Design and Characterization of a Light Frame KB Table and Comparison with a Concrete Block Support

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Abstract

In order to use a Kirkpatrick-Baez (KB) mirror set-up, a new support has been developed at the ESRF. Low mass and high rigidity were primary targets. Particular attention was also paid to the stiffness of the "floor / table" interface. Stability was assessed using vibration as well as static measurements. A direct comparison with a heavy concrete block KB support was performed. Both of them can be moved on a marble floor, with pneumatic pads.
The results show that the lighter KB table, mounted on more rigid feet, provides a more stable solution than the massive assembly. Indeed, the larger overall stiffness to mass ratio leads to higher frequency rigid body vibration modes. The first natural frequency mode (85Hz) explains the superior performance of the light frame table. This table allowed, in particular, to decrease the spot size obtained with a 20keV X-ray beam to less than 0.2x0.2 µm [1].

Keywords: vibration, mechanical stability, stiffness, natural frequency

1. Introduction

Located in Grenoble, France, the European Synchrotron Radiation Facility (ESRF) is operating a powerful source of light in the X-ray range. Serving fundamental research and industry, the ESRF provides experimental facilities to a wide community of scientific users in the fields of physics, chemistry, materials and life sciences.

The high-resolution diffraction beamline is one of the two long beamlines at ESRF, which are located in separate buildings. The distance from the wiggler source to the experimental hutch is 145 m. This provides ideal conditions for applications such as X-ray diffraction topography, tomography, radiography, and X-ray imaging in general. The long distance provides low angular divergence and superior coherence properties.

New experiments using a Kirkpatrick-Baez (KB) mirror set up [2] in order to de-magnify the photon beam to reach the smallest possible spot size require very high dynamic stability of the mechanical support assemblies. A new KB table designed with this need in mind has recently been built at the ESRF in order to fulfill these mechanical stability requirements.

A KB support used on the Microfocus beam line built with different concept and material, has also been measured in dynamic mode. A comparison between these two supports is significant.

2. New Light KB Support

2.1 Principle and Design Choice

Vibration levels present on any given mechanical structure depends on:
- The excitation provided, in our case the floor movements induced by remote or local seismic sources
- The inherent response of the structure, which will exhibit vibration modes of various shapes, which can be derived from the mass, stiffness and damping characteristics.

Therefore, one important factor to be considered when designing a structure is the first natural frequency. In general terms, for a single degree of freedom the fundamental (or first) natural frequency can be expressed as:

$$\mathrm{f} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

f: natural frequency (Hz)
k: stiffness (m/N)
m: mass (Kg)

Since the diffraction beam line floor excitation (roughly decreasing by 3 dB per octave in frequency) shows a peak at 24.6 Hz, the natural frequency should be higher than this value. Therefore the support has to be light, with high stiffness.

2.2 Characteristics

The following characteristics are established to permit the mounting of different set-up, with a maximum load of 500 N, on the diffraction beam line. The drawing Fig. 1 shows the support.

The working surface (top plate) with an area of 900×750 mm can be removed to install an experiment with a central ion pump. In order to benefit from lightweight and relatively high stiffness, a honeycomb table was chosen.

A vertical movement (Z direction) is necessary to adjust the set-up with respect to the X-Ray beam; it is achieved with four lockable manual wedge elevators (stroke: 8mm). Their accuracy (±0.01 mm), and the presence of a ball joint allow an angular adjustment in (ΘX and ΘY) of ±0.5° with ±20 µrad accuracy.

The experimental hutch floor is made in marble with a flatness value of about 0.1mm per square meter. Thus pneumatic air pads allow the displacement of the support, these are described in paragraph 2.3. We retain the possibility of using 3 or 4 air pads to test the best performance. In the 3 feet configuration, they are located at the summit of an isosceles triangle and in the 4 feet configuration, one is adjustable in Z direction. For the frame, aluminum was chosen for its low density. A 90x90mm extruded profile with 18.10^5 mm^4 quadratic inertia is used; all parts are screwed together and sidewalls (8 mm thickness) enclosed the frame. Total mass is about 220 Kg.

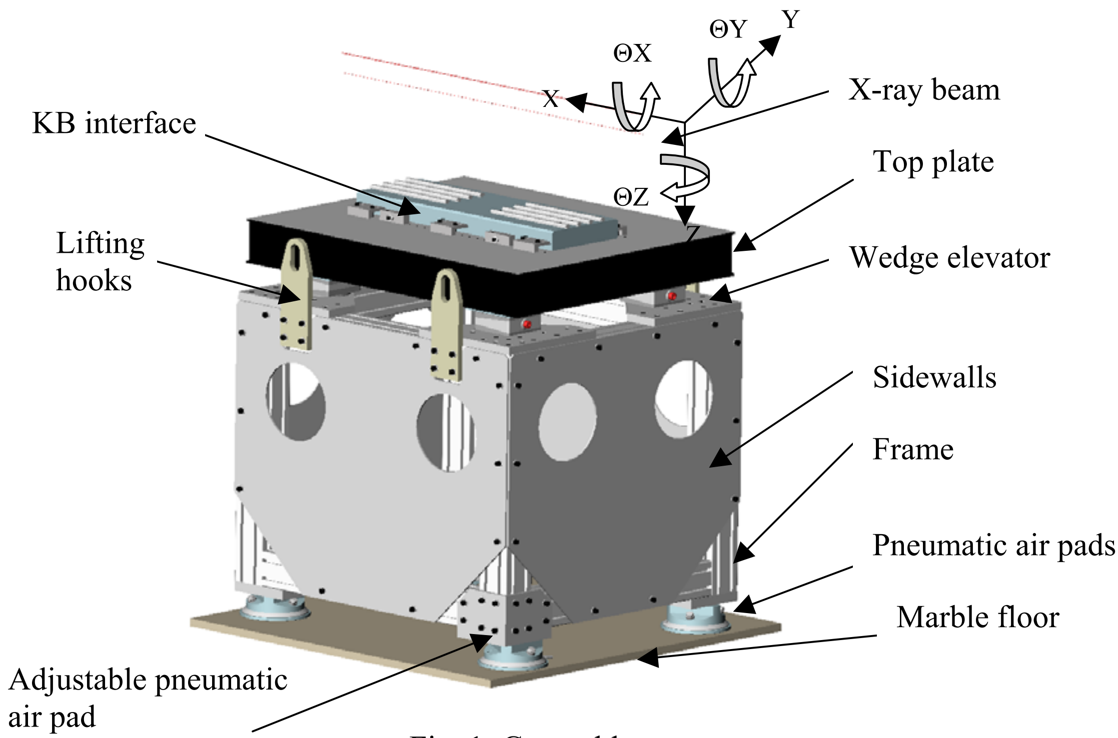


Fig. 1: General layout.

2.3 New Pneumatic Air Pads

Many vibration measurements made at ESRF shows that the pneumatic air pads are a source of instability in all support concerned; there are two main reasons:

- Inefficient ball joint locking implies low stiffness
- Floor contact pressure is not high enough to provide high rigidity

Air pads developed at ESRF partly solve these problems; they are shown in Fig. 2 and Fig. 3.

This air pad is fully lockable with the ball joint blocking screws. Clearance between the screw and the hole allows an angular adjustment of 1°. Material employed for the upper and lower part (brass and stainless steel) with a good surface finish (Ra:0.8) allows smooth movements.

Sliding on the marble is obtained with a 1.5 bars compressed air thin film. The air pad can also be used as a depression chamber. A Viton O-ring, which can be compressed to the marble floor by a external screw mechanism, provides the seal. Vacuum is created using a rotary pump with a pressure limit at 10^{-2} mbar.

Fig. 2: General view of an air pad.

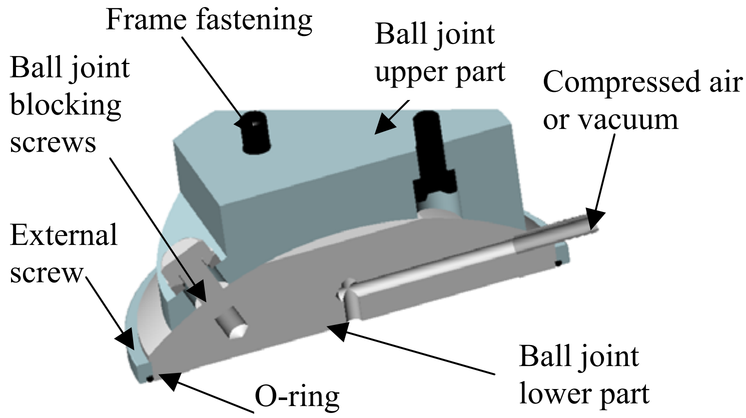


Fig. 3: Section view of a pad.

Having a high adherence under vacuum and a smooth movement with compressed air implies optimization of the compression chamber's volume located in the lower part. When this volume is too large, whatever the air pressure, major instabilities appear and if it is too small, the depression chamber is not efficient. Figure 4 shows a section view of this part.

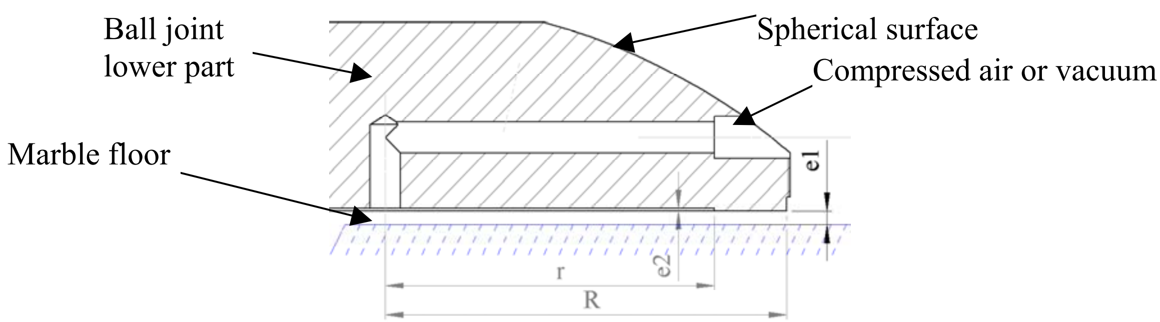


Fig. 4: Partial section view of the lower part.

e1: ride height (mm)
e2: compression chamber (mm)
r: internal diameter (mm)
R: outside diameter (mm)
Air pad ride height, average at value of about 15.10^{-3} mm.

Many tests have been done with compressed air pressure of 1.5 bars. The empirical formula (2) was deduced from these experiment results:

$$e2 \leq \frac{\Delta e1(R^2 - r^2)}{r^2}, \tag{2}$$

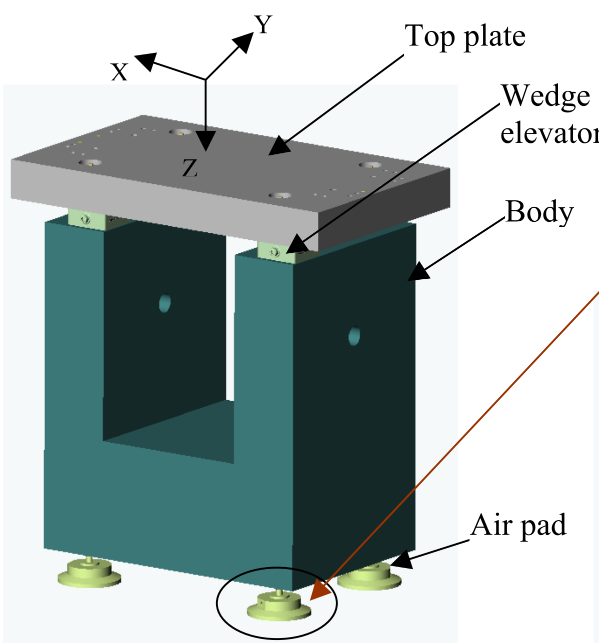
with $\Delta = 10$ (experiment value).

3. Heavy KB Support for Microfocus Beamline

3.1 Design and Characteristics

The support shown in Fig. 5 is a design with a different concept; focusing on the stiffness of the body and having a total mass of 800 Kg. The whole structure is mounted on commercial air pads.

Top plate is in marble and the body in concrete, four wedge elevators allow a displacement of 8 mm and the four air pads are screwed with M16 treaded rod (Fig. 6 and Fig. 7), the ball joint cannot be blocked.



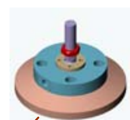


Fig. 6: Commercial air pad.

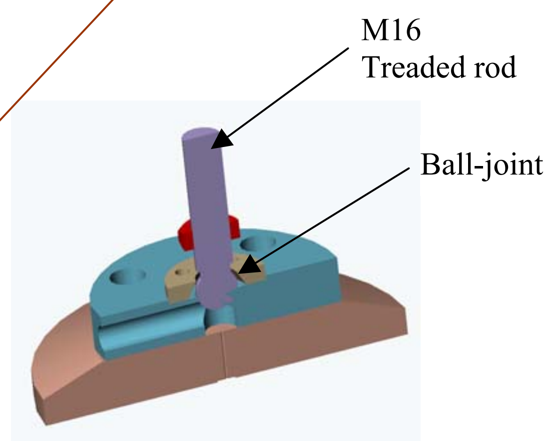


Fig. 5: Layout of heavy support.

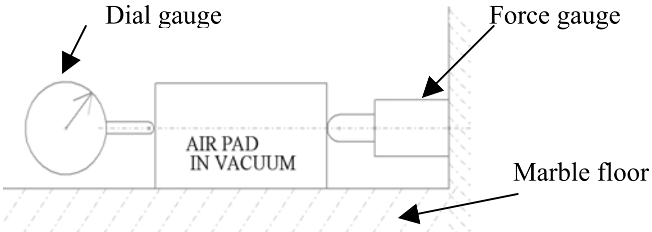
Fig. 7: Section of a commercial air pad.

4. Results

4.1 Static Results (only for the light frame)

4.1.1 Adherence of a New Air Pad

Figure 8 shows the experimental set-up used to determine the maximum lateral force we can apply before sliding occurs. The air pad vacuum is 10^{-2} mbar, O-ring seal is in contact with the marble, and the dial gauge needle begins to move with a force of 20 DaN (reproducibility: 2 DaN).



Precision measurement:
Force gauge: ±10 N
Dial gauge: 10-4 mm

Fig. 8: Sliding test.

4.1.2 Experimental Set Up for Static Measurement

Experimental set up shown on Fig. 9 enables characterization of the static performance of the light support. Dial gauge 1 (Dg1) measures the frame deflection giving the overall stiffness. The sliding occurs when dial gauge 2 (Dg2) indicates a value above 10 µm.

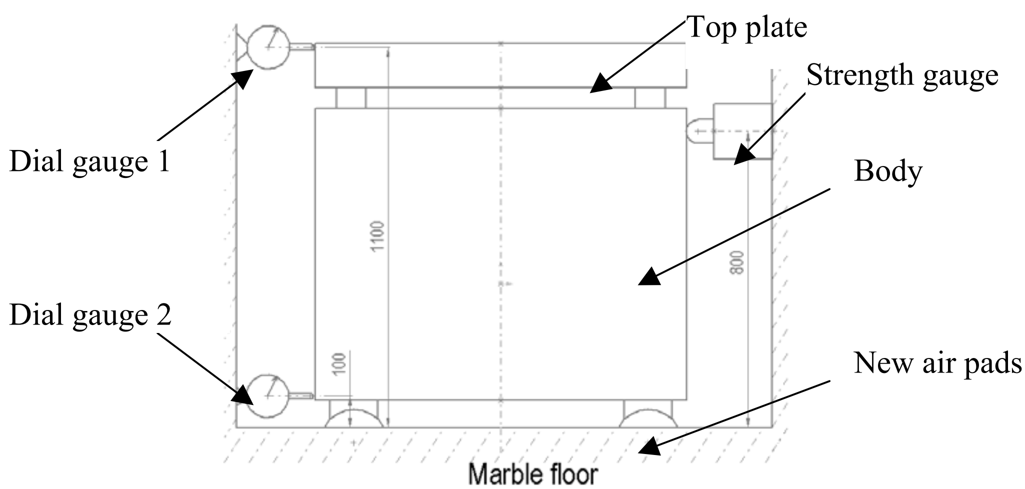


Fig. 9: Set up for static measurements.

Many measurements were made in different configurations. The applied lateral force was stopped when Dg2 moved. In Fig. 10 and Fig. 11, only the values of Dg1 are noted, Dg2 stays at zero.

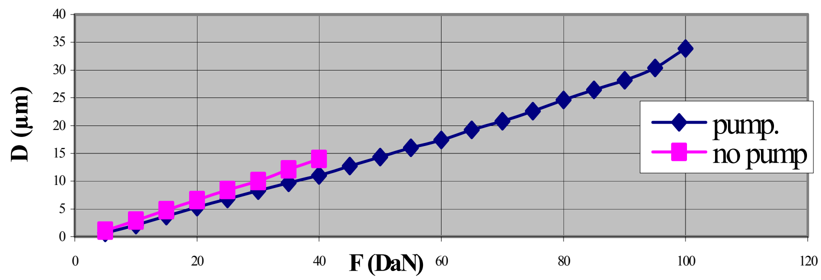


Fig. 10: Static test on 3 pads with vacuum or atmospheric pressure.

Figure 10 shows the difference of adherence when the air pads are under vacuum or not, the support is on 3 air pads. The lateral strength increases by a factor of 2.5 when the depression chambers are under vacuum.

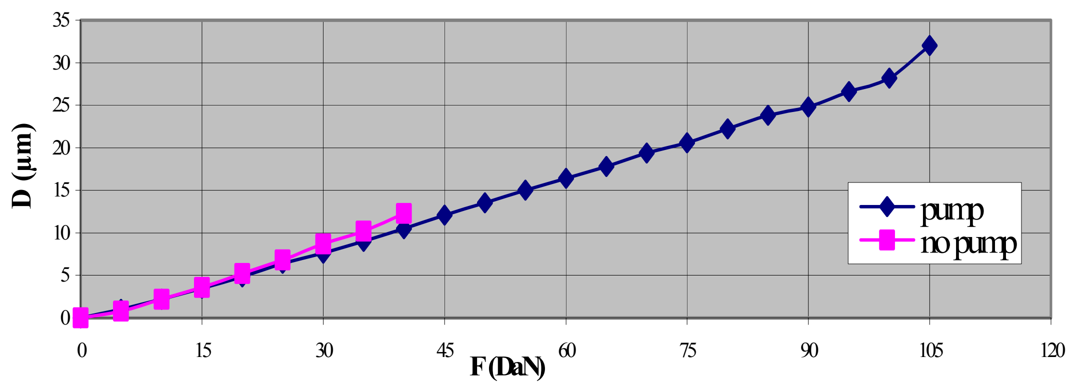


Fig. 11: Static test on 4 pads with vacuum or atmospheric pressure.

Whatever the adjustment of the fourth air pad, we see on Fig. 11, that the lateral strength is the same as in the 3 pads configuration (Fig. 10), this could be explained by the hyper static system.

Figure 12 shows the influence of the sidewalls, the test was made with 4 air pads under vacuum and the four side panels unscrewed.

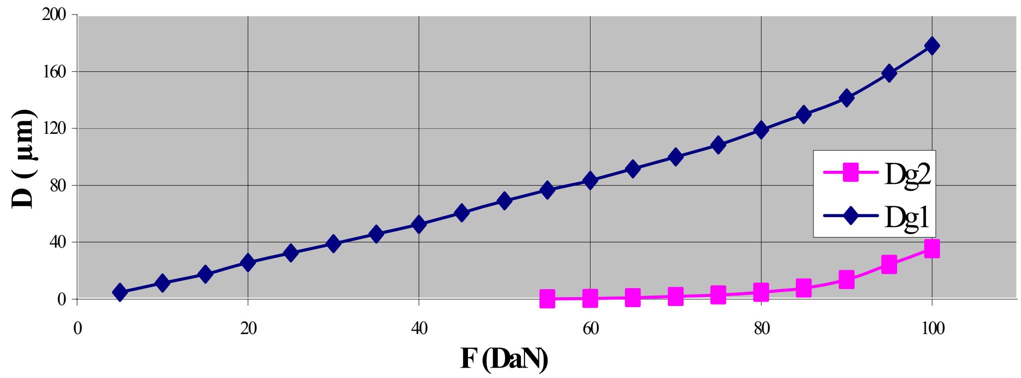


Fig. 12: Influence of the sidewalls.

From the results Fig. 11 and Fig. 12 and using the formula (1), we can calculate the natural frequency F in both configurations.

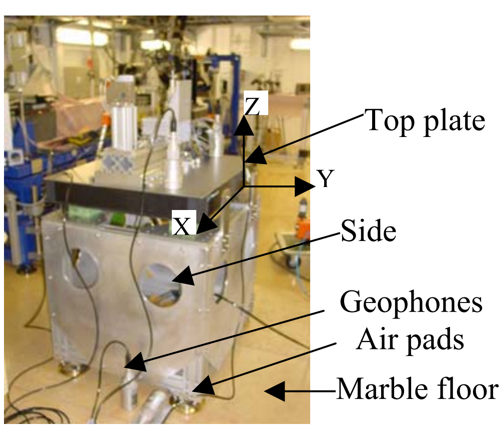
Using the slope in Fig. 11, we deduce a stiffness k_{11}=900/25 10^{-6} =3.6 10^{7} N/m
m=220 Kg
f_{11}= 64 Hz

The same calculation with Fig. 12 gives:
K_{12}=6.6 10^{6} N/m
F_{12}=27 Hz

4.2 *Dynamic Results*

4.2.1 *Experimental Set Up*

Three geophones are installed on the honeycomb table and one on the floor (see Fig. 13) to measure the movements of the top plate related to the marble.



Equipment and data processing:
- L4-C horizontal and vertical geophones.
- SIGLAB spectrum analyser, sampling @ 256 Hz & AC coupling.
- Data processing with Matlab
  Time domain integration, high pass filtering (4 Hz) of geophone signals. Flat top windowing for PSD's.
- Useful bandwidth [4 → 100 Hz]

Fig. 13: Experimental set up for dynamic measurements.

4.2.2 Specific Measurements for the Light Support

The four figures below underline the effects of the most important parameters:

- Fig. 14: Natural frequency increases from 45 Hz to 85 Hz when sidewalls are tightened; the calculations we made from the static mode results are pessimistic (27 Hz and 64 Hz).
- Fig. 15: this test is made on 3 pads, which explains the relatively low natural frequency: 62 Hz, the depression chamber permits a gain of 5 Hz (57 Hz to 62 Hz).
- Fig. 16: Effect of locking the ball joint with 4 pads: the natural frequency shifts from 65 Hz (unlocked) to 82 Hz (locked).
- Fig. 17: The frame of the light support allows the mounting of 3 or 4 pads. Due to the hyper static mode on 4 feet, the values for static results (Fig. 10 and Fig. 11) are similar. In dynamic mode we can measure a real difference: from 62 Hz (3 feet) to 85 Hz (4 feet).

Therefore, the ideal set-up of this support as far as stiffness is considered would be with 4 feet, ball joints locked and side panels firmly screwed on the frame. The depression chamber under vacuum has only a marginal effect.

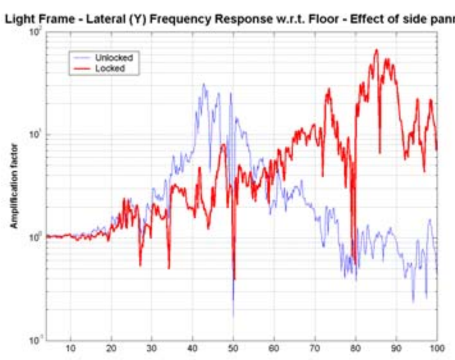


Fig. 14: Effect of sidewalls (4 pads).

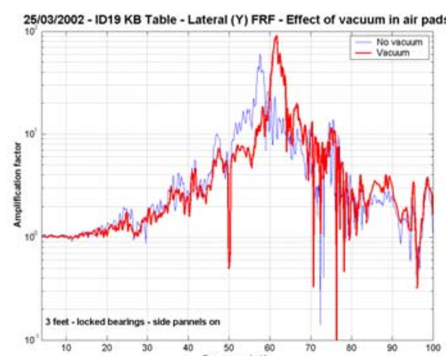


Fig. 15: Effect of air hole (3 pads).

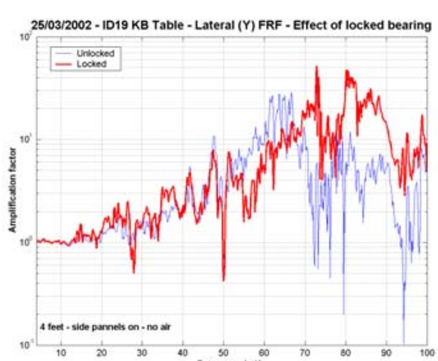


Fig.16: Effect of locked ball joint (4 pads).

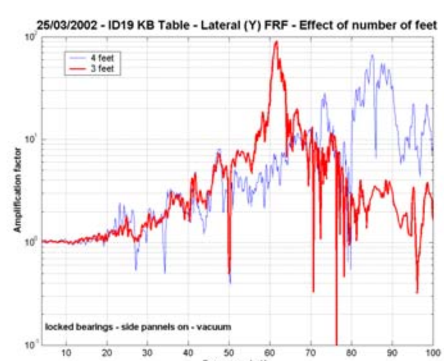


Fig.17: Effect of number of feet (4 pads).

4.2.3. Comparison Between Light and Heavy Support

The comparison of the light and heavy supports in dynamic mode is shown in Figs. 18, 19, and 20. In all directions the benefit of the new table with "vacuum/air pads" is significant.

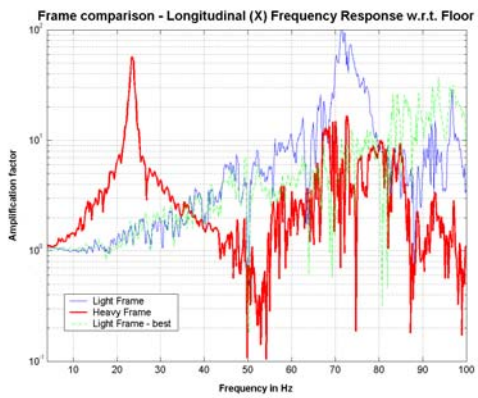


Fig. 18: Longitudinal (X) frequency response with respect to the floor.

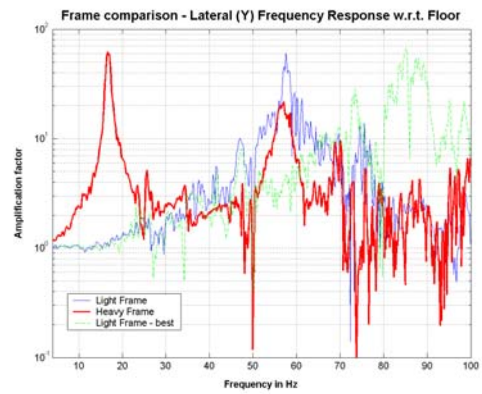


Fig. 19: Lateral (Y) frequency response with respect to the floor.

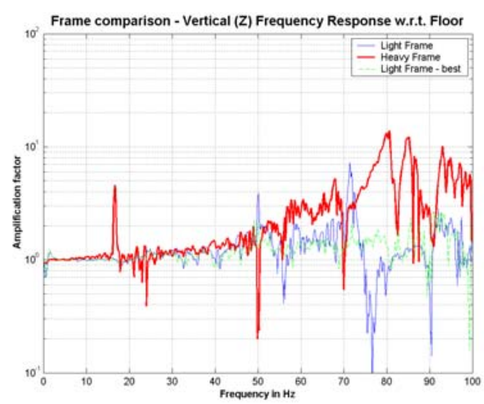


Fig. 20: Vertical (Z) frequency response with respect to the floor.

Results are summarized in Table 1. According to the frequency values listed in Table 1, it is clear that the light support is much stiffer than the heavy structure.

Table 1: Comparison of the First Natural Frequency (Hz)

	Longitudinal (x)	**Lateral (Y)**	**Vertical (Z)**
Light support	>90	85	>90
Heavy support	23	16	16

From Eq. (1) and the lateral frequency response in Table 1 (the worse case), we can calculate the ratio of the rigidity of the two supports:

$$\frac{fl}{fh} = \frac{\sqrt{\dfrac{kl}{ml}}}{\sqrt{\dfrac{kh}{mh}}}$$

With: fl=lateral frequency (light support): 85 Hz
fh=lateral frequency (heavy support): 16 Hz
kl=stiffness (light support) (N/m)
ml=mass (light support): 220 Kg
kh= stiffness (heavy support) (N/m)
mh=mass (heavy support): 800 Kg

The calculation gives: kl=7.8 kh.

This result shows clearly that the low stiffness of the commercial pads is the most penalizing parameter of the heavy support even more important than the mass factor. This is illustrated in Table 2, which lists the peak-to-peak levels and amplifications with respect to floor.

Table 2: Finals Results for Comparison of Light and Heavy Support

	Air	S.P.	Feet	Bear		Vertical (Z)			Longitudinal (X)			Lateral (Y)			Θy Rot.
						Floor	Top plate	Rel. %	Floor	Top plate	Rel.%	Floor	Top plate	Rel.%	
Heavy Frame	No		3	Unl.	dpp	0.76	0.83	9.7	0.94	1.2	27.8	0.46	1.97	326.7	0.25
					rms	0.12	0.13	5.5	0.09	0.12	44	0.07	0.29	291	0.04
Light Frame	No	Yes	3	Lock	dpp	0.65	0.65	0	0.41	0.46	10.8	0.42	0.43	2.1	0.06
					rms	0.11	0.11	0.8	0.06	0.07	6.8	0.06	0.07	3.8	0.01
	Vac	Yes	4	Lock	dpp	0.67	0.69	2.5	0.31	0.33	7.7	0.49	0.53	7.6	0.09
					rms	0.11	0.11	1.5	0.05	0.05	3.1	0.07	0.07	4.9	0.01
	No	No	3	Lock	dpp	0.56	0.56	0	0.46	0.51	12	0.44	0.59	34.5	0.08
					rms	0.09	0.1	2	0.07	0.08	7.1	0.07	0.08	13.8	0.01

Legend for Table 2:
Air Vac → under vacuum, No → atmospheric pressure
Side Panels Yes → fully tightened, No → loose
Feet 3 or 4 air pads configuration
Bearing Ball joint locked or unlocked
Peak to peak (ddp) and rms displacement level

The amplification relative to the floor is also indicate (expressed as the ratio of the table motions/floor). All results are expressed in μm and μrad, and are valid for a bandwidth from 4 Hz to 100 Hz.

5. Conclusion

The best configuration of the light support (4 pads, pad under vacuum, ball joint locked, side panels tightened) gives good results. The relative amplification to the floor is 13.8% maximum rms displacement (Table 2) compared to the 291% for the heavy support. The critical value for the KB experiment is ΘY, the maximum value is 0.09 μrad, which is acceptable.

The light support permits the use of the KB set-up on the diffraction beam line and focuses the beam down to 0.2 × 0.2 μm.

6. References

[1] O. Hignette and P. Cloetens, private communication.
[2] P. Kirkpatrick and A.V. Baez, J. Opt. Soc. Am. **38**, 776.