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Technical report

Vibration measurement in XFEL

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Objective

This project has for purpose the study of vibrations inside the bio I laboratory, room 209 at the x ray free electron laser (FEL), main building, in European XFEL.

Observing vibration behavior at this laboratory enables us to characterize the frequencies that are affecting the equipment, as well as to identify their sources, and thus, further procedures will follow to reduce these vibrations.

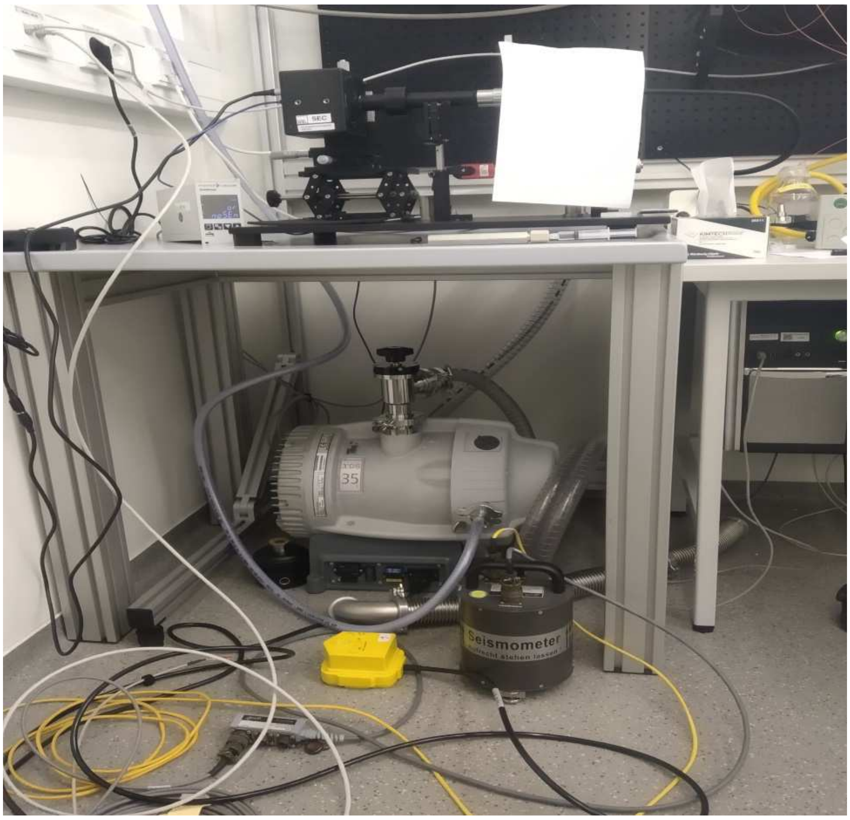
Equipment

The devices used in this project are seismometers and geophones. Seismometers contain three sensors in perpendicular direction which are (vertical z) direction, horizontal (north- south and east -oust) direction. The seismometer we used is made by the company GURALP systems, model CMG-6TD.

Geophones are also used for the same purpose and contain horizontal and vertical sensors,

The two devices provide raw data and are both controlled remotely.

They were placed next to each other, facing the north direction; the geophone fixed to the earth, and was moved to different places depending on the needs of the experiment.



1 Methodology

For the measurements in the bio I laboratory, only the seismometer was used.

The lower the frequency is, the higher its contribution to the isplacement. That’s why in this study, it is more interesting to focus on the frequencies that can cause remarkable displacement: the low frequencies. the choice of seismometer as a tool for measurement came straight ahead as it gave more detailed signal for low frequencies (below 100Hz) when compared to the Geophone readings.

The seismometer was placed around in different places and always maintained facing the north direction.

For data comparison, results of measurements that were gathered in the xfel XTD8 tunnel (currently empty) were used. as vibration attenuation is inversely proportional to depth. This site, situated 20 meters under, is the best location where a signal that is (more or less) quiet can be displayed.

2 Software and data

The geophones and seismometers are controlled using a software provided by Mark Lomperski called vibration client , it allows us to get the transformed raw data into PSD and RMS values for the horizontal and the vertical directions in form of asci files, and then can be plotted together with in function of the frequency, using Microsoft excel.

2.1 Data analysis

The function describing the displacement power spectral density (psd) can be defined as :

$$S_k = 2T\tilde{u}_k\tilde{u}_k^*,$$

in terms of the Fourier transform of ground displacement , $\tilde{u}_k . k = fT$

fT an integer between 0 and the normalized frequency and When expressed with the Fourier transform of ground velocity

$\tilde{\dot{u}}_k$

$$S_k = 2T\frac{\tilde{\dot{u}}_k\tilde{\dot{u}}_k^*}{(2\pi k/T)^2},$$

The factor two in the previous equations appears because the values above the Nyquist frequency $f_N = f_s/2 = N/2T$ are mirrored due to the aliasing effect, i.e., $S_k = S_{N-k}$. In fact , the previous two equations are equivalent. In these measurements, $f_s = 200\,Hz$ is the sampling rate and $T = 1$ minute. The relations above also take into account that the Fourier transform of the motion and velocity are related by

$$\tilde{u}_k = -i\frac{\tilde{\dot{u}}_k}{2\pi k/T}.$$

The discrete fourier transform is defined in general as, for N nubmers

$\dot{u}_n.$

$$\tilde{\dot{u}}_k = \frac{1}{N}\sum_{n=0}^{N-1} \dot{u}_n e^{-ik\frac{2\pi}{N}n},$$

And the reverse transform is given by :

$$\dot{u}_n = \sum_{k=0}^{N-1} \tilde{\dot{u}}_k e^{ik\frac{2\pi}{N}n}.$$

The rms of displacement, $\sqrt{(u)^2{}_l}$, above a cut-off frequency, normalized such that $f = l/T$, can be calculated from the power spectral density

$$\sqrt{\langle u^2\rangle_l} = \sqrt{\frac{1}{T}\sum_{k=l}^{N/2} S_k}.$$

The PSD of displacement has a unit of $\mu m2/Hz$. For better resolution of spectral details, the spectra are averaged over 15 minutes or even longer periods. Since “cultural noise” is dominant at $f \geq 1\,Hz$, in this work, the displacement PSDs measured were integrated at $1 \leq f \leq 80$ Hz, the upper limit matching the seismometer upper frequency response

. The spectrum of correlation $K_k$of two synchronized signals $\tilde{u}_k$ and z_k, for any value k, is estimated by averaging over many 1 minute measurement data sets, is defined as :

$$\sqrt{\langle u^2\rangle_l} = \sqrt{\frac{1}{T}\sum_{k=l}^{N/2} S_k}.$$

Kk is a complex number by definition and coherence between two signals is hence defined as :

$$C_k = |K_k|^{\ 2}$$

By definition, coherence of two signals is between 0 and 1.

3 Measurements

At first, the seismometer and the geophone were put on the optical table in a regular working day, at 04:00 pm.

Once the recording of data was completed, the two devices were moved to the floor, under the optical table, in the same position and always facing the north

In this position, the measurements period was for one week, so that variation with respect to day and night, weekday and weekend can appear.

when comparing the measurements that were done at the 209 room, on the optical table and on the floor, where we could see appearing a range of intriguing frequencies interesting for exploration:

10, 20, 29, 49, 59, and 89 hz

To track the distribution of these frequencies, the seismometer was moved inside the room over different places.

The main reason that triggered this investigation was a complaint from Dr. Mohammad Vakili, who reported obtaining blurred images from his high-speed camera, suspected to be due to high vibration level, despite the camera is actually placed on the optical table that is supposed to attenuate vibration.

Once in the Lab, we could notice at first sight that the camera was indeed placed on the optical table, but the table itself was in direct contact with a computer desk from one side, and the external wall from the other.

As a first step and before starting the measurements, we suggested to put a separation gap between the tables from each other, to avoid any transmission of vibrations from one surface to another, then see how the image appearing in camera can be affected, once made in action, the images appeared less blurry, one can exclude the contribution that can be coming from the plain possible sources (the gas pipes, the computer fan) and then do the measurements .

However, due to limited space, the tables were not able to be separated, so I proceeded to the measurements mainting the contact between the computer desk, the wall and the optical table.

Since the room was shared with another experimentalist, there were two other vacuum pumps working permanently and other instruments that couldn't be turned off during the measuring time, so, all i had control over was to turn on and off a vacuum pump which Mohammad Vakili used for his work, and that was placed right under the optic table.

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Room 0.209

In this section, we will take a look at the main interesting frequencies obtained in our measurements

3.1.1 The 10 Hz frequency

When measuring on the ground, and on the tables, with the pump turned off, we observe this frequency appearing in the vertical component. when comparing its intensity, we see that it's value on the ground and on the optical table is very close. Whereas on the desk, there is a high peak of intensity. it seems that the dumping structure of the optical table prevented this vibration from transmitting.

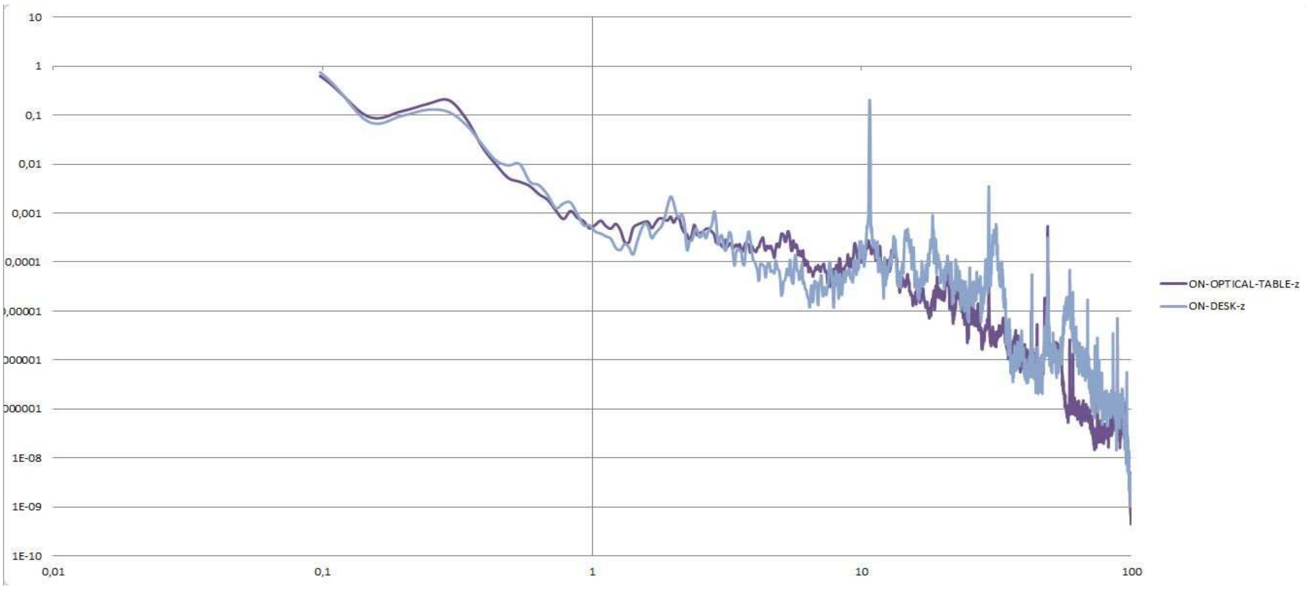

Fig. : comarasion between vertical PSD values measured in the optical table and computer desk

3.1.2 The 20 Hz frequency

This frequency does not show on the measurements done on the ground, but rather appears on the optical table, while the seismometer was touching the wall and on the computer table in the north-south and the east-west directions only. it does not transmit vertically. As it is shown only in the surfaces that have firm contact with the adjacent walls. they should be the main transmitters.

3.1.3 The 29 Hz frequency

3.1.3.1.1 When the pump is off :

It gets more intense the more we get closer to the other pumps placed in the room, that were running, while it maintains the same intensity when to the north-south directions it has the same intensity, (the two graphs are more or less identical)

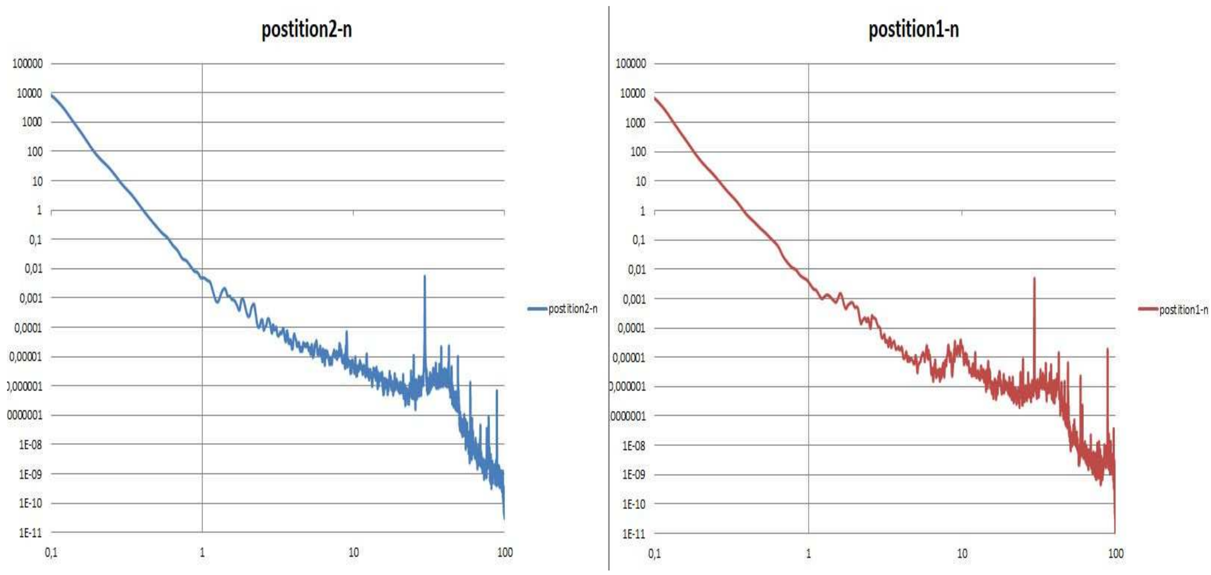

Abbildung 1 PSD values for the north direction

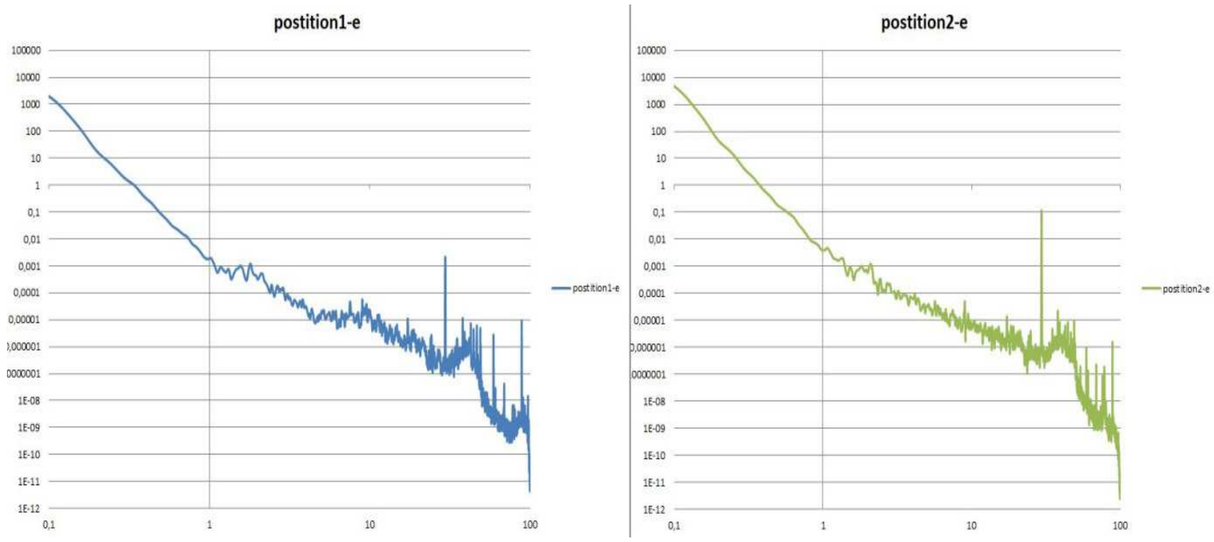

Fig : PSD values for the east-west direction

Since there is the corridor outside the room in the west direction, this can be explained that inside the same room, there must be another (pump) that is vibrating in the same frequency.

3.1.3.1.2 When the pump is on :

The displacement, as seen in the RMS plot, is very remarkable on the optical table, compared to its value on the ground, while the 10Hz and 20Hz diminish. This led us to give more attention on 29Hz frequency.

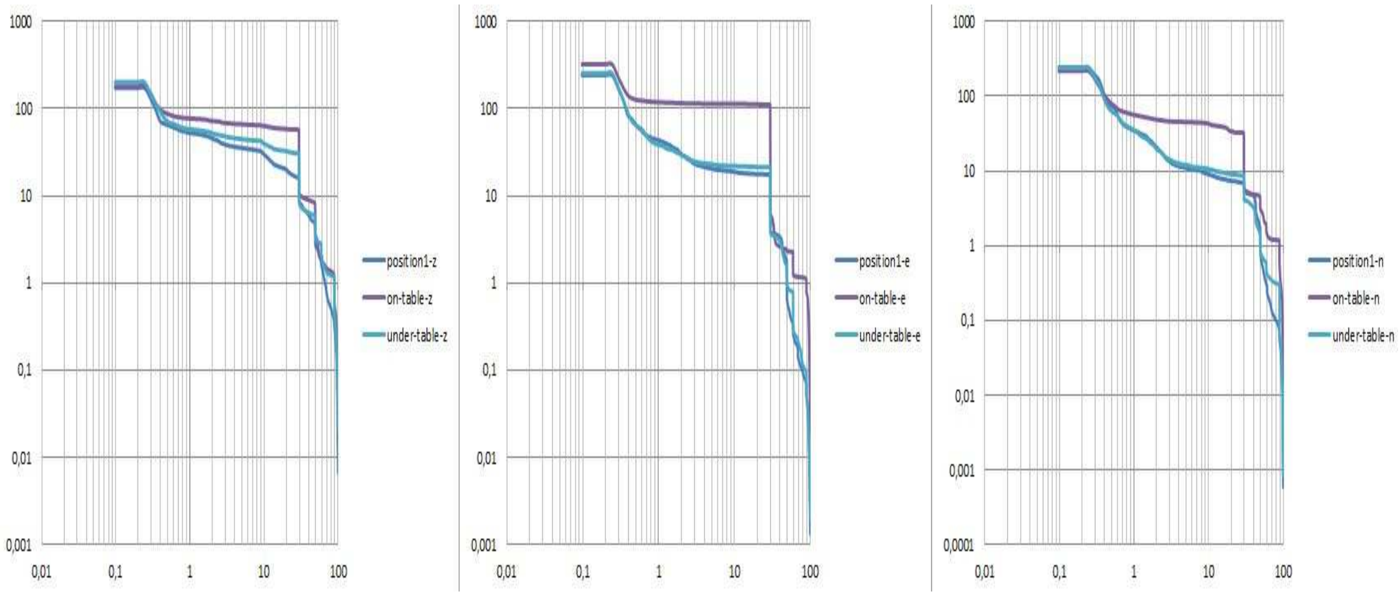

Fig: RMS values comparison

3.1.4 Possible sources

Exploring the area around and above the room 0.209 is crucial if we want to list possible sources for these frequencies.

Fig. laboratory ceiling plan that show the position of cooling units

The ceiling of this bio lab area, as shown in fig. above. contains 20 air conditioning units in total, some of them are aligned.

As this is a huge source of vibrations to be considered, investigating the way they vibrate can be a start to identify many unknown frequencies.

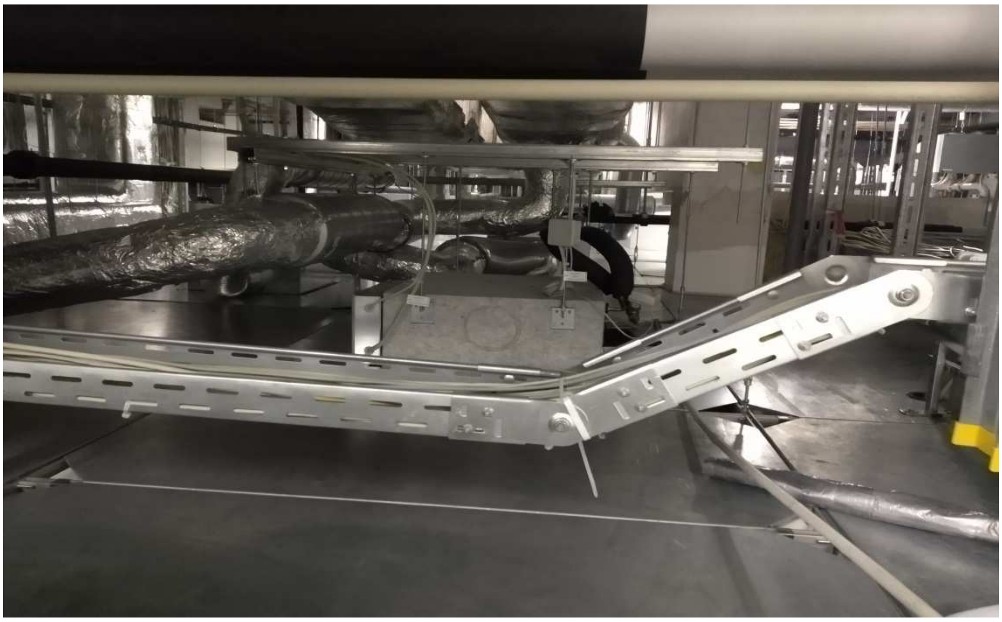

Fig.: cooling unit placed on bio I laboratory roof

As for the 10 Hz and 19 Hz frequency seen in the measurements. these vibrations could be transmitted through interior walls of the room 0.209,

However, as we pointed out before, near the exterior wall, the 20Hz frequency has maximum intensity, but when observing the plan issued from the building company Lindor, one can see that this wall is a double structure concrete wall and such structures are supposed to reduces any vibrations running through it.

Still is interesting to do further work about how do these frequencies appear so strongly on this wall…

When to the 30 Hz frequency, the huge steps seen in the RMS plots on the optical table and only when the pump was on, explains that the displacement is caused mainly by this frequency. In other words, the vacuum pump is the main responsible for the shakes seen in the camera.

The detection of this frequency in the floor, when our pump was off, and while the others were running can indicate that the main way of transmission is through the floor, especially if confirmed that the lab floor area has no special design to attenuate vibrations.

The XTD8 tunnel

The most intriguing part in this work was that, inside this empty tunnel, one could see appearing some intense frequencies despite the quietness and the depth (20 meters) of this location. When looking into previous vibration measurements done in xfel, we can see that some frequencies (49 hz, especially) appear almost all around the xfel site (experimental hall, tunnels, laboratories, etc…)

The 49Hz frequency was explained to have for source the electrical European standard grid . However , considering that the electric frequency corresponds to the number of times the electric current alternates between positive and negative voltage in a second,

The question that arises is, how can this frequency be sensed by a seismometer ?

In an attempt to answer this question, I went through the process of exploring XFEL facility. the assumptions that follow are very interesting.

4 Unlocking the low frequency mystery

Investigation of possible source of vibration within the entire site led us to go through multiple sources for documentation. many of them have been checked with scrutiny and revealed many "vibrating" equipment installed within XFEL

we could easily observe that the building contains many rotating equipment, Motors, compressors, pumps, fans...etc. we will go through some of them in an attempt to explain how they could be source of many of these Unknown or "un characterized" frequencies.

AC system
Ventilation system and Ducts (on the roof)
Compressors
Flow pumps
Chillers

Going back to Bio Lab, we observed at first that we are dealing with 29Hz frequencies,
And since frequency describes how many times a phenomenon is repeated in a time unit. 29 Hz in normal language is 29 pulses per second.
it happens actually that this is about the same frequency the vacuum pump motor is running at, in fact, the vacuum pump present inside the Lab room 0.209 uses a Schroll motor that runs at 1750 revolution per minute, and it is 29.16 revolutions per second.
The below technical sheet of the pump confirms the numbers. (XDS35i)

PRODUCT DATA SHEET edwardsvacuum.com

Technical data

	Units	XDS35i	XDS35i Enhanced
Peak pumping speed	m^3h^{-1} (cfm)	35 (21)	
Ultimate vacuum (1)	mbar (Torr)	0.01 (0.008)	0.03 (0.02)
Ultimate vacuum with gas ballast 1	mbar (Torr)	0.02 (0.015)	0.04 (0.03)
Ultimate vacuum with gas ballast 2	mbar (Torr)	< 10 (7.5)	
Max inlet pressure for water vapour	mbar (Torr)	35 (23)	
Water vapour handling capacity GBII	gh^{-1}	240	
Maximum continuous inlet pressure	mbar a (Torr a)	40 (30)(2)	1000 (760) *
Maximum gas ballast/purge pressure	bar gauge (psig)	0.5 (7)	
Motor data			
Supply voltage	V	100-120/200-240 (+/- 10%)	
Supply frequency	Hz	50/60	
Nominal rotation speed	rpm	1750	
Power at ultimate	W	440	
Motor power	W	520	
Power connector		IEC EN60320 C19	
Recommended fuse, 230 V (115 V)	A	16 (3) (15)	
Physical data			
Weight	kg (lb)	48 (105)	
Inlet connection		NW40	
Exhaust connection		NW25	
Noise level at ultimate	dB(A)	57	
Vibration at inlet flange	mms^{-1} (rms)	< 4.5	
Leak tightness (static)	mbar ls^{-1}	$< 1 \times 10^{-6}$	
Operating temperature range	°C (°F)	5 to 40 (41 to 104)	

** Use at higher inlet pressure speeds up tip seal wear*
(1) measured as total pressure
(2) These pumps are designed to pump down from atmospheric pressure, but prolonged operation at inlet pressures higher than specified may reduce bearing life.
(3) for UK 240 V use 13 A fuse

Fig.2: Data sheet for XDS35i pump

The same type of motor (compressor) are part of the big AC outdoor units, there are 10 units placed at the same location behind the XHPSC pump house.

[https://www.carrierenterprise.com/zp54k5e-pfv-830-54-000-btuh-copeland-scroll-compressor-for-r-410a-refrigerant-zp54k5e-pfv-830]

Most of such units contain a Schroll compressors running at 3550 rpm, or 59Hz. in frequency terms.

Fig. 2 : AC units

Fig.6: Air compressor

Inside the XHPSC room, there are strong air compressors (fig. above) running exactly at 2940 rpm (which is 49Hz), not very far from both the experimental hall and the tunnels, and here we come to a conclusion that this is most likely the source of the 49Hz that appears all around xfel site. We need to stress here, on the fact that we are in front of several 18.5Kw units aligned within the same location, which explains the fact that this particular frequency travels far around in every direction. Which is technically proven since it’s well known that it appears almost everywhere in XFEL.

Fig.7: Specs plate for Air compressor

Conclusion

The main goal of this report was to investigate the source of the annoying vibration causing the High-speed camera in Lab 0209 to produce blurry pictures.
we can conclude without doubt that the main causing source of this vibration is the vacuum pump spinning at 1750 rpm, in addition to residual traveling vibration coming from nearby rotating equipment.

By analogy, we could as well unlock the mystery of uncharacterized low frequency vibrations observed over time in XFEL facility.
we can say with high level of confidence that the different rotating equipment are most likely the major source of the vibrations all over the XFEL facility and should be considered as such at early stages of any investigation dealing with vibrations effects.

The assumption of the current frequency being in link with these kinds of phenomenon is very unlikely, as the current intensity is not in such level to translate into vibration energy capable of shaking such structures as walls and floors. the 50Hz of a socket plug express polarity inversion frequency of the AC current and can't be in our case linked with mechanical vibration.

The investigation of possible vibration sources could be extended to take measurements near by any rotating equipment to assess the level of vibration it emits and include it in a global survey study to identify and characterize their impact on the neighboring sensors used in day to day operations in the different labs within XFEL.

Once located and characterized, the vibrations effect could either be attenuated, contained or taken as an input for correction in later data process or interpretation.

Furthermore, nowadays, vibration systems are heavily studied and data is often exploited as inputs in behavioral model for maintenance prediction and failure prevention of equipment and structures. this is to tell how important is the study of such vibration phenomena for critical sites such as XFEL

References

[1] Measurement of ground motion in various sites : Wilhelm Bialowons, Ramila Amirikas, Alessandro Bertolini, and Dirk Krücker Deutsches Elektronen-Synchrotron DESY, 22603 Hamburg, Germany (Dated: October 26, 2007)

[2] https://www.carrierenterprise.com/zp54k5e-pfv-830-54-000-btuh-copeland-scroll-compressor-for-r-410a-refrigerant-zp54k5e-pfv-830

[3] Edwardsvacuum.com

[4] Vibration.desy.de

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