi = .74$ Hz

This frequency is still too high to give the desired 30 dB of attenuation at 1 Hz.

The bellow’s stiffness needs to be suitably neutralized.

To do this the vertical and horizontal stiffnesses are treated separately.

The problem of neutralizing the bellow stiffness can be solved by building a system with 4 IP mini-towers, complete with a MGAS top filter (F0) as illustrated in figure 1, 2 and 5. The base of each tower would be mounted on top of a pier and the four mini-towers would support the ends of the two cross beams.

Each IP must support 1.3 tons of weight and a budget of 200 Kg of F0 gear.

The anti-spring constant of an infinitely flexible IP is

$K = - M g / h$

where M is the applied load [Kg] and h is the effective IP leg length [m].

To get a desired anti-stiffness $K_y = -4.4\ 10^4$N/m (to neutralize the transversal K of the bellow) we require a maximum leg length of

$K_{as} = -4.4\ 10^4 = - 1500 * 9.8 / l$ [1/m].

$l_{IP} = .334$ m = 334 mm

To neutralize the bellow stiffness in the transversal direction, we need the entire anti-spring component of this 334 mm IP. In order to preserve the entire negative stiffness we cannot afford any significant positive stiffness in the IP support. Therefore we use, on both ends of the IP, the practically stiffness-free tensional joints presently implemented at the top of the TAMA IPs. The added advantage of tensional joints is that they are easier to use, buckling free and allow for larger angular movement.

To allow for the residual stiffness of the flex joint, and to provide adequate safety margin we designed the leg somewhat shorter than 334 mm. For this reason we chose an IP length of 300 mm (length to be fine tuned on a field test).

The IP provides the same anti-spring component in both horizontal directions. The antistiffness sufficient to neutralize the bellows in the transversal direction is too much in the longitudinal direction.

For this reason an additional corrective spring of $K = 3.8\ 10^4$ N / m is necessary, parallel to the bellow's axis to complement the 6000N/m longitudinal bellow stiffness. This correction is made with a simple Virgo-like cantilever blade attached with a wire along the bellow axis.

The other transversal (vertical) stiffness of the bellow is compensated using a negatively tuned F0.

This top filter would be a simplified F0 without the baricentral case used in suspended filters, and it would be equipped with the external frequency tuning mechanism as used in the SAS prototypes.

The simplified F0 would be mounted in the usual way on the IP and the cross beams would be bolted directly below the F0 business end.

Alessandro Bertolini and Duccio Simonetti have made a scaled test coupling an accelerometer GAS spring to a helical spring. The GAS blade alone is compressed 5.3% of its length to get neutral stiffness. The test found that the additional spring's constant could be neutralized with a compression of 5.8%, roughly 10% more than the usual GAS compressional rate. On a typical 400 mm GAS blade, a mere 2 mm additional radial compression is needed to provide the required anti-stiffness to neutralize the bellow's stiffness. This means that we can simply use standard GAS blades, without changing their shape.

Note that we have chosen to use a GAS F0 geometry as opposed to the monolithic (MGAS) geometry because the GAS geometry uses separate suspension blades that can even be replaced in situ and therefore offers a much more flexible use. As an additional benefit the GAS geometry allows a much more efficient use of the maraging steel sheet with substantial cost savings.

The elimination of the rigid wedge blade mount (not necessary upstream of the attenuation stacks replaced by the simpler bolted mount) and of the baricentral F0 body will bring more substantial savings and will result in a more versatile geometry.

Initial implementation and performance limitations

If the ground is stable enough, it should be possible to tune both the horizontal and vertical frequencies to 100 mHz or below by tuning dummy loads on the F0 case for the horizontal frequencies and the compressional rate of individual GAS blades for the vertical component. Driving the frequencies at lower frequency in a purely passive way requires a more laborious procedure.

A tuning at 100 mHz has the potential to provide the system with 2 orders of magnitude of attenuation at 1 Hz and above.

A perfectly tuned and well designed IP can deliver attenuation performances of 60 dB. It is difficult to foresee exactly the performance of a system as complex as the stack's cross beams supported on a low frequency system. The seismic noise would feed through the IP, F0 and bellows. IP legs can be counterweighted to feed through negligible noise. The limiting factor in the horizontal direction in a SAS system is given by the mass ratio of the legs divided by the F0 mass, corrected by the balancing effect of the leg's counterweights. The attenuation plateau in TAMA SAS was measured at better than 60 dB. In the remedial LIGO system the leg to load mass ratio is more than one order of magnitude more advantageous than in TAMA SAS, therefore the effects of reasonably counterweighted IP legs can be neglected. It is difficult to evaluate the effect of the bellow's mass. The bellow's mass is of the order of one Kg (only the actual bellow mass, excluding the mass of the flanges, must be counted) while the cross beam structure weighs two thousand Kg. Therefore, in a simplistic evaluation and in absence of strong resonances, an attenuation plateau of 10^{-3} can be expected. Resonances in the bellows will degrade this high value of attenuation. If it is possible to damp the bellow's resonances below 10 (with gels or Eddy current damping), it should be possible to attain the required 30 dB of attenuation.

A similar argument gives the same estimated value for the vertical direction.

The soft suspensions are an ideal platform to provide tidal strain corrections with negligible forces. Milli-Newton actuators will be sufficient for this task.

As an additional benefit, if we allow for a few mm movement range in all directions, the soft passive attenuation system will give LIGO I an Olympia-class earthquake immunity.

Staging the implementation

The completely passive system discussed above is already sufficient to satisfy the requirements to solve the present LIGO I seismic problems. Other, stageable, improvements of the performance are possible.

Stage two: (semi-passive)

This system may become necessary if the ground or the piers were not stable enough to allow passive operation of the pre-attenuator at or below 100 mHz. Pier instabilities, especially tilt fluctuations, asymmetric creep in the bellow and support structures, and other causes may cause the IPs to drift out of the desired working point when tuned at very low frequency. A weak correction force would be necessary to chase the changing ambient conditions and maintain the desired working point. The system providing this force could be the same also providing tidal correction, as the required correction forces are of the same magnitude. The same system can be used to remotely tune the IP/F0 system to ultra low frequency to reduce the micro seismic noise perturbations.

For this implementation half a boot-and-shoe system (one LVDT and one actuator) can be mounted in parallel to each of the four IPs with tangential orientation as shown in figure 3 and 4. Similarly a LVDT and actuator system (identical to the ones installed in the TAMA-SAS F0) would be mounted in the four LIGO I F0s for the vertical direction and the tilts.

We can use the co-located LVDTs and Constant Force Actuators connected with a simple Op-Amp to generate a soft corrective electromagnetic spring and electrically drive the collective passive resonances much below 100 mHz (procedure already done successfully years back by L. Holloway on an IP and recently testet by Iida on a F0 in the 3 meter SAS experiment). This trick is particularly useful to reduce the laboriousness of the tuning procedure of the vertical degree of freedom and allows for remote tuning of the system main resonances and working point.

A tidal and working point drift correction signal can be added to the Op-Amps, thus making the LVDT/constant-force-actuators units ideal to track and correct for tides, tilts, and any other slow drifts.

Stage three: (external inertial damping)

Finally one can implement accelerometers on the IP and F0 (figure 6) and apply the standard IP inertial damping SAS scheme to damp the stack inertial resonances and/or add active LF isolation.   This scheme requires full MIMO DSP controls, topologically identical to those foreseen for the hydraulic system. The only difference being the much smaller forces required by the constant force actuators in the soft system and the fact that accelerometers operating on pre-attenuated seismic platform will be more sensitive and effective.

It is also worth noticing that this scheme (IP/F0 pre-attenuators plus stacks) is the mechanical analogous (although at higher frequencies) of the successful Virgo super-attenuator chains, i.e. a low frequency pre-attenuator equipped with active inertial damping, followed by a chain of four passive oscillators. The entire Virgo inertial damping scheme has been fully validated and worked well. It should be possible, , to adapt it to work at the stack's higher frequencies even if in this case a 6 d.o.f. MIMO system is necessary.

Mechanical observations

It is useful to note that we do not have to guess any relevant parameters to build the proposed mechanical system as we know well the IPs and GAS filters, the actuators, the LVDT and the accelerometers performance and design.

The old Advanced-LIGO SAS test tower, still sitting in the Synchrotron, presently carry 360 Kg load with four 80 mm wide blades and is designed to house up to 12 blades each up to 120 mm wide for a maximum load capability of 1.62 tons. To achieve the required 1.3 ton of load per pier we simply need to mount twelve 96 mm wide blades.

The IP legs would be much shorter than in the prototype, but would use (at both ends) flex joints identical to the prototype's top joints, which are well known and tested.

Sensors and actuators are all tested and work equally well in air.

Of course this remains a large enterprise and, although hardware-wise it is reasonably easy to build and install it will need a lot of effort to first characterize the effective passive performance and then for the development and implementation of its dedicated active MIMO control system.

HAMs can be treated similarly

Installation scheme

The assembly procedure would be as follows:

- The IP/F0 units, which have been pre-assembled and immobilized with its shipping posts and clamps arrive and are inspected
- One of the four pier supports is relieved of the load by taking the load of cross beams arm with the crane. The load is verified on a load cell.
- The scissor table and all of the present mechanics is removed.
- If the load of the beam is found to differ from the nominal value by more than the acceptable tolerance (80 Kg) the F0 is opened and two or more F0 blades are interchanged to match the load. Then the unit is immobilized again in the transport configuration
- The IP/F0 unit is slipped in place under the cross beam arm
- The pier extension is positioned over the pier and bolted
- The cross beam arm is bolted to the F0 support disk (IP and F0 are still immobilized)
- The procedure is repeated for the other three piers
- The initial positioning is recorded by the LVDTs
- The vertical degree of freedom is released in the 4 F0s
- Ballast is added to the cross beams to reach the floating point of the F0
- The F0 blade compression is adjusted to achieve the desired vertical oscillation frequency using the vertical LVDTs readout
- The IPs are all released
- The 4 complementary springs along the bellow's axis are tuned
- The auxiliary positioning springs are tuned to fix the horizontal working point
- Ballast is added on the 4 F0s to tune the IP horizontal frequencies using the horizontal LVDTs readout
- Second iteration is done to fine tune the passive frequencies

The low frequency seismic isolation is operational. If no major, in situ, modifications will be found to be necessary, the installation procedure is expected to last a week for the prototype LASTI BSC.

Cost and Schedule

Prototype time schedule estimation

- Three weeks to finalize and detail the drawings
- Four weeks for production and shipping (all materials is in house already)
- One week for installation.

The drafting and production times have been estimated by PROMEC and G&M for crash projects.

The installation time estimation is based on the experience of installation gained from the TAMA towers.

Of course extensive testing and characterization of the system and some optimization will be necessary before taking production decisions or trying the implementation of stage 2 and 3.

Bulk production: after a two months of material procurement, delivery could be done at the rate of two or three units (of 4 IP towers each) per week.

Production cost estimation

The production costs are just an estimation; the estimation, made by Mr. Galli, is based on the overall assembly and not on the detailed part designs.

Extension pier	Eu	415
Base disk	Eu	580
Inverted pendulum legs (3)	Eu	500
Transport rods (3)	Eu	500
Inverted pendulum bases (3)	Eu	1100
Inverted pendulum heads (3)	Eu	1000
F0 base disk	Eu	580
F0 base ring	Eu	750
F0 top disk	Eu	580
F0 spring disk and safety structure	Eu	750
F0 hook wires (12)	Eu	2420
F0 blades (12)	Eu	3000
F0 blade clamps (12)	Eu	1500
Bellow correction spring	Eu	300
Total (per pier)	Eu	13975
Grand total (per BSC)	Eu	55900
	US$	48400

Although a simple estimation the above prices, being based on past production experience, should not be off by more than 30%.

Price reductions are expected for series production. The above prices do not include the sensors and actuators (1 Horizontal LVDT [535 Eu], 1 vertical LVDT [200 Eu], 1 horizontal accelerometer [3500 Eu], 1 vertical accelerometer [n/a], 1 motorized spring [400US$], 1 vertical motor [150 US$], 1 horizontal constant force actuator [557 Eu], 1 vertical voice coil [100 US$], my estimation is of about 4800US$ for each pier, i.e.19200 US$ per BSC) and electronics (an estimated 8000 US$ per BSC for the NIM linear drivers of LVDTs, Actuators and Accelerometers, based on TAMA prices) .

The total including electronics, and adding 4000$ for shipment and other costs, but excluding DSP controller modules, adds up to an estimated 80,000. US$ for a fully controlled inertial damping system.

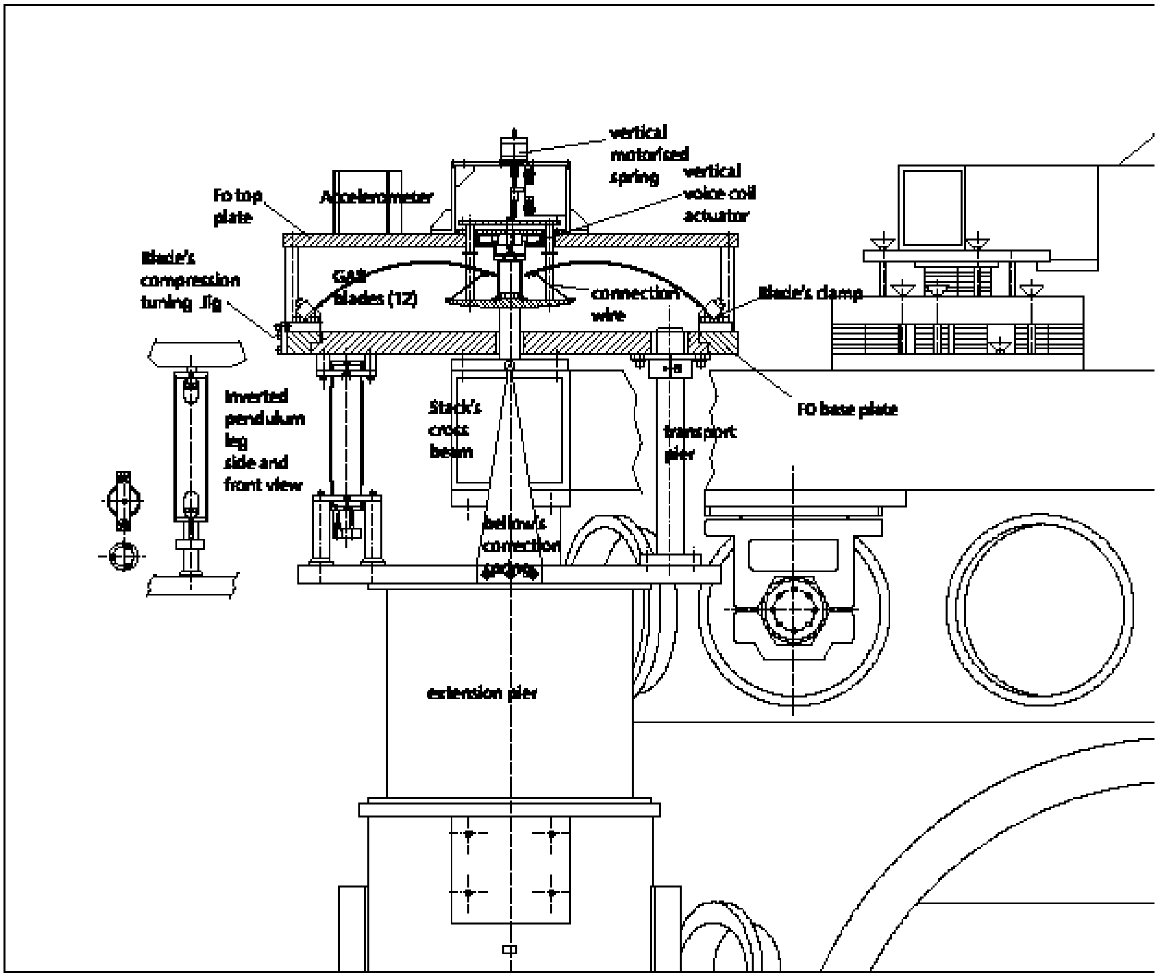

Figure 1: View cut along the bellow axis of a SAS mini-tower mounted on top of a pier and supporting the LIGO stack cross pipe structure. One of the three transport piers doubles up as earthquake oscillation range limiter.

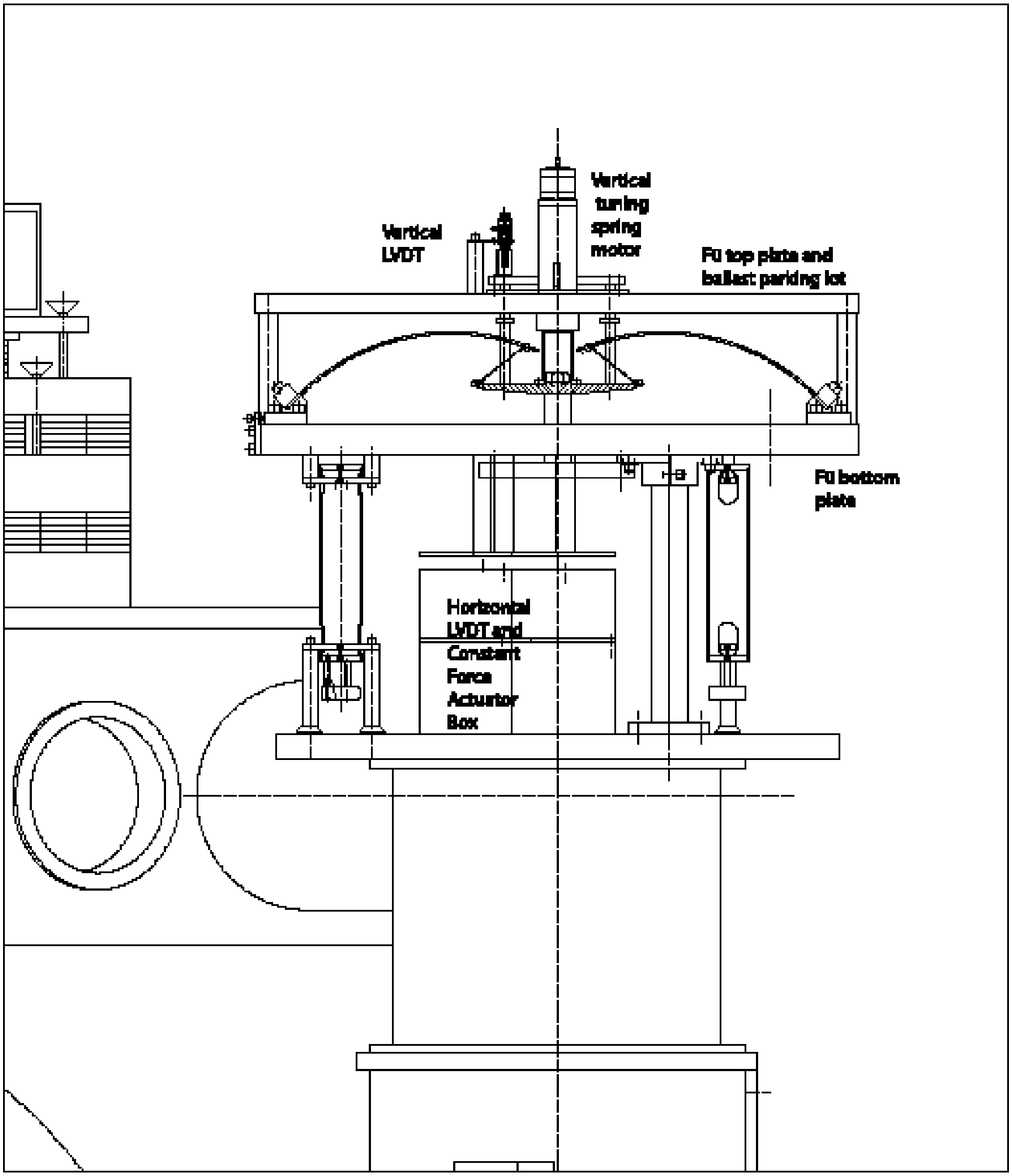

Figure 2: Side View of IP and F0 unit.

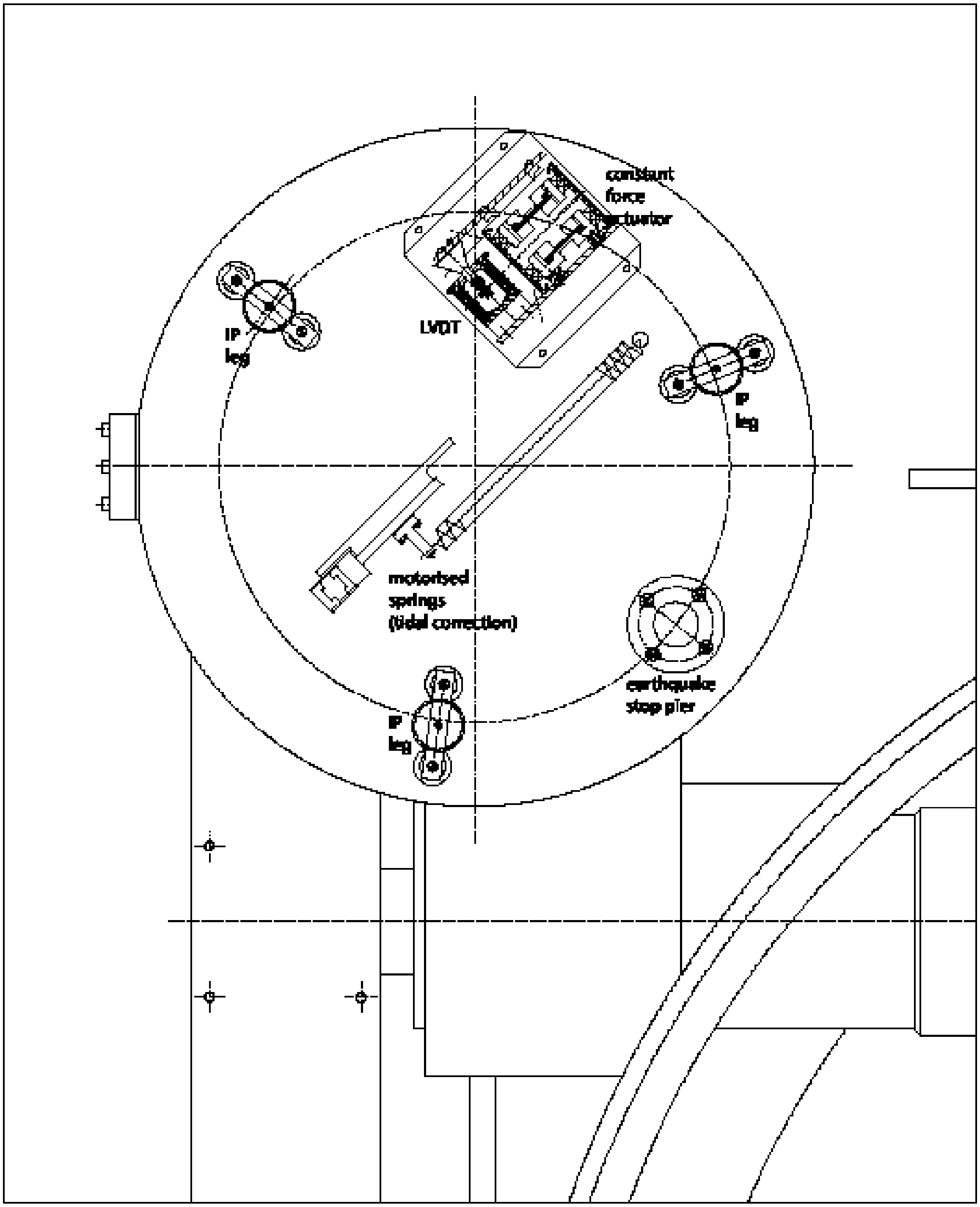

Figure 3: view from above the F0 bottom plate, to illustrate positioning and tangential orientation of horizontal LVDT and actuators.

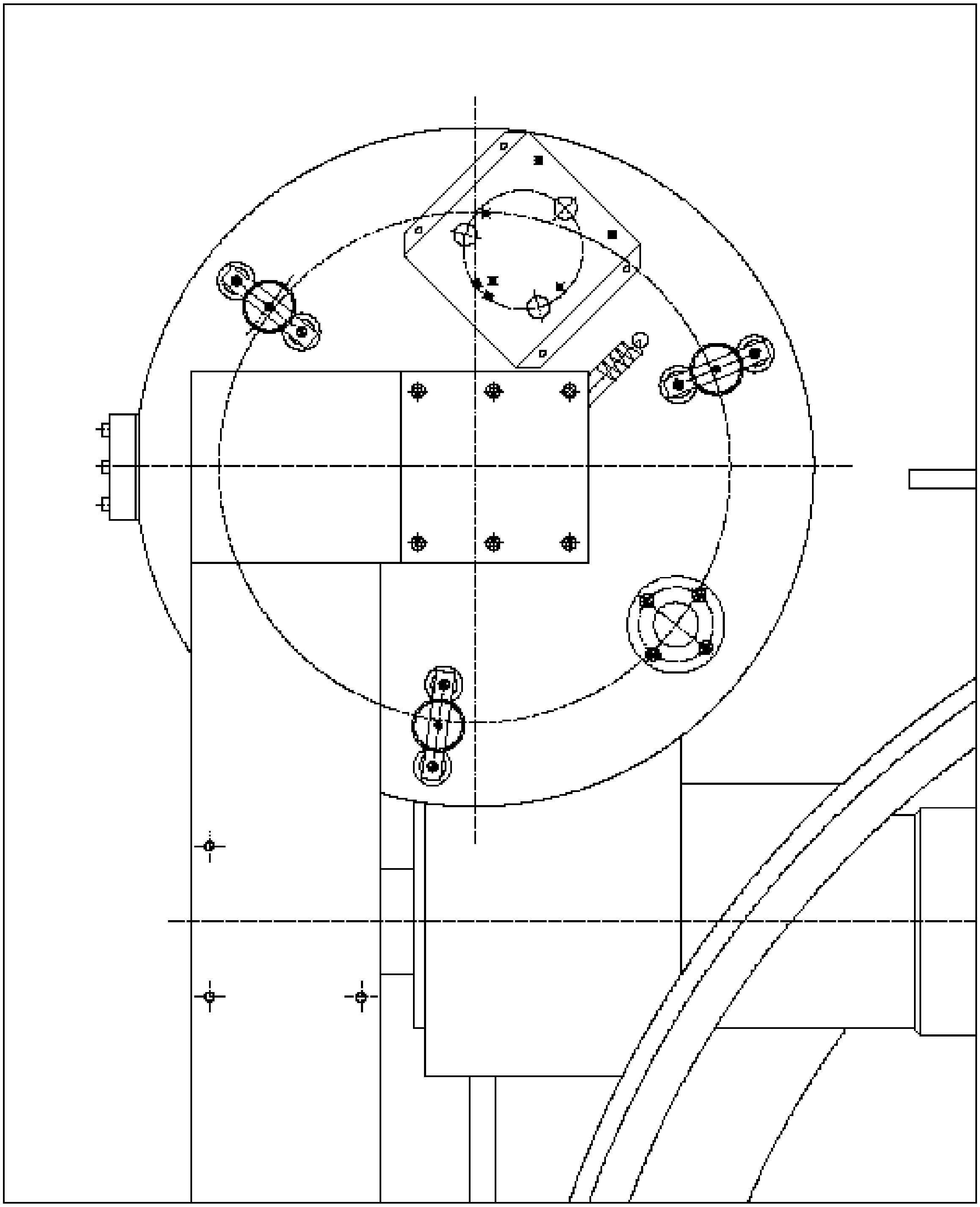

Figure 4: View from above the stack cross beam, to illustrate the relative positioning the existing structure and of the IP legs and safety stops.

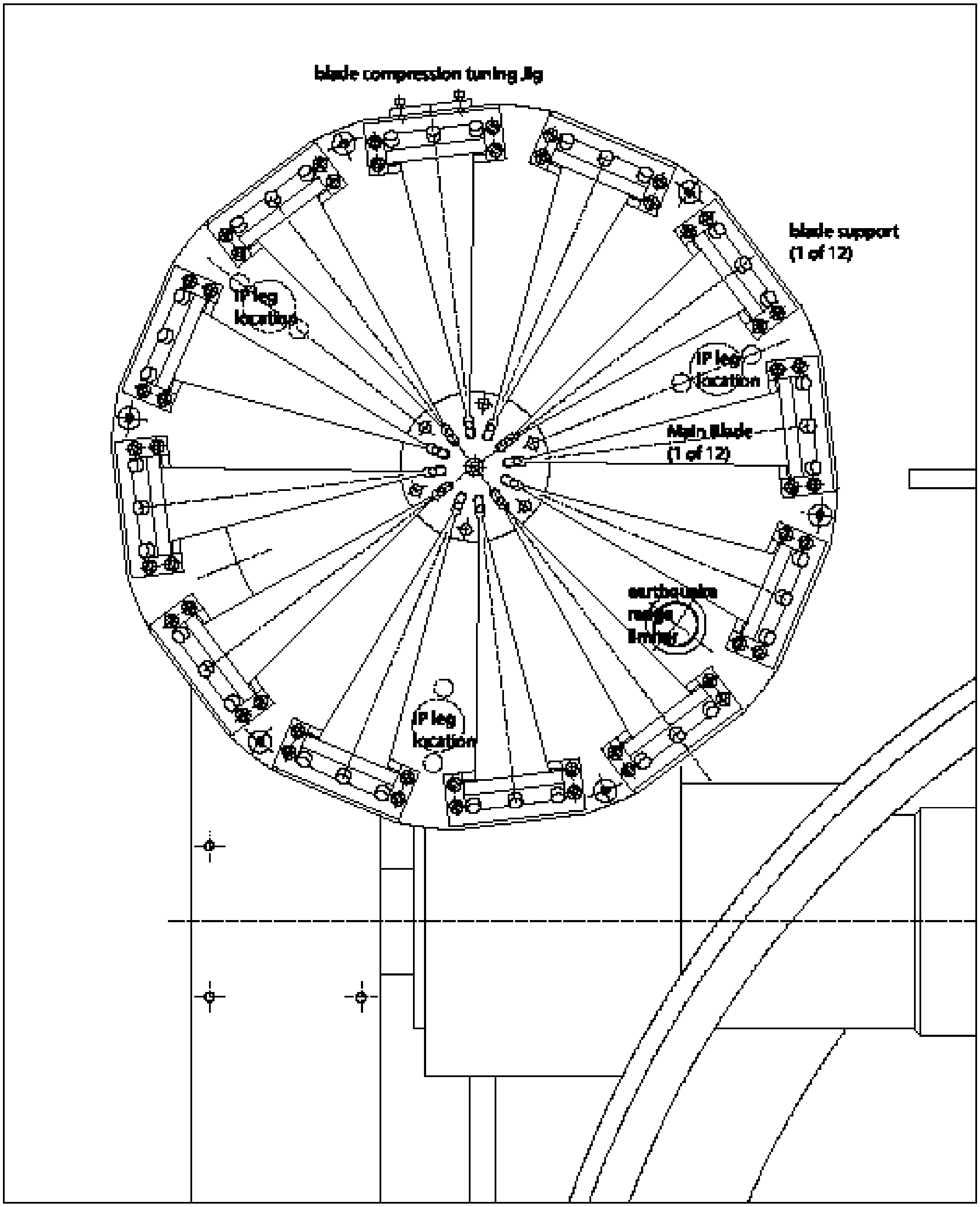

Figure 5: Top view of the GAS F0 after removing the cover to make the 12 suspension blades visible

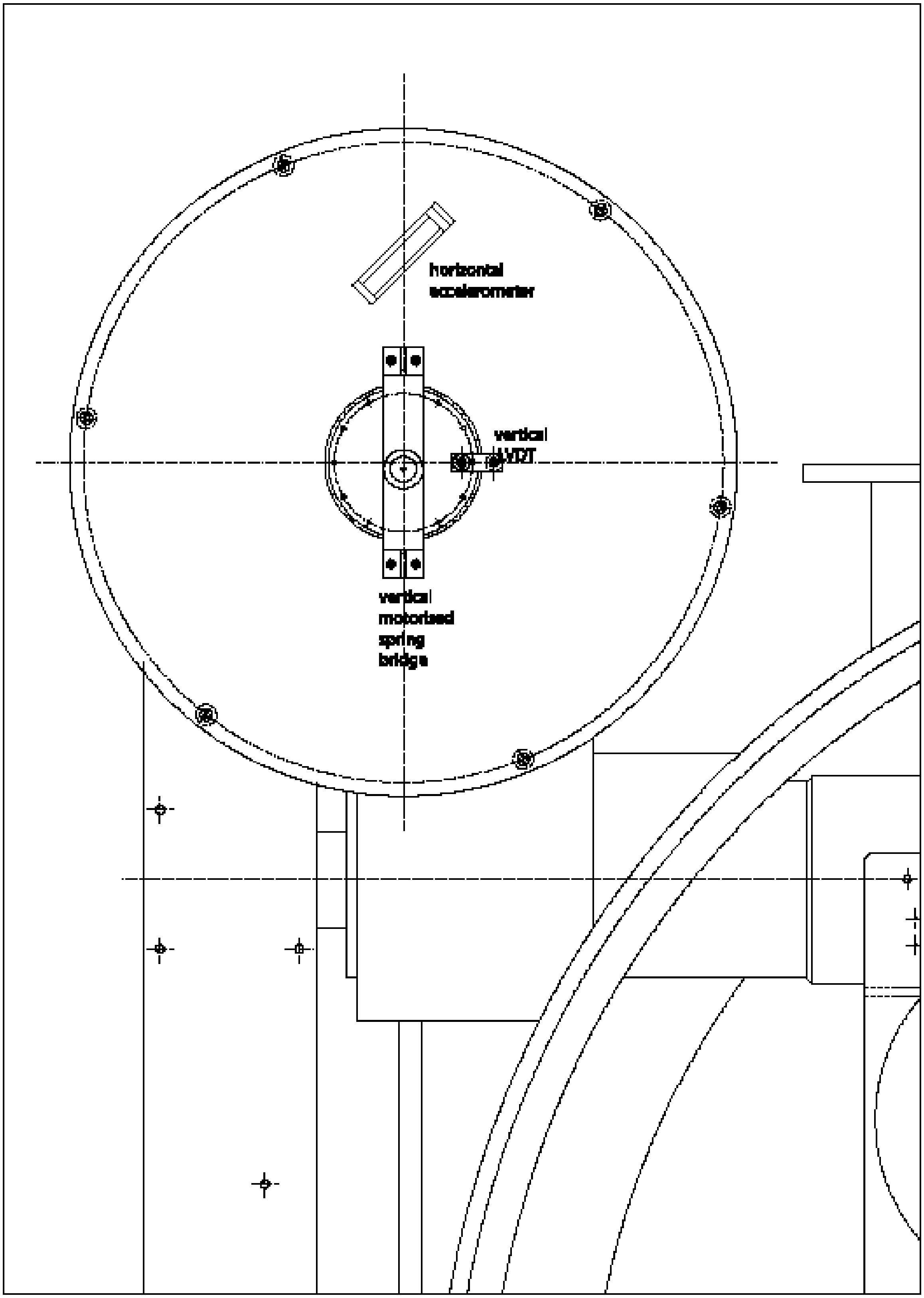

Figure 6: top view of the F0 to illustrate vertical accelerometer, LVDT and actuator positioning.

References

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