Modal analysis of a scale model of QD0

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Abstract

The last focusing magnets of the future Compact Linear Collider (CLIC) are critical elements needed to reach the desired luminosity. Designed to guide the nanometer sized focused beams, they need to be as stiff as possible to avoid any unwanted ground motion vibration amplification. Following our recent study concerning CLIC's ground motion mitigation techniques such as the active seismic isolator, the next step is to build a real scale prototype of the QD0. This mock-up is needed to validate experimentally the proposed control strategy. Such a prototype isn't yet available, hence this first study with a scale model of QD0. In this paper, modal analysis is used to analyze the dynamic characteristics of the structure of the prototype. This analysis identifies mode shapes, frequency and damping parameters. The purpose of this paper is to provide model verification by comparing experimental and theoretical modal analysis. The knowledge of these modes would later allow to validate experimentally ground motion vibration damping on that scale model of QD0, and finally on the real scale mock-up of QD0 by predicting the effect of design change.

1. Introduction

The CLIC project is right in the development phase (2012 – 2016) during which the worldwide scientists and engineers have to demonstrate the feasibility to solve all the technological barriers. In this prospect, the final objective of the final focus stabilization is to transfer all the acquired experiences and methods on a real scale prototype and to reduce the displacement of this structure as it is needed for CLIC.

For budget reasons, the QD0 magnet will not be machined during this development phase, but only a slice of it has been already produced by CERN for various tests like magnetic fields (see Fig. 1). However, a real scale structure ("a dummy magnet") will obviously be conceived and machined. The goal is to reduce the cost while maintaining the same main characteristics (dynamics behavior, dimensions, load…).

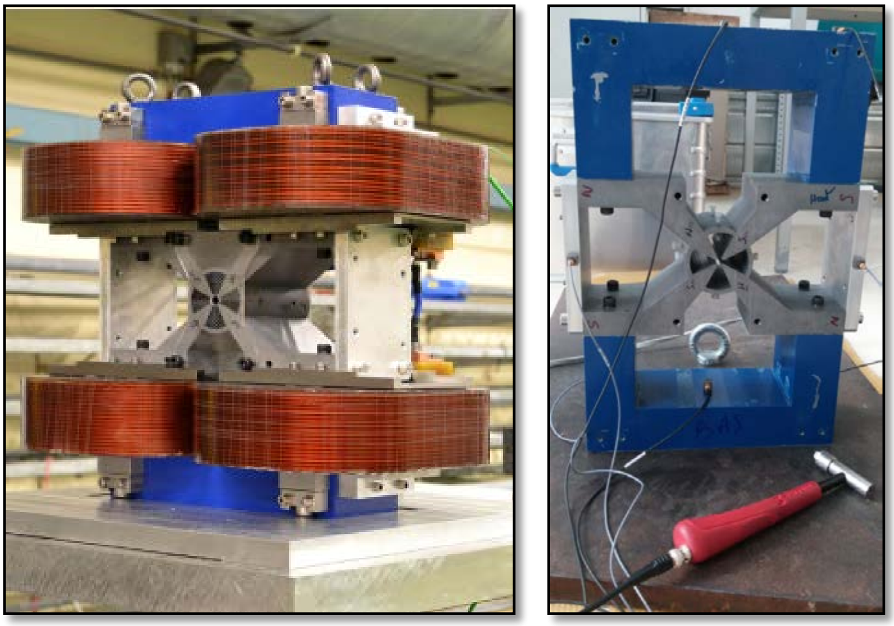


Fig. 1: Slice of QD0 magnet with and without coil.

Each slice is made out of 3 different parts. The central X-shaped part is made of permendur alloy. The right and left sides of the X-shaped part are link by an aluminum plate screwed with a tightening torque of 15 Nm. The upper and lower part of the X-shaped part are screwed to a U-shaped part made of steel with a tightening torque of 20 Nm

2. Theoretical analysis

A finite element model was created in ANSYS in order to evaluate the modal response of the structure for two different boundary conditions. A first one without constrains and a second one with the base perfectly clamped.

Three different isotropic materials were employed in the simulation. A first material (steel) for the upper and lower U-shaped parts with an elasticity modulus of 205 GPa, a Poisson ratio of 0.28 and a density of 7800 Kg/m3. A second material (permandur) assigned to the X-shaped core with an elasticity modulus of 225 GPa, a Poisson ratio of 0.33 and a density of 8125 Kg/m3. A third material associated to the lateral walls (aluminum) with an elasticity modulus of 70 GPa, a Poisson ratio of 0.33 and a density of 2700 Kg/m3. **Different approaches were employed in the modeling of the surface contact between the different components, all of them leading to similar results.** Among the contact models used in the simulations we can mention the perfect bonding, the welding point, and the employment of bolts. **Since no significant differences were observed due to the effect of the surface contact nature, the results shown in this document correspond to those obtained using a perfectly bonded contact model.**

The element type used in the finite element simulation was the SOLID45 tetrahedral which is used for the three-dimensional modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The final model contains 7147 nodes.

3. Experimental setup

Measurement and modal analysis have been split in two campaigns. In the first one, the magnet has been clamped to the ground while in the second test; a free-free modal analysis has been setup by suspending the magnet with a strap. Each test has been done along each horizontal direction. Axes, sensors positions and hammer inputs are shown in Fig. 2 and Fig. 3. Data acquisition software used in this project is Bruel & Kjaer PULSE data recorder type 3560-B-020, 2 DeltaTron tri-axial accelerometer type 4524 and 3 DeltaTron mono axis accelerometer type 4508-B-003. Modal analysis has been realized using ME'scopeVES, a specialized tool for curve fitting the theoretical transfer functions derived with PULSE to the measured transfer functions. Apart from the data acquisition software, the upper and lower magnet motion is also recorded using accelerometer (Wilcoxon 731A, Sensitivity: 10 V/g), 16 bit resolution board (dSPACE ds2004 A/D converter), the signal conditioning realized using Krohn-Hite Model 3384 amplifiers, and the analysis using Matlab. This second (and redundant) measurement is set to strengthen the first experimental setup.

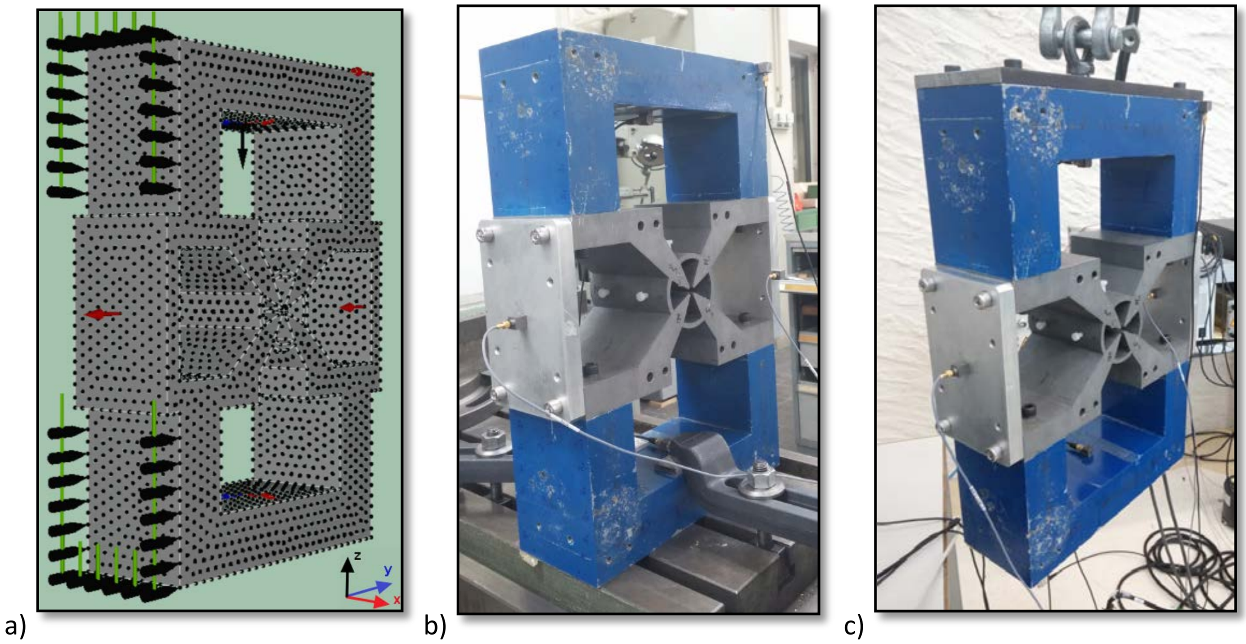


Fig. 2: Measurement campaign with pulse + ME'scopeVES along y direction a) Axes, sensors and hammer positions, b) Clamped QD0, c) Free-free QD0.

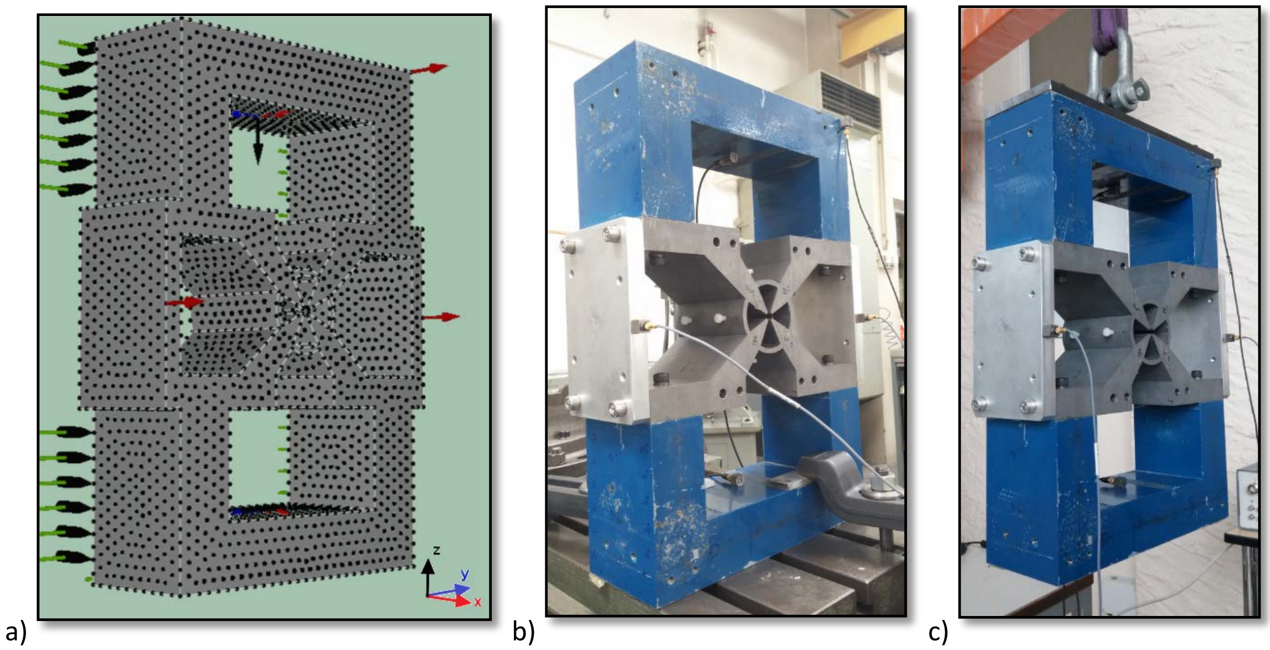


Fig. 3: Measurement campaign with pulse + ME'scopeVES along x direction a) Axes, sensors and hammer positions, b) Clamped QD0, c) Free-free QD0.

In this experiment, the analysis frequency was set as 8192 Hz, average number as 3, with an exponential data window and the manual-armed trigger. With every hit of the hammer, Pulse was triggered by the force transducer on the tip of the hammer. This data is valid only if there is only one hammer hit per data block, which is visible in the excitation time signal, and if the coherence is near 1 which indicates a good signal-to-noise ratio. Time domain waveform and Frequency Response Functions (FRF) data are then generated between each input (respectively 42 and 36 for x and y directions) and output (9 accelerometers). The Pulse operator can accept or reject the data frames with each hit of the hammer based on these criteria. In this case, since the average number was set to 3, three valid data frames will need to be acquired for every excitation point. The FRF data is automatically imported to the correct point on the shape model. ME'Scope analyzes the resonant frequencies and damping factors of all this data to generate the modal shapes shown in the next section using vector interpolation equations (total of 5962 vectors, corresponding to each node of the meshing of QD0, see Fig. 4).

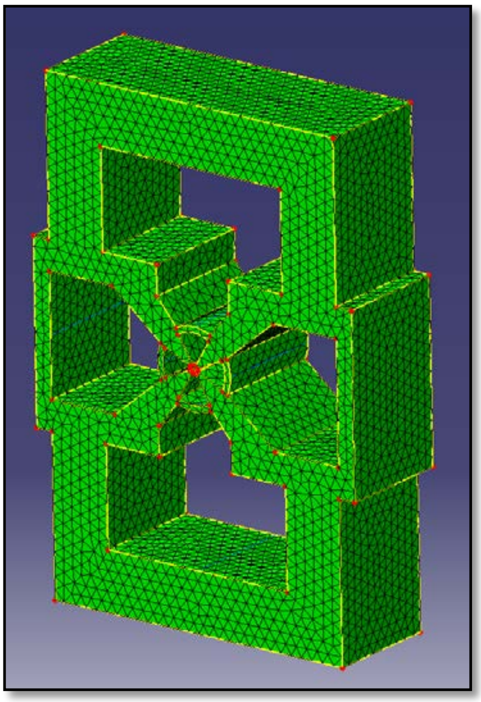


Fig. 4: Triangular 10mm sized surface meshing of QD0 for modal shapes visualization.

4. Experimental results

4.1 Clamped modal analysis

4.1.1 PULSE Labshop + ME'scopeVES

The following results (see Fig. 5 and Fig. 6) represent the first 9 modes and modal shapes measured in each horizontal direction. They are also summarized in section 6. p.15.

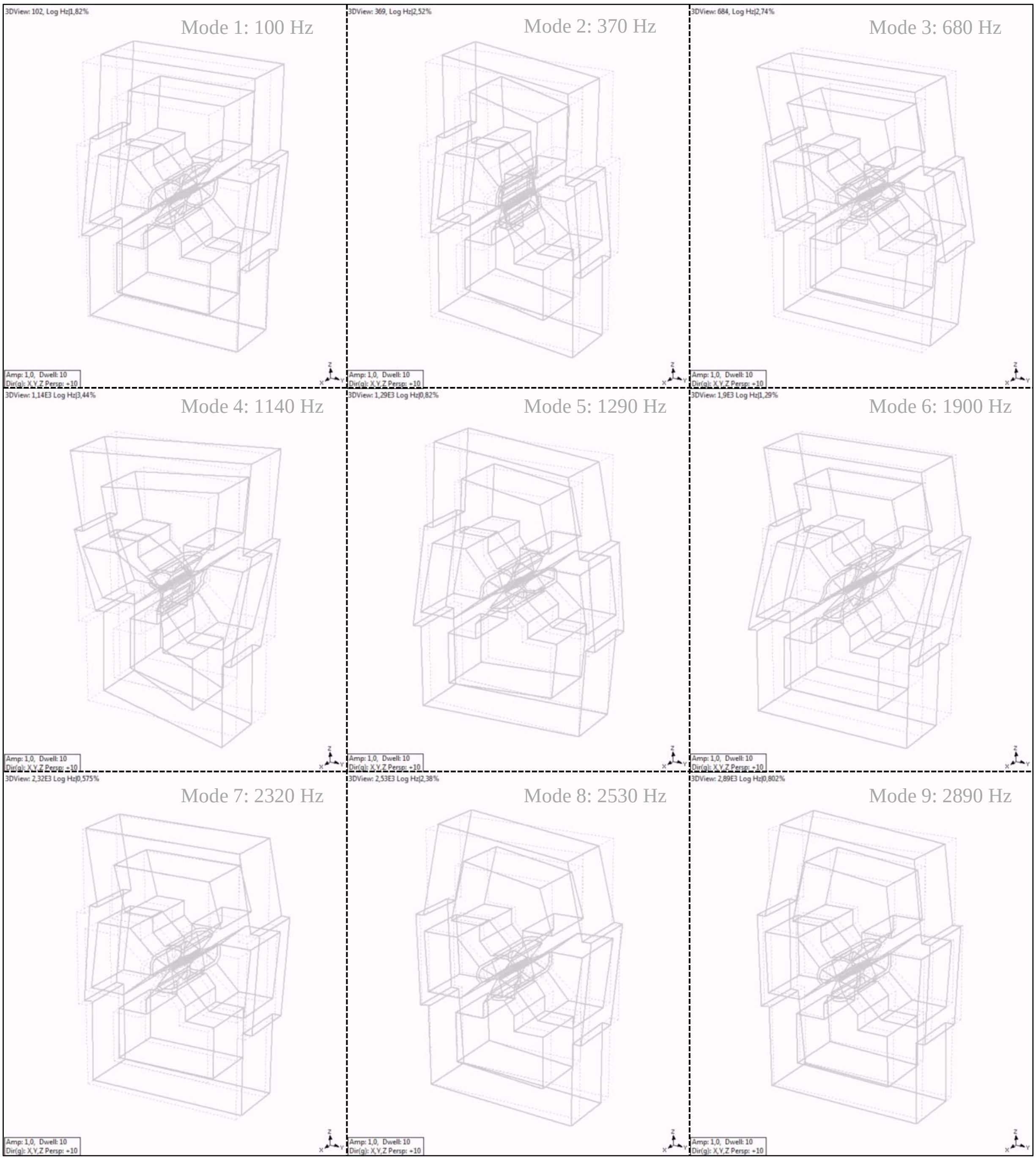


Fig. 5: Clamped modal analysis along x direction (beam axis).

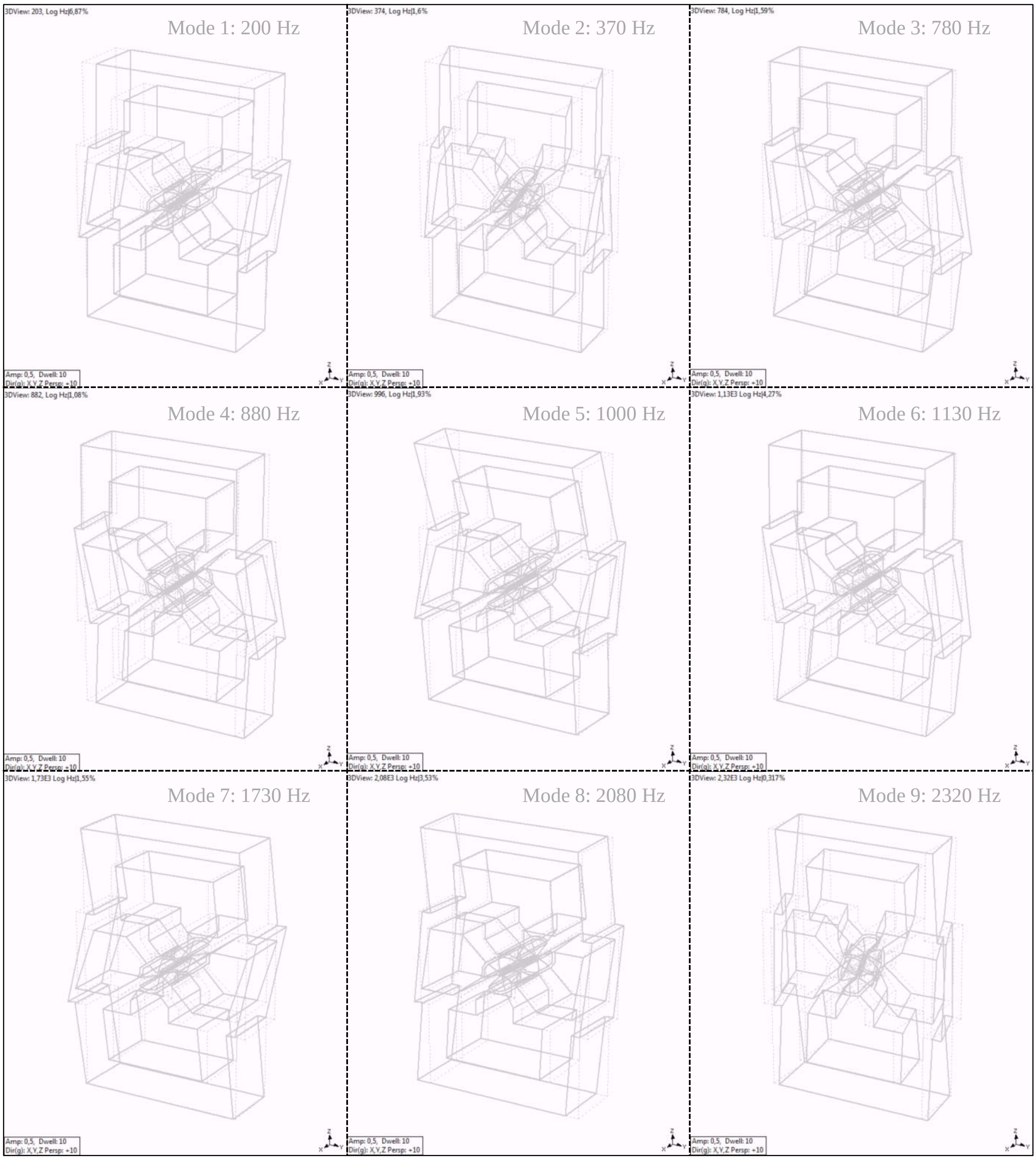
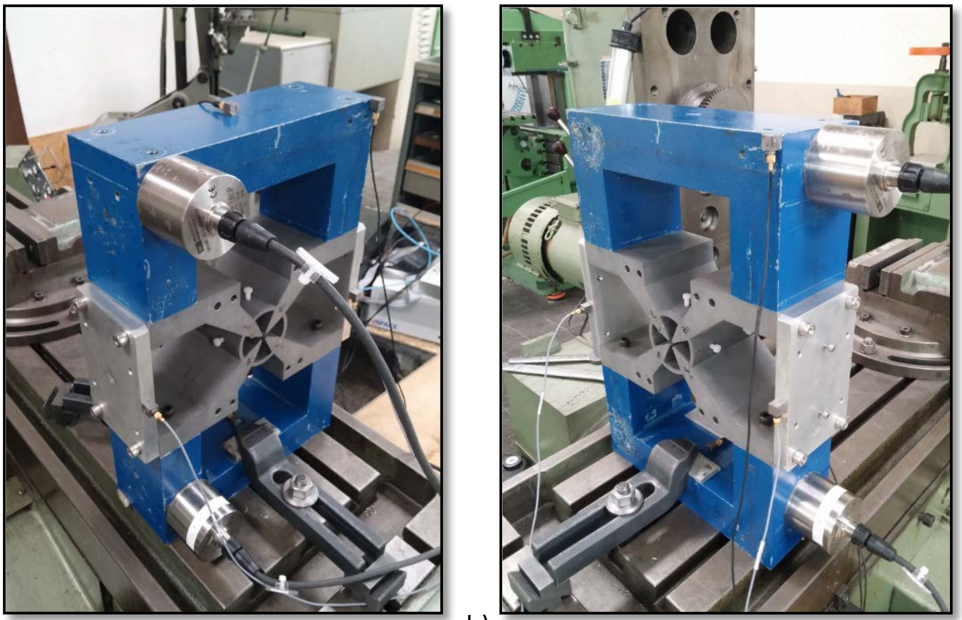


Fig. 6: Clamped modal analysis along y direction (horizontal and perpendicular to the beam axis).

4.1.2 dSPACE + Matlab

Complementary measurements have been realized to strengthen the first analysis. Note that in this experiment, the accelerometers placed at the upper and lower side of the magnet (see Fig. 7) measure its vibrations caused by its environment. Hence, the measured signals (Fig. 8 and Fig. 9) should contain both: frequencies of interest corresponding to the mode shapes of QD0 and other resonant frequencies corresponding to environmental noise (rotating machines in the mechanical workshop such as milling and boring machines).



a) b)

Fig. 7: Measurement campaign with dSPACE + Matlab a) Along x, b) along y.

The following plots show the upper and lower PSD (Power Spectral Density) of the acceleration of the magnet. Note that the sensitivity of the accelerometers being 10V/g, the PSD unit in volts V^2/Hz is equivalent to the PSD unit in acceleration $(m/s^2)^2/Hz$.

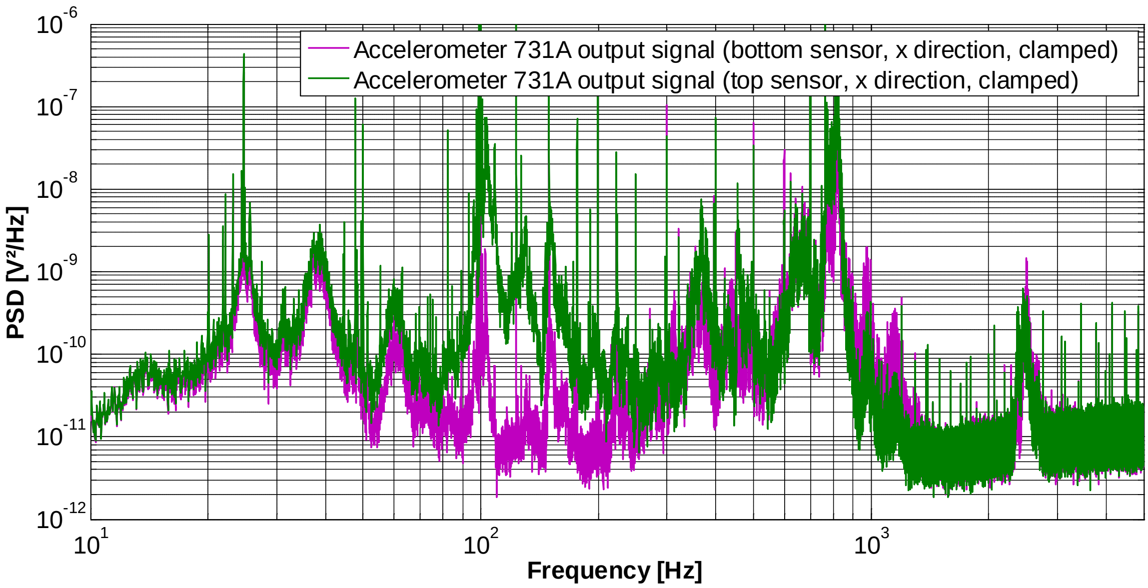


Fig. 8: Clamped QD0 upper and lower acceleration along x.

(b)

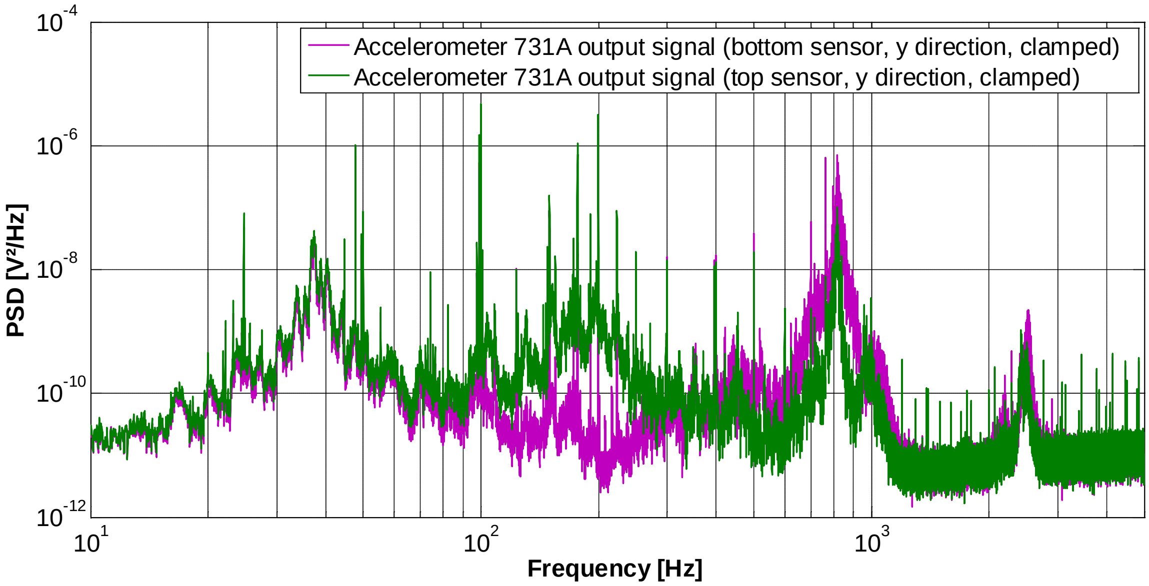


Fig. 9: Clamped QD0 upper and lower acceleration along y.

It is not possible to distinguish easily between mode shapes and environmental noise. However, using the previous study, it is possible to select the pics of interest. The most striking pics have been summarized in the Table 1a and Table 1b in section 6.

4.2 Free-free modal analysis

4.2.1 PULSE Labshop + ME'scopeVES

The following results (see Fig. 10 and Fig. 11) represent the first 9 modes and modal shapes measured in each horizontal direction. They are also summarized in section 6.

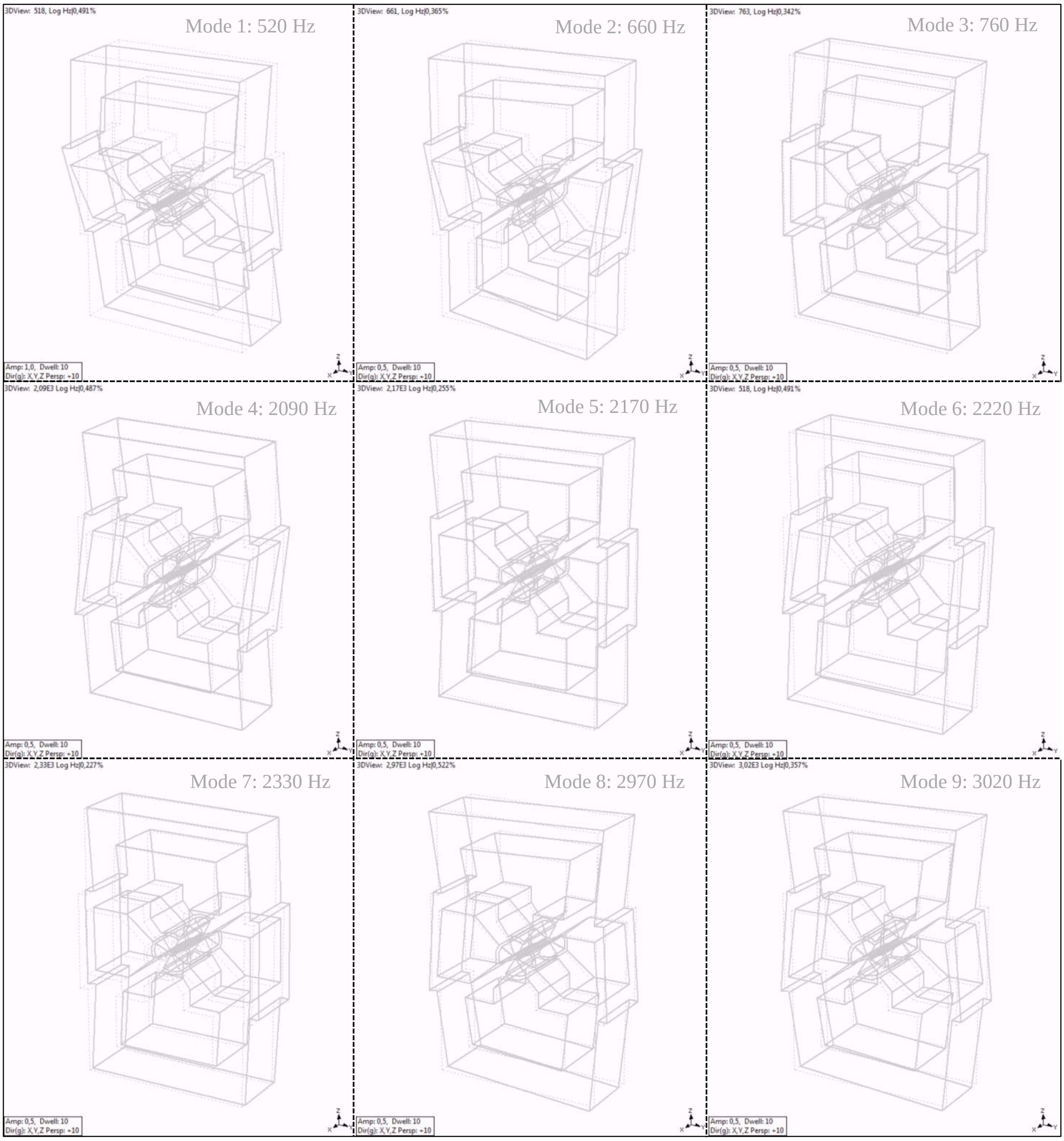


Fig. 10: Free-free modal analysis along x direction (beam axis).

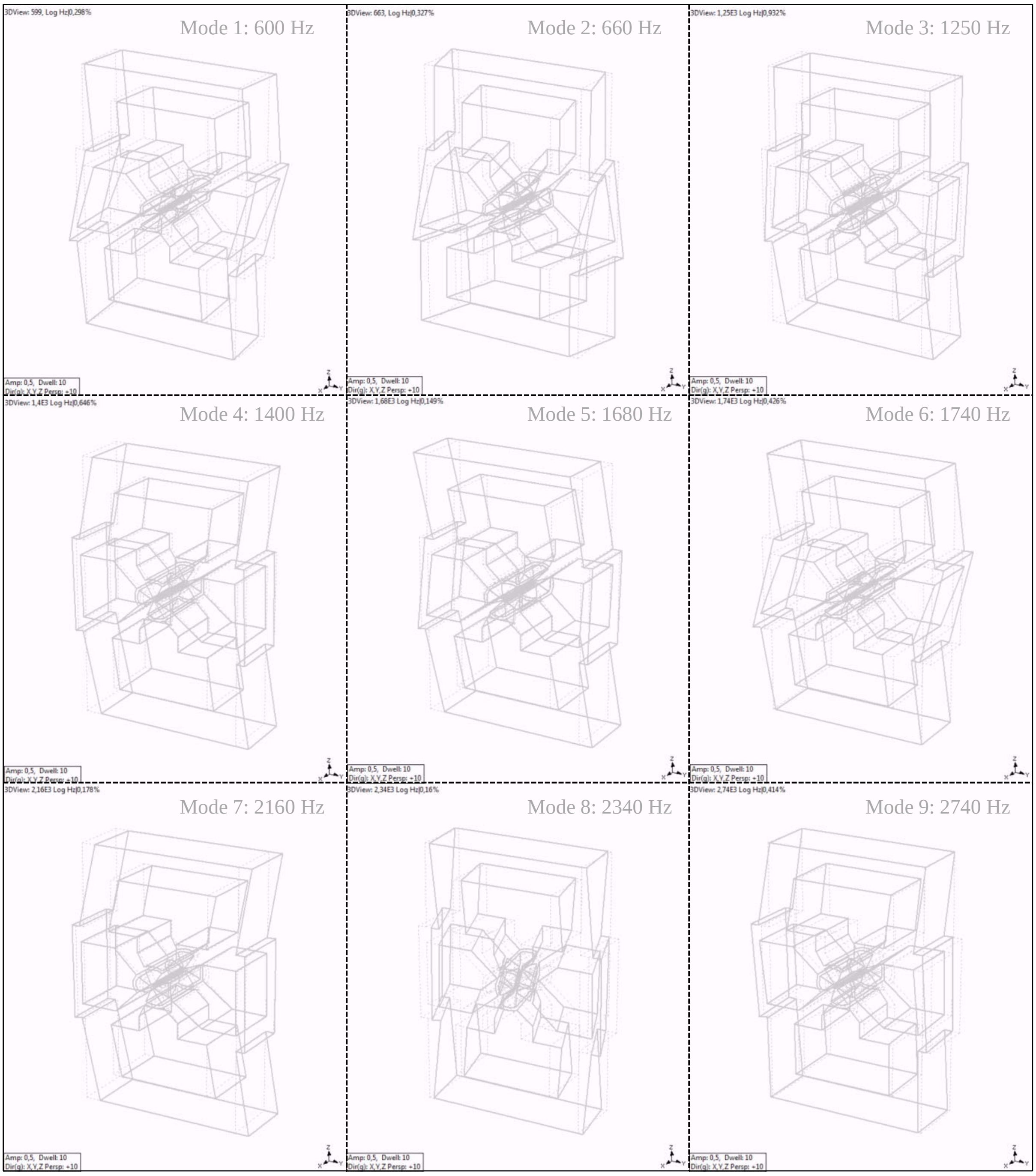


Fig. 11: Free-free modal analysis along y direction (horizontal and perpendicular to the beam axis).

4.2.2 dSPACE + Matlab

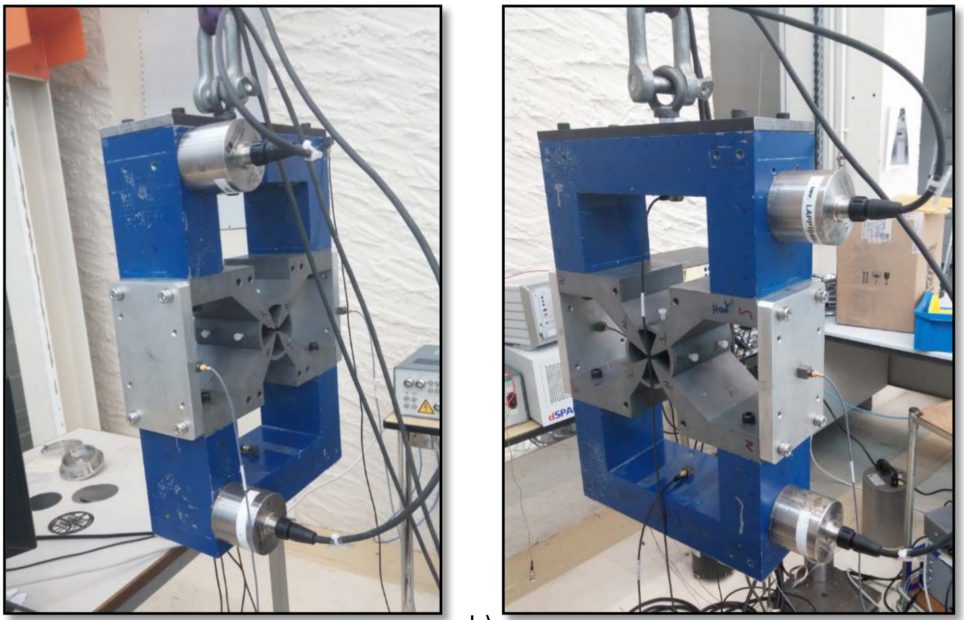

a) b)

Fig. 12: Measurement campaign with dSPACE + Matlab a) Along x, b) along y.

(a)

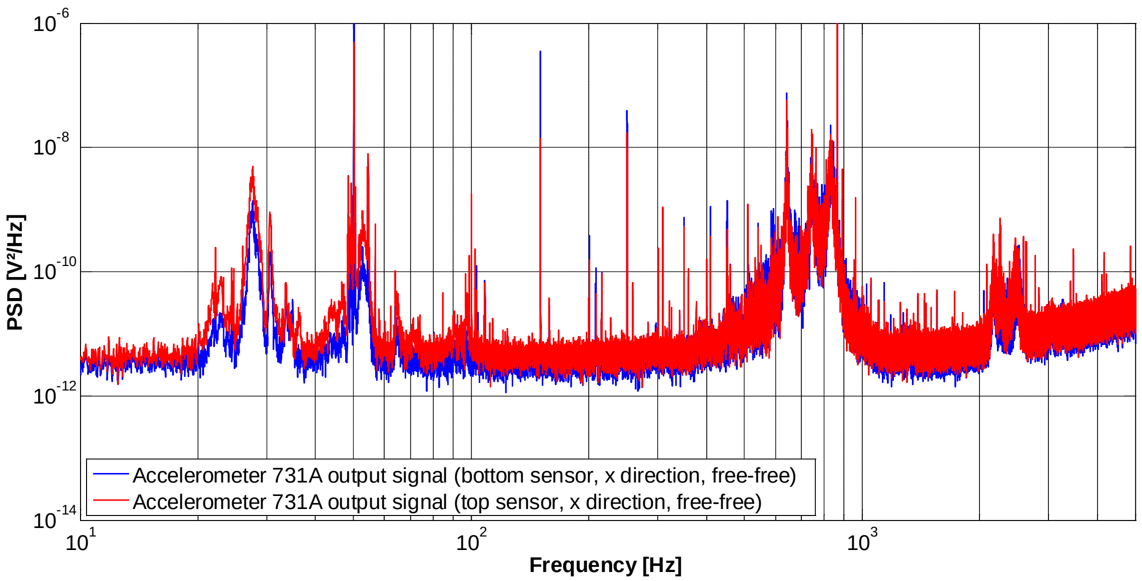


Fig. 13: Free-free QD0 upper and lower acceleration along x.

(b)

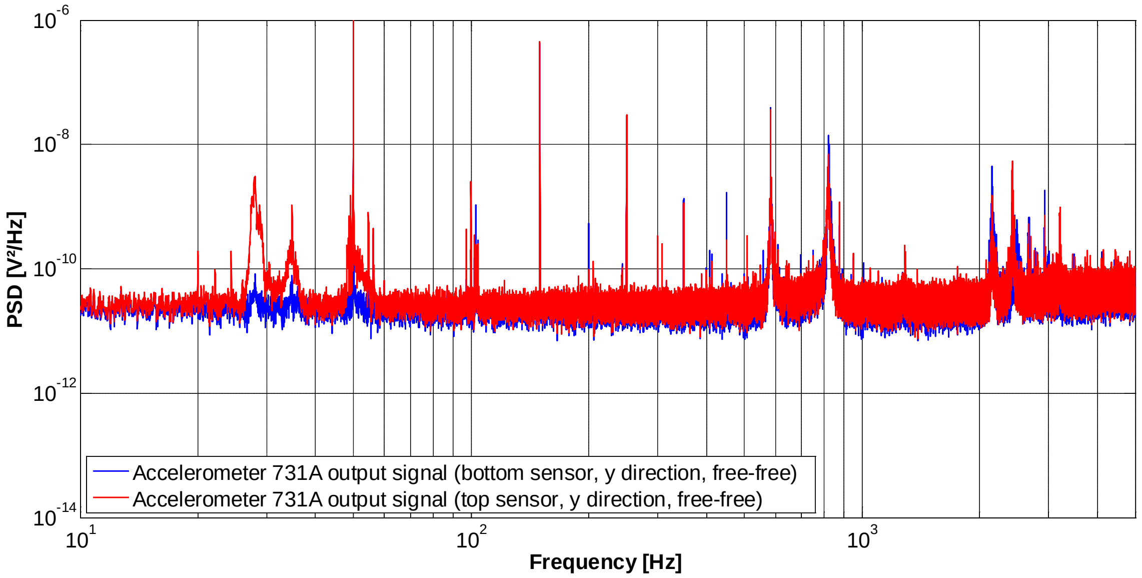


Fig. 14: Free-free QD0 upper and lower acceleration along y.

The suspension of the magnet with a strap highly damps the natural vibrations from the ground reaching the magnet. Hence, only a few pics appear on the PSD above. They are summarized in the Table 3a and Table 3b in section 6.

5. Theoretical results

5.1 *Clamped modal analysis*

Fig. 15 shows the first 6 mode-shapes of the bottom-clamped structure.

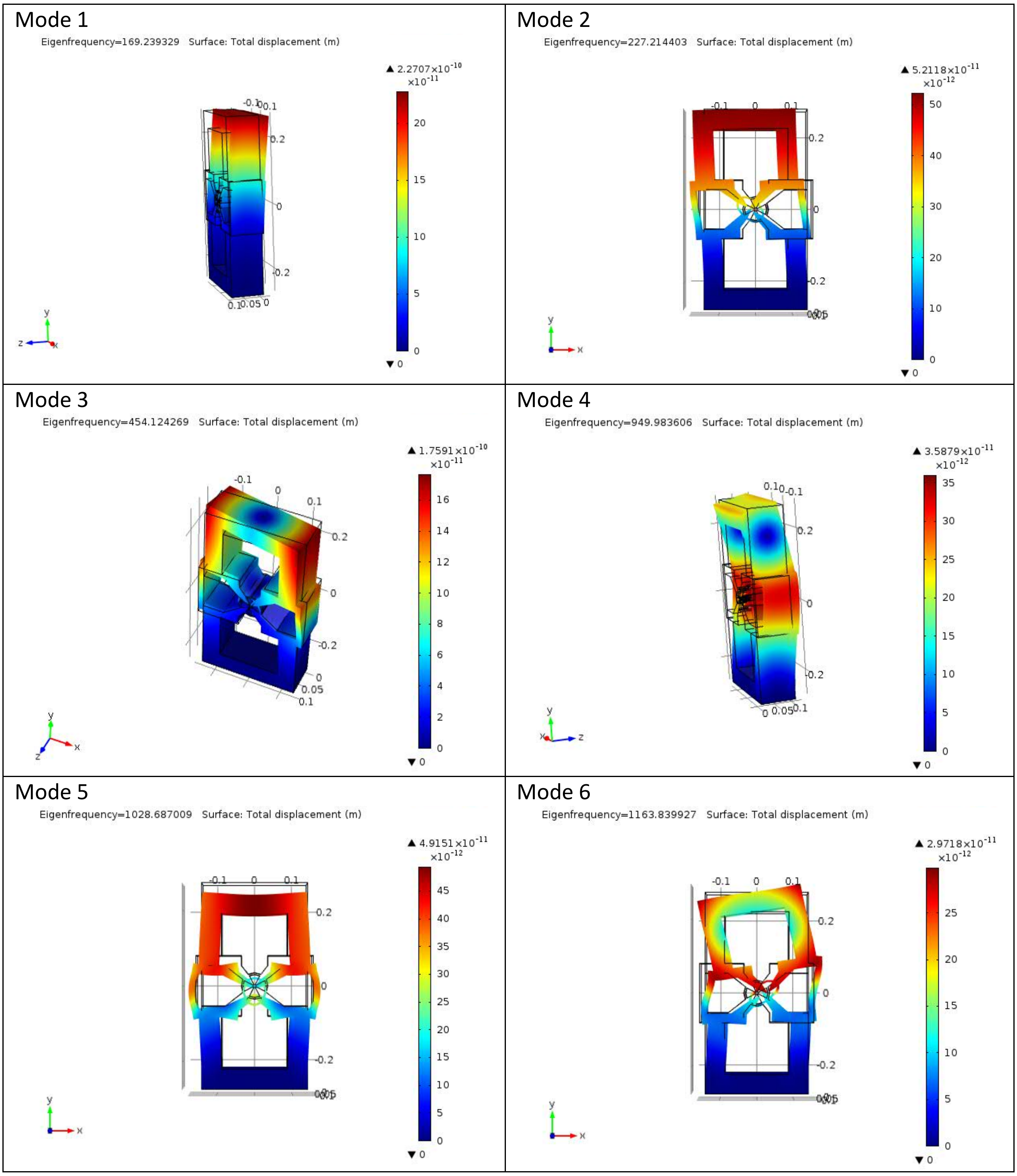


Fig. 15: Bottom clamped QD0 finite elements mode-shapes.

5.2 *Free modal analysis*

Fig. 16 shows the first 6 mode-shapes of the free structure.

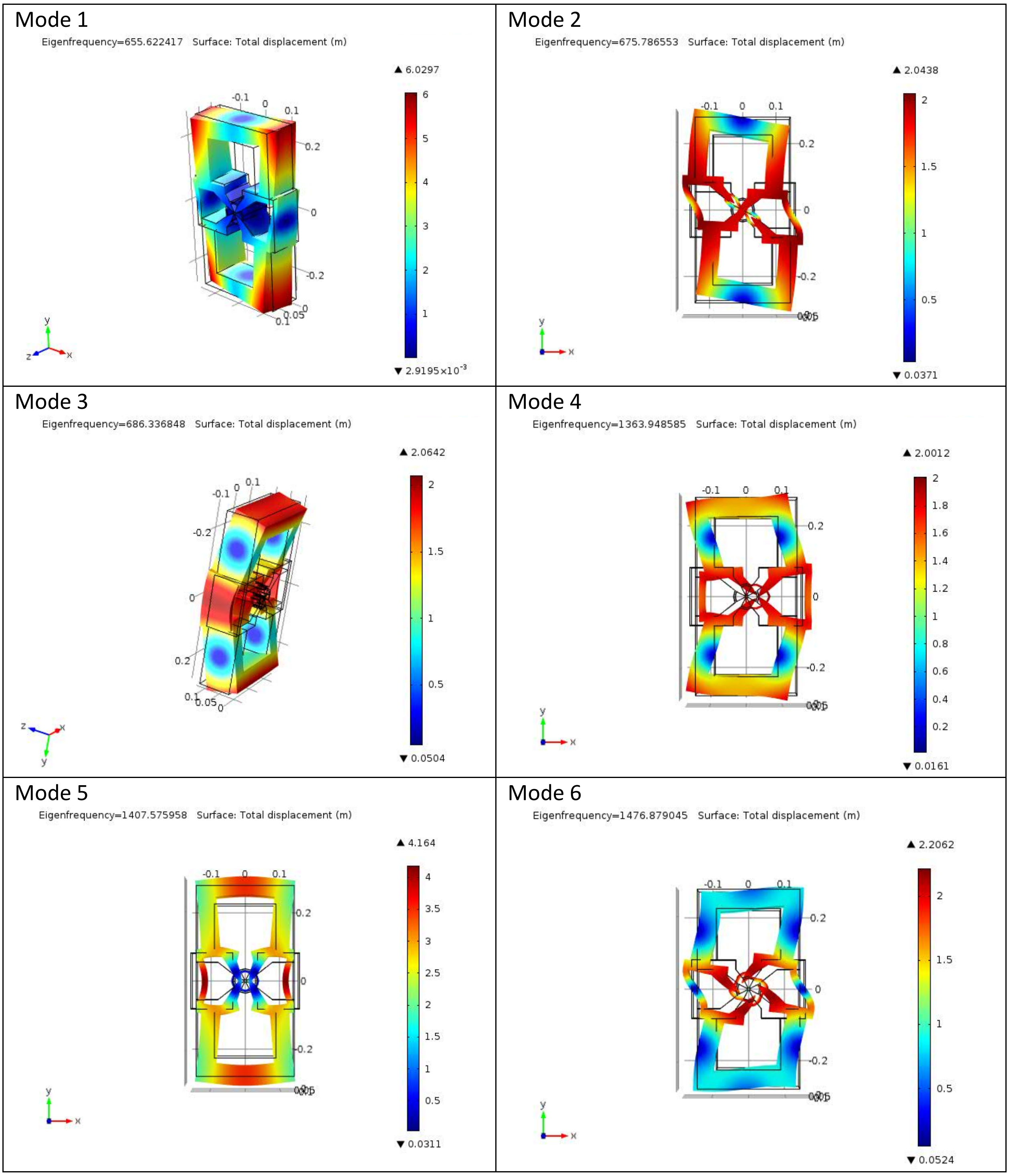


Fig. 16: Free QD0 finite elements mode-shapes.

6. Synthesis

Table 1a
Experimental modal analysis with clamped magnet (Pulse+Me'scope and Dspace+Matlab)

	Pulse+Me'scope	Dspace+Matlab	Pulse+Me'scope	Dspace+Matlab
Modes	x direction		y direction	
1	100 (106) Hz	100 Hz	200 Hz	200 Hz
2	370 (369) Hz	370 Hz	370 Hz	350 Hz
3	680 (691) Hz	640 Hz	780 Hz	820 Hz
4	1140 (1190) Hz	1150 Hz	880 Hz	
5	1290 (1290) Hz	1300 Hz	1000 Hz	1000 Hz
6	1900 (1920) Hz		1130 Hz	
7	2320 (2250) Hz		1730 Hz	
8	2530 (2530) Hz	2450 Hz	2080 Hz	
9	2890 (2820) Hz		2320 Hz	2500 Hz

Numbers in parenthesis in the first row have been obtained by loosening all the screws with a tightening torque of 10 Nm (instead of 15 and 20 Nm). Numbers shows that the tightening torque has almost no effect on the stiffness of the structure, and thus on its modal shapes.

Both experimental studies show a really good correlation between results. In certain case, it hasn't been possible to find a corresponding frequency pic using dSPACE + Matlab measurement (mostly at high frequencies). This can be explained by the poverty of the vibrations at high frequencies and the sensor's noise limits.

Table 2b
Theoretical versus experimental modal analysis with clamped magnet

	Pulse+Me'scope	Theoritical	Pulse+Me'scope	Theoritical	Pulse+Me'scope	Theoritical
Modes	x direction		y direction		x and y directions	
1	100 Hz	169 Hz	200 Hz	227 Hz	370 Hz	454 Hz
3	680 Hz	949 Hz	780 Hz			
4	1140 Hz		880 Hz			
5	1290 Hz		1000 Hz	1163 Hz		
6	1900 Hz		1130 Hz			
7	2320 Hz		1730 Hz			
8	2530 Hz		2080 Hz			
9	2890 Hz		2320 Hz			

Table 3a
Experimental modal analysis with clamped magnet (Pulse+Me’scope and Dspace+Matlab)

Modes	x direction		y direction	
	Pulse+Me’scope	**Dspace+Matlab**	**Pulse+Me’scope**	**Dspace+Matlab**
1	520 Hz	540 Hz	600 Hz	580 Hz
2	660 Hz	640 Hz	660 Hz	650 Hz
3	760 Hz	740 Hz	1250 Hz	
4	2090 Hz		1400 Hz	
5	2170 Hz	2170 Hz	1680 Hz	
6	2220 Hz		1740 Hz	
7	2330 Hz	2450 Hz	2160 Hz	2150 Hz
8	2970 Hz		2340 Hz	2400 Hz
9	3020 Hz		2740 Hz	2800 Hz

Table 4b
Theoretical versus experimental modal analysis with free-free magnet

Modes	x direction		y direction		x and y directions	
	Pulse+Me’scope	**Theoritical**	**Pulse+Me’scope**	**Theoritical**	**Pulse+Me’scope**	**Theoritical**
1	520 Hz		600 Hz	675 Hz	660 Hz	655 Hz
4	760 Hz	686 Hz	1250 Hz			
5	2090 Hz		1400 Hz	1363 Hz		
6	2170 Hz		1680 Hz	1476 Hz		
7	2220 Hz		1740 Hz			
8	2330 Hz		2160 Hz			
9	2970 Hz		2340 Hz			

7. Conclusion

Experimental results differ significantly from those obtained theoretically. This difference is probably due to the difference between the real and theoretical boundary conditions. It is suspected that the rigidity of QD0 structure is comparable to that of the clamping arrangement employed when measuring the mode-shapes.

As for the free condition, the results are more in agreement but the study is still not conclusive. A similar exercise with a larger structure in order to validate the resonant modes found with a finite element simulation has to be performed.