Measurement of vibration noise of one granite bench and one Newport optical bench

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Introduction

We need to select a bench for the new EGO optics and noise laboratory. This bench will be dedicated to measurement of mechanical modes of the Advanced Virgo optical components. The set requirement is that the bench plus support system (we call "table") is stiff and rigidly connected to ground up to high frequencies, possibly up to some hundred Hz. Bench resonances would absorb energy and cause coherence loss in the mechanical transfer function measurements we want to perform on this bench.

This note describes measurements of vibration noise of two tables. The first one is a granite bench supported on conical legs, which is located in INFN-Pisa clean rooms. The second table is a Newport-RS1000-with-tuned-damping bench deployed on four Newport-RL-2000 legs, which is located in the INFN-Pisa Virgo laboratory. For both benches we measured the motion of the bench with respect to ground. In particular, we measured the frequency of modes and give rough evaluation of Q factors. Also we give an indication of which modes are associated to the support system and which instead to the bench itself.

1. Measurement setup

The test setup was similar for both table measurements. The test setup consisted in two single axis accelerometers (one PCB-393B31 and one PCB-393B12) read out by one spectrum analyzer (ONO-SOKKI). Accelerometers have the same sensitivity, but differ a bit in the low frequency intrinsic noise and high frequency cutoff. In particular: PCB-393B12 weights 210gr, has a flat unit response (±10%) from 0.1Hz to

2000Hz and intrinsic noise of 3µm/s2 at 10Hz; PCB-393B31 weights 630gr, has a flat unit response (±10%) from 0.07Hz to 300Hz and intrinsic noise of 3µm/s2 at 10Hz.

One accelerometer (PCB 393B31) was positioned on the floor beneath the bench and always kept along the vertical direction. The second accelerometer (PCB 393B12) was placed on the bench, subsequently in two different positions: A) bench middle, B) bench corner, and aligned along different orthogonal directions (V=vertical, H1=horizontal along bench short side, H2 = horizontal along bench long side). To assure a rigid connection of the accelerometer on the bench top, we mounted the accelerometer on an aluminum support allowing vertical and horizontal orientations, and fixed this support to the bench using a stud. The accelerometer on floor was just laid there, but its larger weight and wider base plate we think assured a sufficiently good contact.

2. Granite bench

Figure 1 shows a picture of the bench on the support. The bench is a solid single slab of “African black” granite, whose mechanical properties are listed in Table 1. The bench size is 200x100x22cm^3 and its weight is 1250kg. The bench surface is polished, a grid of 16 equally spaced through-holes M8 size is drilled on its top face. The bench is supported by four conical legs (), Figure 1b shows the detail of the contact point.

Table 1: Properties of granite bench material, as from http://www.microplan-group.com/mpg/ITA/materiali.html

Material type	Black granite
Density (kg/dm3)	2.85
Porosity (%)	0.09
Elasticity coefficient (Gpa) (Young MODULUS)	60 – 95 (*)
Poisson coefficient (granite)	0.2-0.3 (*)
Compression resistance (Mpa)	244
Resistance to flexion (Mpa)	24
Thermal expansion coefficient (m/m°C)	6.5 E -6
Shore Hardness (0-100)	90
Thermal conductivity (W/m°K)	2
Origin	Africa
(*) the exact value depends on the single piece	

Figure 1. (left) picture of granite bench; **(right)** detail of support leg contact point.

Figure 2 compares vertical acceleration spectra. The bench accelerometer was at the bench center position. Red line is the vertical acceleration of the bench center in quiet condition (no extra noise applied). The bench moves as the ground up to 80Hz or so, with very little amplification at some modes (see below) visible between 60Hz and 70Hz. Above 100Hz or so the bench moves significantly less than the ground. Note that the flat noise floor in the bench accelerometer appearing above 1kHz or so, corresponds to the intrinsic noise of the instrument, while the accelerometer on floor response starts decreasing around 300Hz (from specifications) and fully drops around 1kHz.

Two peaks are visible at 65Hz and 72Hz. They get excited when a force is applied on the table. They appear to excite easier when a force is applied on the floor doing little jumps on the floor next to the bench (yellow line in Figure 2) than when force is applied on the bench top (grey line in Figure 2 corresponds to knocking on the bench top). These modes look quite dumped. Figure 3 shows a tentative measure of the floor to bench top transfer function. The tentative fit (by-eye) gives an estimation of the Q factor of these modes: Q = 8.

More peaks are visible at higher frequency, as evidenced in Figure 2.b. First one is at 330Hz, then 820Hz, 860Hz, 1215Hz, 1335Hz, and more above 1500Hz (Table 2). These peaks are sharper. Their Q is around 100 (as roughly estimated in Figure 3). Knocking on bench excites them, while they are almost insensitive to floor vibrations. In particular the 330Hz peak excites easier, higher frequency modes seems much harder to excite.

Figure 4 shows how the bench vibrates in the horizontal direction. The most interesting feature is one pronounced peak at 11Hz. Its Q is around 50 (as estimated from the width at half height Δf in Figure 5, Q=Δf/f0). At this frequency the bench moves horizontally about ten times more than along the vertical direction. At higher frequencies we recognize the same peaks identified in the vertical spectra which here seem just a bit reduced (factor 2) in amplitude (except the 330Hz which looks the same amplitude).

Figure 5(left) compares Vertical bench motion measured in the middle of bench and in one corner, and Figure 5(right) compares Horizontal bench motion measured in the direction of the short bench side and long bench side. We note no big differences, apart the fact that one additional peak around 80Hz in present in the vertical spectrum measured in the corner position.

Tentative interpretation of the peaks:

- The 65, 72 and 80 Hz (vertical) and 11Hz (horizontal) peaks are modes associated to the legs support structure, more precisely to the elasticity of the contacts between the legs and the bench. This guess comes from having found similar modes when measuring tables with similar legs at EGO-Virgo.

As depicted in Figure 1, the joint has a sandwich structure: an adjustable screw (size M30) a sphere, accommodated into spherical cavity formed by two screw-nuts and a top plate (all stainless steel). It could be interesting to compare the measured elasticity constants (K = w^2 * M, M=bench mass, w=2πf, f=70Hz or 11Hz) with a mechanical model of the joint.

- The high-Q peaks at 330Hz, 820Hz and above are internal modes of the granite slab. Formula below is taken from Landau book "Theory of Elasticity", pg. 145, and gives the vibration modes of a slab laying on its perimeter, in the approximation that its width h is much less than its sides (a,b).

GRANITE table			
Measured frequency (Hz)	Estimated Q	Interpretation	Predicted frequency (Hz) (rough model)
65,72,80 Hz	8	Vertical Elasticity of support	
11 Hz	50	Flexural Elasticity of support	
332	90	granite block mode	217 (n=1,m=1) 347 (n=2,m=1) 564 (n=3,m=1)
822 858		granite block mode	738 (n=1,m=2) 869 (n=2,m=2) (n=4,m=1)
1212 1336 1376		"	1086 (n=3,m=2) 1250 (n=5,m=1) 1390 (n=4,m=2)
1560 1789		"	1607 (n=1,m=3) 1737 (n=2,m=3) (n=1,m=6)

			1780 (n=5,m=2)
2291 2382		"	1955 (n=3,m=3) 2260 (n=4,m=3)
2804 2926		"	2824 (n=1,m=4) 2954 (n=2,m=4)

Table 2. Measured mode frequencies (column 1) and Q (column 2). In column 4 are modes frequencies estimated with a rough model.

$$\omega_{n,m} = h \cdot \pi \cdot \left(\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 \right) \sqrt{\frac{E}{12\rho(1-\sigma^2)}} \quad with\ n, m = 1,2,3, \ldots$$

Table 2 lists the modes derived from this formula up to order 4th, in the hypothesis E=80Gpa, σ=0.25, h=0.22m, a=1m, b=2m. The overall agreement is good. The interesting information is that the mode frequency rises just as the square root of the Young Modulus, while it is proportional to the bench thickness. We can estimate how the first resonant frequency (assuming it is not 332Hz) scales for a bench which is 1mx1mx0.16m (standard size by micro-plan), and we get 386 Hz.

Figure 6 shows the first mode (found at 337Hz) found by the ANSYS simulation of the granite bench (by Andrea Basti). The simulated material is granite with mechanical parameters: Young Modulus=95000 MPa, Density=2.85e-006 kg mm^{-3}, Poisson's ratio = 0.3, Bulk Modulus=79167 MPa, Shear Modulus=36538 MPa. The simulated geometry is one single slab 1000mmx2000mmx220mm. The slab is laid on four points located at the position of the legs, and these points are imposed a null displacement (X=Y=Z=0).

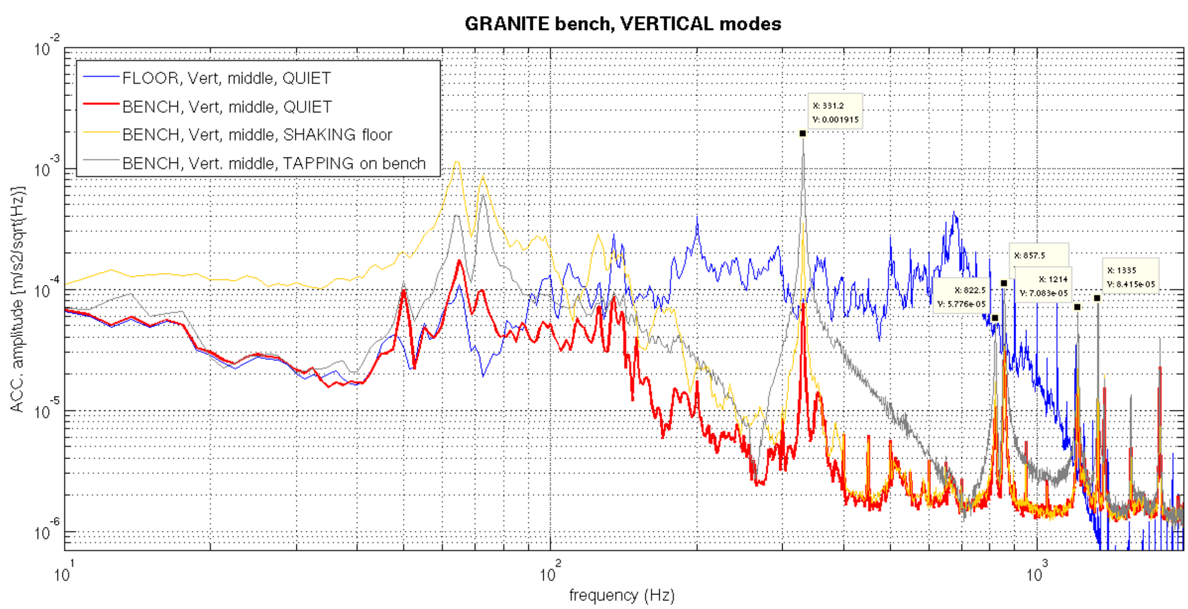

Figure 2.a Vertical acceleration of granite bench top (red) and floor (blue) in quiet condition. Bench motion is measured at the bench center. Grey curve is the bench top acceleration when knocking on the bench, Yellow curve is the bench top acceleration when stepping hard on the nearby floor.

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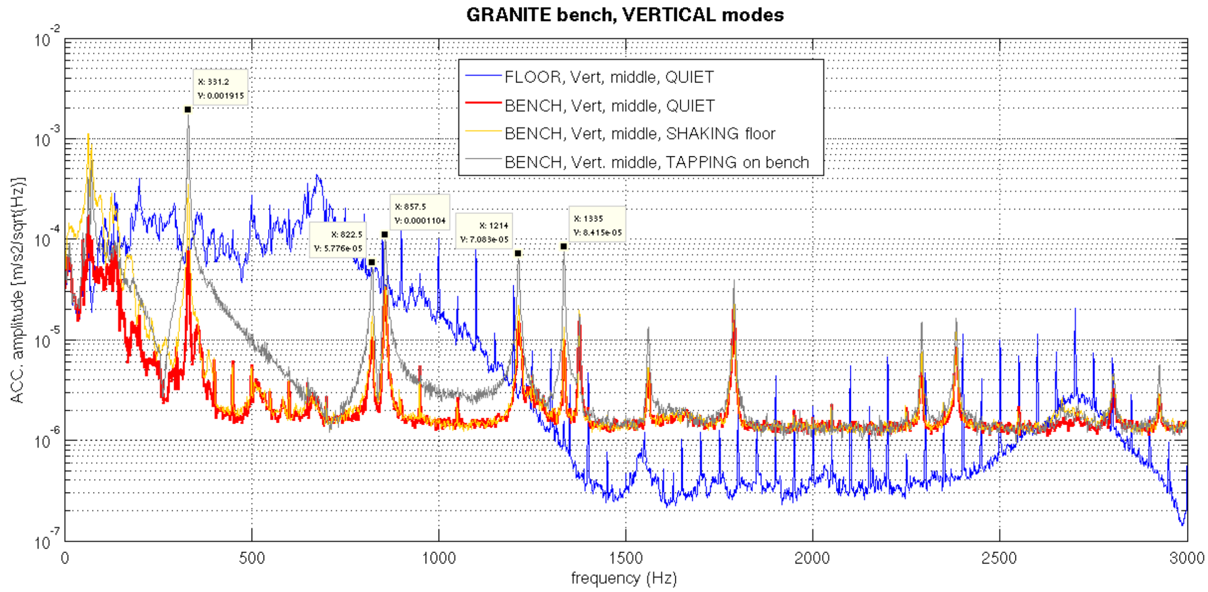

Figure 2.b Same as above but on linear scale, to better show high frequency modes.

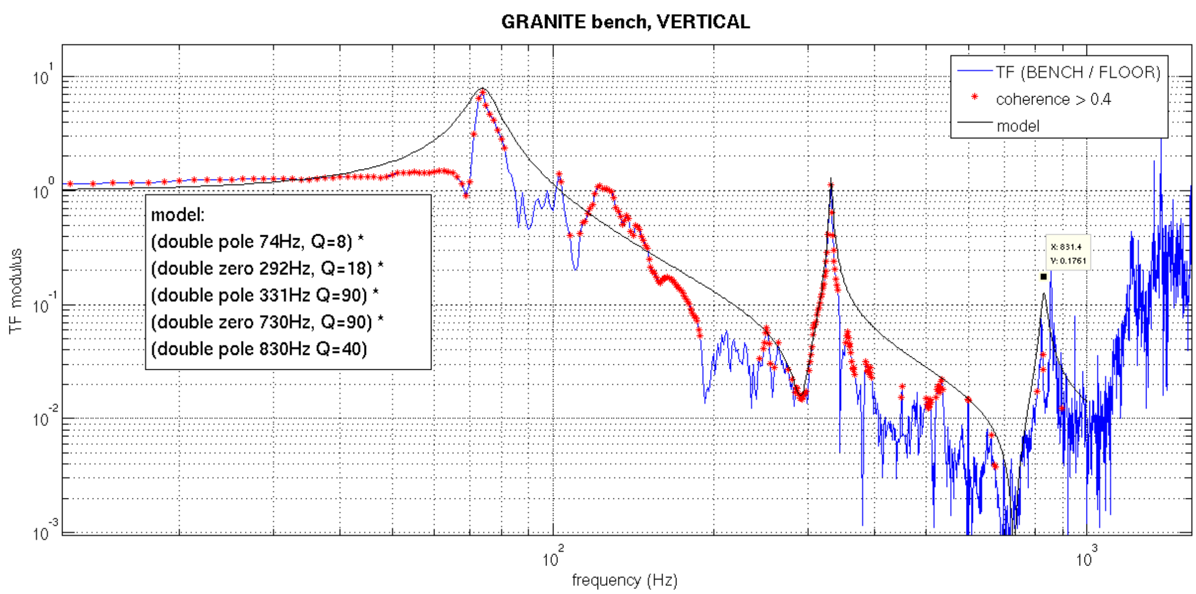

Figure 3 Transfer function of vertical seismic vibration from floor to bench top. Measurement is good at red points where a good coherence is measured. In the range 300Hz to 1kHz could be a bit over-estimated because of the reduced response of floor accelerometer, above 1kHz it is non-sense. Black line is a ad-hoc tuned curve to roughly reproduce the main features, its poles and zeros are given in the inset.

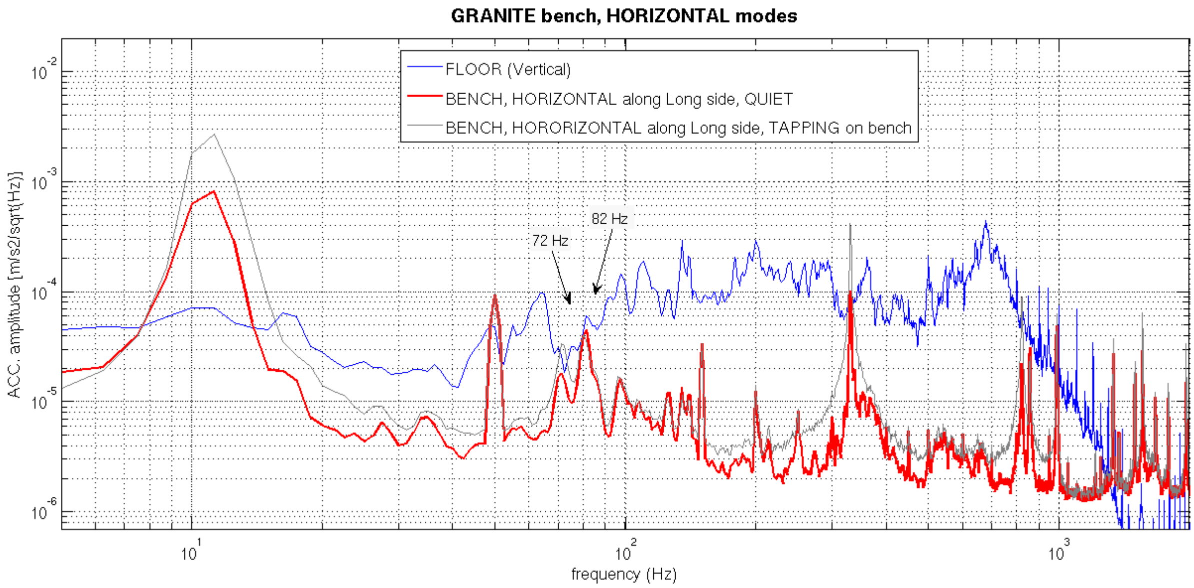

Figure 4 Horizontal acceleration of granite bench top (red) measured at bench center, and Vertical acceleration of floor (blue). The blue line is shown for reference. Grey line corresponds to knocking on bench side.

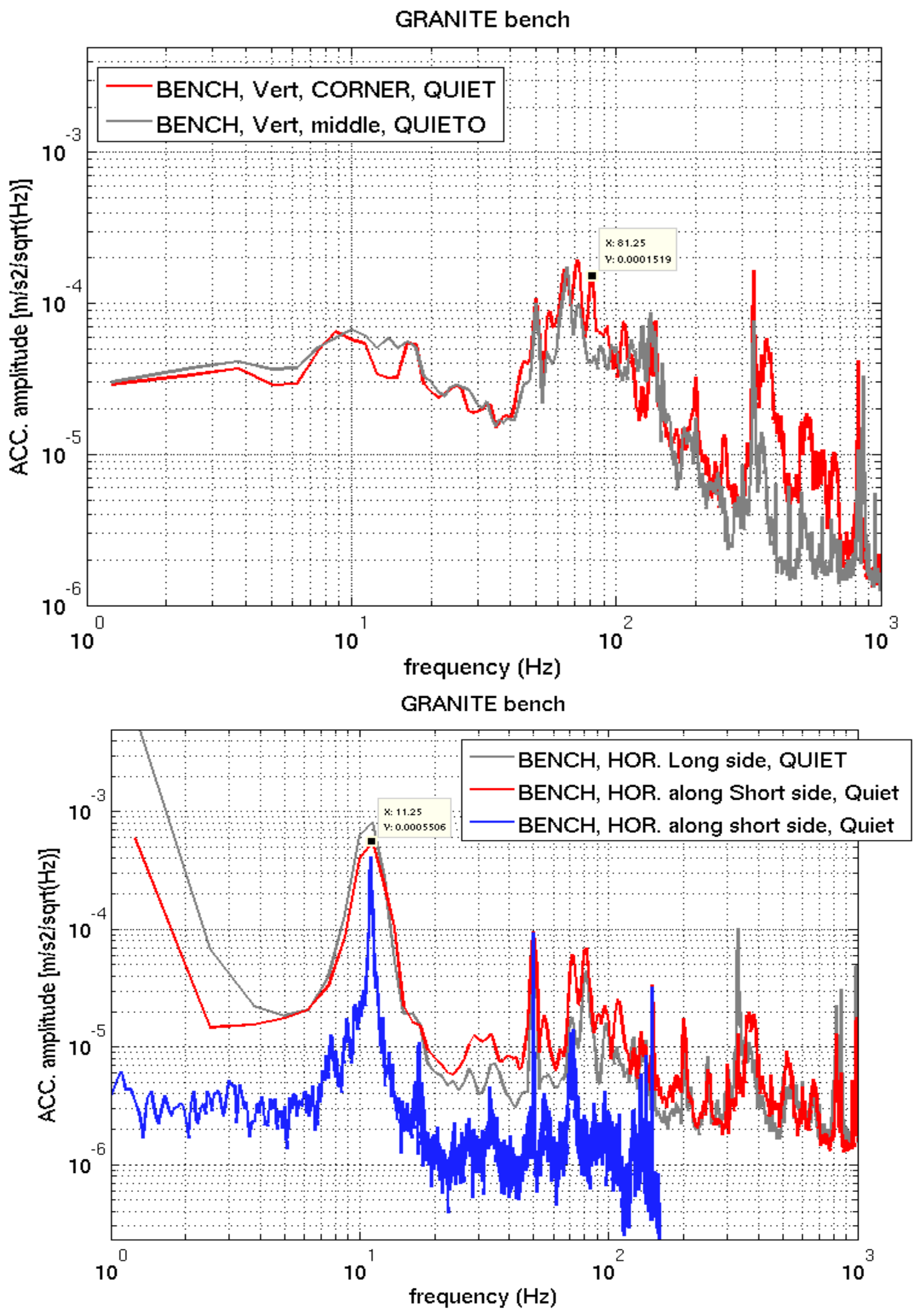

Figure 5 Vertical and Horizontal vibration of bench top in quite condition, in the bench center and one corner. Blue curve in the bottom plot is taken with a finer frequency resolution. The rise at low frequency in the bottom plot is an instrumental artifact.

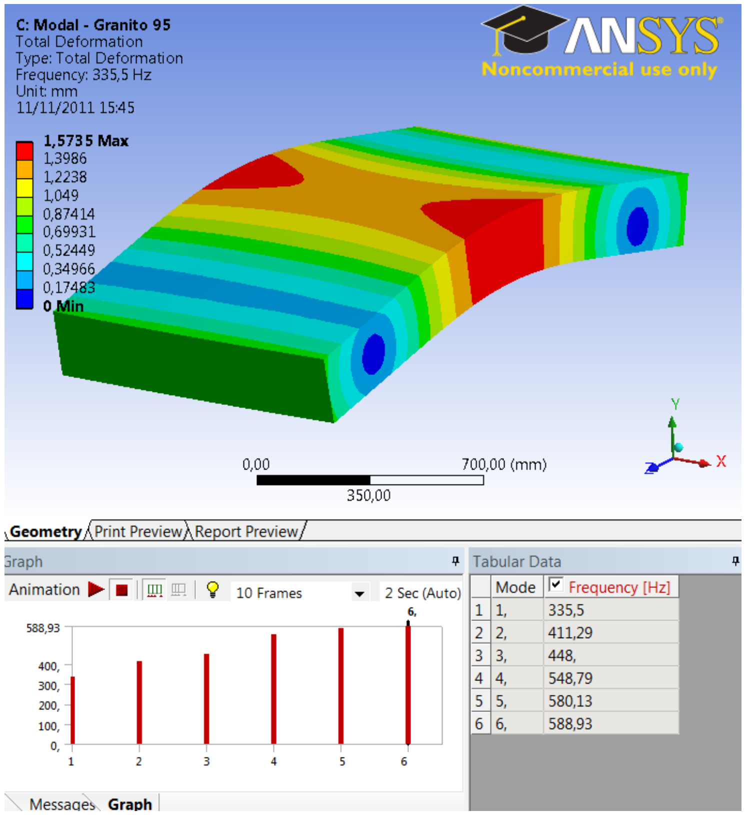

Figure 6 ANSYS simulation of granite slab first mode (Young Modulus=95000MPa, Density=2.85e-006 kg mm^-3, Poisson's ratio = 0.3, Bulk Modulus=79167MPa, Shear Modulus=36538 MPa). See text.

3. Newport bench

Figure 7 shows a picture of the bench and supporting legs. The bench is a model RS-1000 "Sealed hole table top with tuned dumping" by "Newport", size is 240x120x20cm3, weight about 500kg (Newport catalogue). The bench is supported on four single legs model "LabLegs RL-2000" by "Newport". This bench implements a tuned dumping system designed to reduce the Q of internal bench modes (http://www.newport.com/servicesupport/Tutorials/default.aspx?id=134).

Figure 8 below compares vertical acceleration spectra. Figure 9 shows a tentative evaluation of the vertical transfer function, and Figure 10 shows bench horizontal vibrations.

Similarly to the granite table we note a few peaks around 50Hz in the vertical (more precisely: 44Hz, 50Hz and 62Hz, Q=10) and one peak at 13Hz (Q looks a bit smaller than for granite, our guess is Q=30) in the horizontal direction. At these frequencies, in quiet condition, the bench top moves a bit more than the floor. As well, there are peaks at higher frequencies, starting from 167Hz (Figure 9) then 205Hz, 300Hz, 520Hz. The Q of these higher frequency modes is relatively small (smaller than for granite), ranging from 40 down to 10 (Figure 9). All these modes (including the 50Hz) excite easily when knocking on bench.

We would associate the 50Hz vertical modes and the 10Hz horizontal mode to the elasticity of legs contacts (although the fact that they excite easier knocking on the bench than jumping on floor, is puzzling). The higher frequency modes (from 167Hz) could be bench modes.

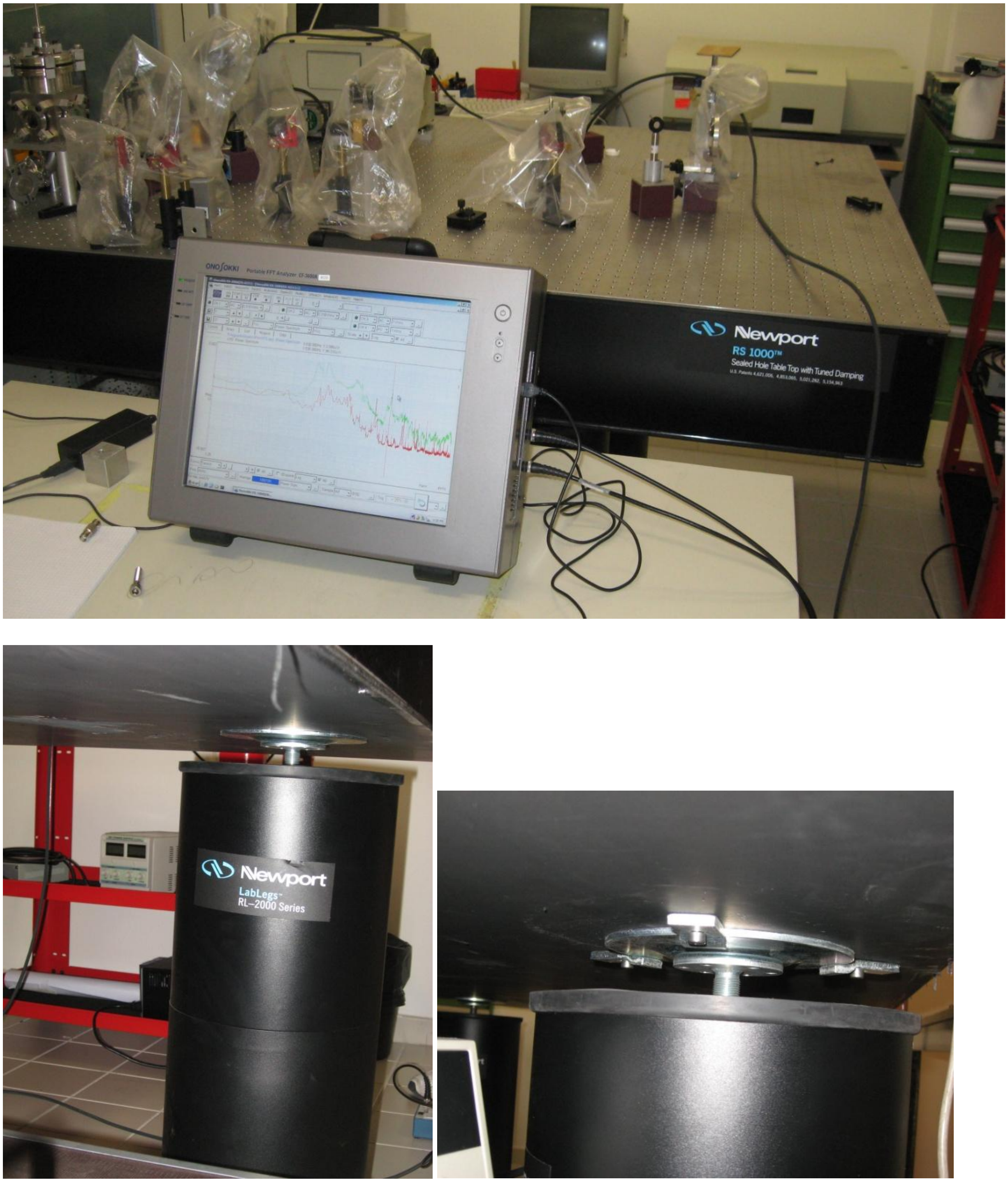

Figure 7 (top) picture of Newport bench; **(bottom)** details of legs.

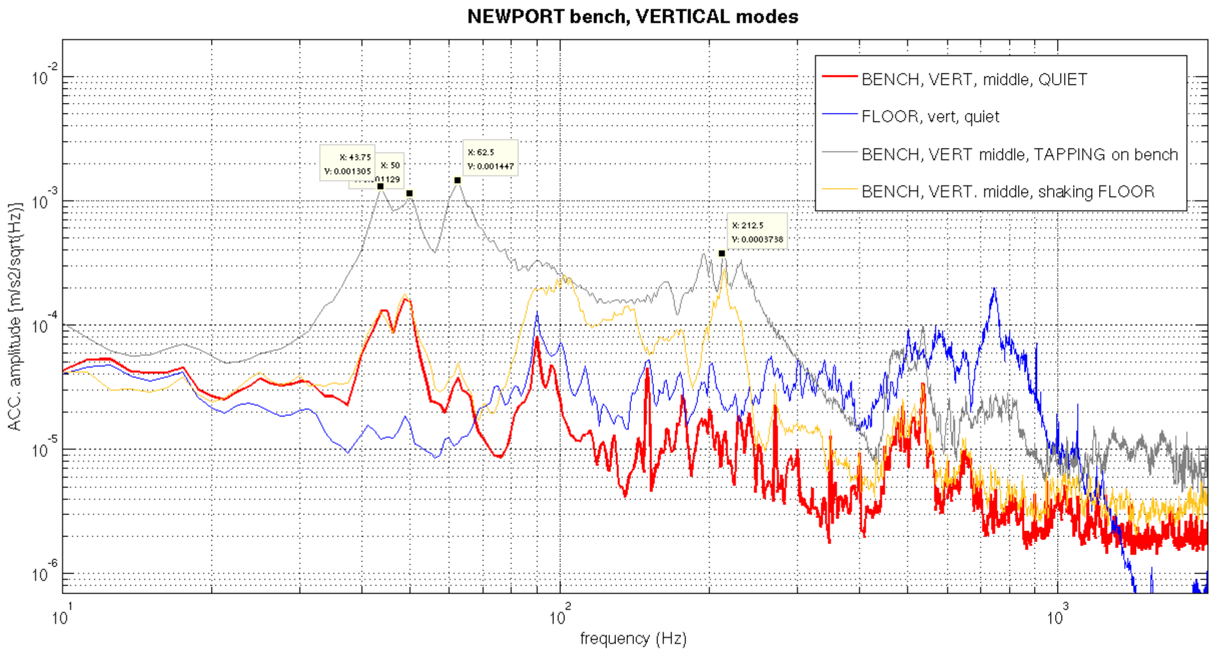

Figure 8 Vertical acceleration of Newport bench top (red) and floor (blue) in quiet condition. Bench motion is measured at the bench center. Grey curve is the bench top acceleration when knocking on the bench, Yellow curve is the bench top acceleration when stepping hard on the nearby floor.

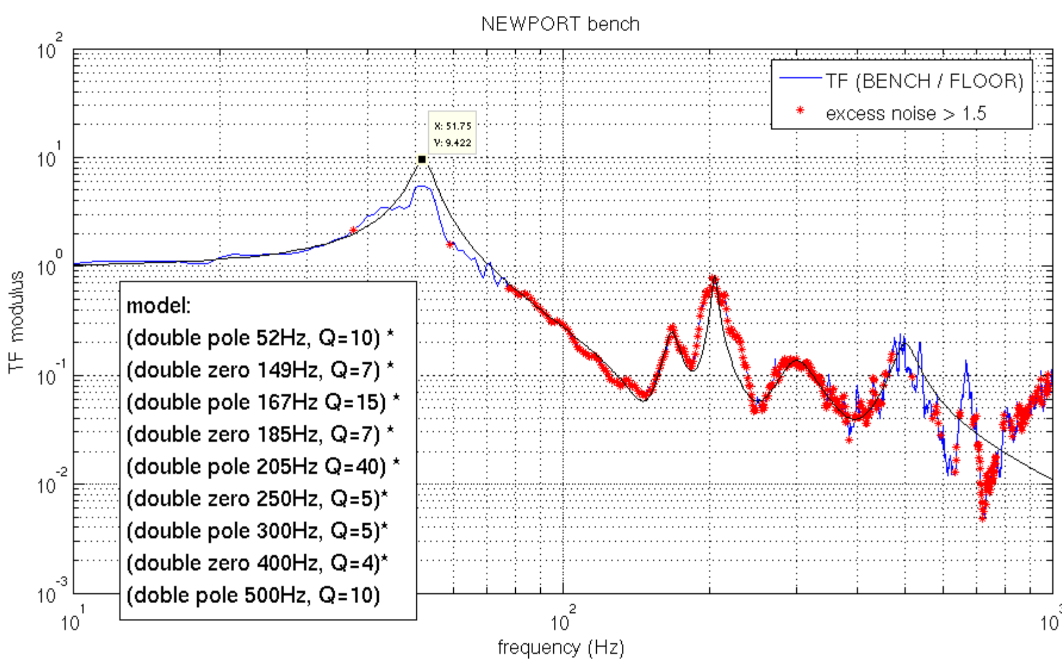

Figure 9 Transfer function of vertical seismic vibration from floor to bench top. Black curve is a by-eye model.

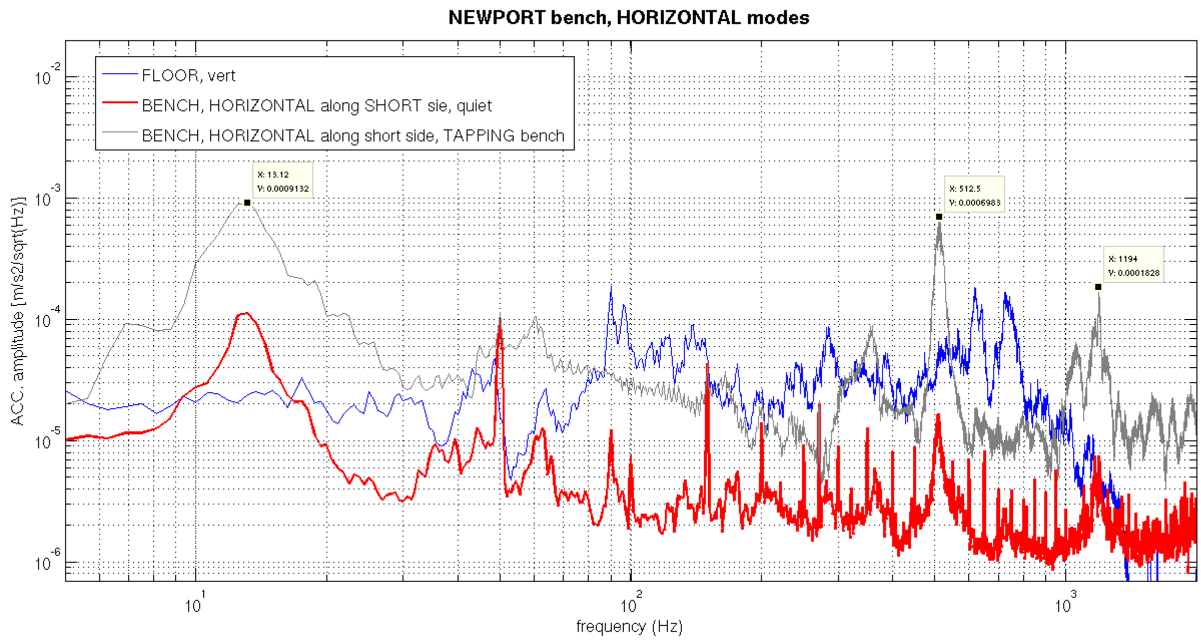

Figure 10 Horizontal acceleration of Newport bench top (red) measured at bench center, and Vertical acceleration of floor (blue). The blue line is shown for reference. Grey line corresponds to knocking on bench side.

4. Conclusions

Apart from modes associated to the table structure, when considering the rigidity of the bench plate itself, the granite one is preferable. The bench is rigid up to 800Hz, except for one single resonance at 330Hz. This sole resonance has relatively high Q (around 100) which makes reasonably easy to dump it with a tuned resonator (similar to the one realized for the End Benches) if needed.

Other items that remain to be defined are: (1) we need M6 through-holes on the bench to clamp test setups, a grid of 10cmx10cm holes could be sufficient, this can be done by the vendor; (2) we do not need an exceptionally good bench planarity (as required when granite bench are used for metrology applications), a value of planarity deviation of 60µm over the entire bench surface (corresponding to “grade 3” standard, as quoted for example by Micro-plan) is sufficient, being it better that the corresponding value quoted for standard optical benches as for example Newport; (2) we have to study how to make the table support more rigid. However, standard conical legs can be adopted at first. This solution does not prevent us inserting a more rigid support underneath the bench at a second time.