White Paper

Micro-vibration modeling and measurement on a Sentinel 4 UVN calibration assembly using a piezoelectric 6-component force dynamometer

Abstract

The Sentinel 4 (S4) Ultraviolet Visible Near-Infrared (UVN) instrument is a high-resolution spectrometer embarked on the MTG-S platform. The radiometric accuracy of the UVN instrument depends on regular in-orbit recalibrations performed with the Calibration Assembly (CAA). This CAA mechanism comprises a multifunctional wheel equipped with calibrated diffusers. Positioning is handled by a stepper motor. Since the instrument is mounted on the MTG-S platform, it is imperative that the resultant micro-vibrations and torques are controlled, because the MTG IRS instrument is extremely sensitive to them. For this purpose, CSL has developed a Simulink model that inputs a motion profile to simulate the real-world mechanisms, generating the torques and micro-vibrations at the satellite's center of gravity. To validate this prediction, a specially designed Kistler dynamometer is deployed to measure the actual forces and torques exported by the CAA qualification model.

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1. Measuring with piezoelectric dynamometers

Micro-vibrations consist of extremely small accelerations with very low intensities. Measuring them is a very challenging task, and methods for properly doing so have only become available in the past few years. Piezoelectric force sensors and dynamometers are ideal for this purpose. Their exceptionally high span-to-resolution ratio of more than 100,000 is a particular advantage. This makes it possible to measure dynamic force changes down to 0.01 N, even when the object being measured weighs more than 10 kg. The static weight can be "eliminated" by resetting the charge amplifier: this acts like a tare function, effectively re-zeroing the scale. Another advantage is that the very high stiffness of piezoelectric force sensors permits natural frequencies of 1,000 Hz or more.

The measurement setup itself is also a key factor in optimizing the system. As can be seen in Figure 1, the dynamometer must be mounted on a vibration-isolated table so that the results are not affected by structure-borne sound or external vibrations. These external influences can severely distort measurements because the dynamometer – and the mass of the object being measured – can themselves generate high distortion signal caused by external vibrations. With a correct setup, the interference signal can be kept to levels below 0.01 N or 0.003 Nm (RMS; 3 … 350 Hz).

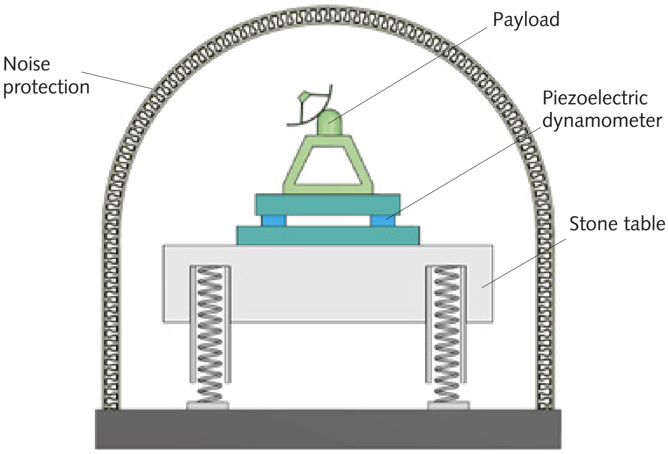

Figure 1: Micro-vibration measurement setup: payload (green), piezoelectric dynamometer (dark blue), stone table (gray). An outer dome is used for noise protection

The achievable measurement frequency range is typically from 1 Hz to 350 Hz. The lower limit is defined by the natural frequency of the vibration-isolated stone table, while the upper limit is determined by the natural frequency of the system consisting of the dynamometer itself together with the measured object.

Correct mounting of the measured object on the dynamometer plays a critical part in obtaining good measurement results. The dynamometer and the measured object must be fastened with a sufficient number of bolts to ensure a proper mechanical coupling.

Last but not least, sound and electromagnetic interference (EMI) should be avoided in or near the measurement setup. The dynamometer is connected to the charge amplifier with a special high-insulation cable. The cable length should be as short as possible and it should not move. Data recording is handled via a laptop and an AD converter.

2. New measuring trends

As mentioned above, the maximum measurable frequency for micro-vibrations is currently in the range of about 350 Hz. However, demand is now growing for higher cutoff frequencies so that larger objects can be measured. Unfortunately, the success of attempts to meet these requirements is limited by the standard dynamometer design. Recent standard dynamometers consist of four three-axis force sensors sandwiched between a top plate and a base plate, each made of steel (as shown in Figure 2).

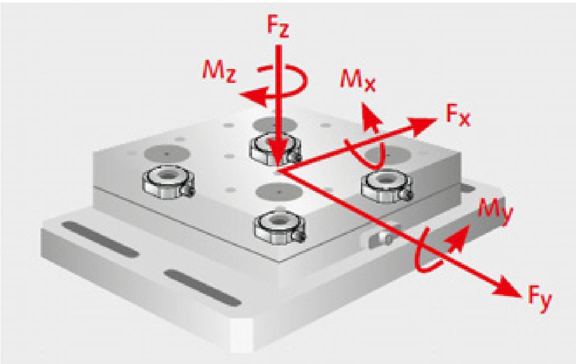

Figure 2: Structure of a piezoelectric dynamometer to measure micro-vibrations with four 3-component sensors

The dynamometer behaves like a second-order spring/mass system with a dominant natural frequency, so measurements must be taken well below this natural frequency. Addition of any further mass results in an even lower natural frequency. On a small dynamometer, therefore, a major influence can be caused simply by mounting a heavy object for investigation: this could lower the natural frequency of the system (as illustrated in Figure 3).

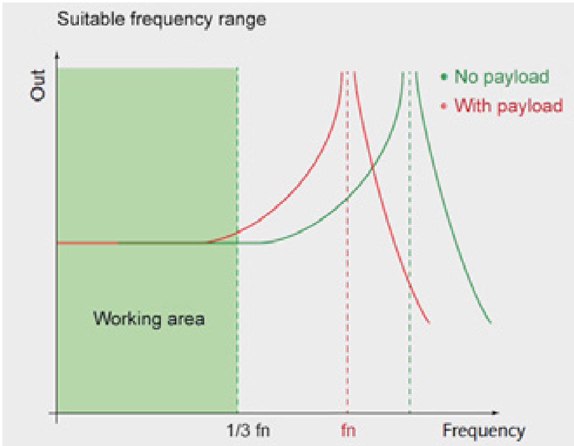

Figure 3: Natural frequency with and without payload versus suitable frequency range

If measurements up to 500 Hz are required, the dynamometer should have a natural frequency of >1,500 Hz; otherwise, resonance will exert too much influence on the measurement signal. It follows that a high natural frequency is essential.

The dynamometer's size and stiffness have a considerable effect on its natural frequency. The larger the dynamometer, the heavier the top plate will be – and this will, in turn, reduce the natural frequency. Unfortunately, this effect cannot be entirely compensated by increasing the stiffness of the sensors.

However, higher natural frequencies have now become possible thanks to recent advances in dynamometer design, making it easy to isolate micro-vibrations so that more can be done to reduce their causes.

Another relevant factor is the introduction of new testing requirements: dynamometers of increased size are needed so that complete subsystems and entire small satellites can be tested. Taken together with the higher frequency requirement, this means that the design limits with the use of known materials have already been reached; any further improvements would merely be incremental, and they would require enormous time and cost. This situation has prompted consideration of new materials for the dynamometer's top plate.

3. Ceramic top plate dynamometer

As explained above, size has a critical impact on the unit's natural frequency; heavy top plates are especially unfavorable in this respect, despite the additional stiffness they provide. A search for potential new materials for the dynamometer's top plate showed that ceramics offer highly advantageous properties (see Table 1).

	Steel 17-4 PH	Ceramic (Al2O3)
Specific gravity	7.8	3.84
Modulus of elasticity (Young´s modulus)	190,000	370,000
Tensile strength	1,200	300
Thermal expansion	10.8	5.7

Table 1: Steel and ceramic – material properties

The low specific gravity and high modulus of elasticity offered by ceramics are clear benefits, but their low tensile strength and low thermal expansion would be drawbacks.

As seen in Figure 4, finite element method (FEM) calculations showed that natural frequencies could be increased by 40% if ceramic top plates with similar dimensions to those of steel plates were used. This would lead to significantly improved detection of micro-vibrations.

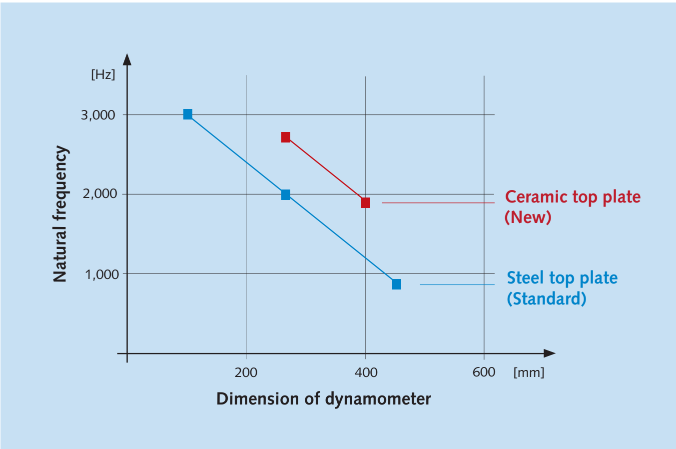

Figure 4: Natural frequency in Fx,y direction in relation to dynamometer size

Lower strength could be acceptable in such a case, given the very small forces and loads involved in micro-vibration measurements. To ensure that the dynamometer could still be mounted correctly, the steel base plate was retained because it has no effect on the natural frequency of the dynamometer.

Measurements of natural frequency in the z direction showed a very well-defined peak at about 2,570 Hz (Figure 5). In the shear directions (Fx,y), the natural frequency was about 1,950 Hz. By way of comparison, dynamometers with steel top plates reach about 1,300 Hz in the shear direction.

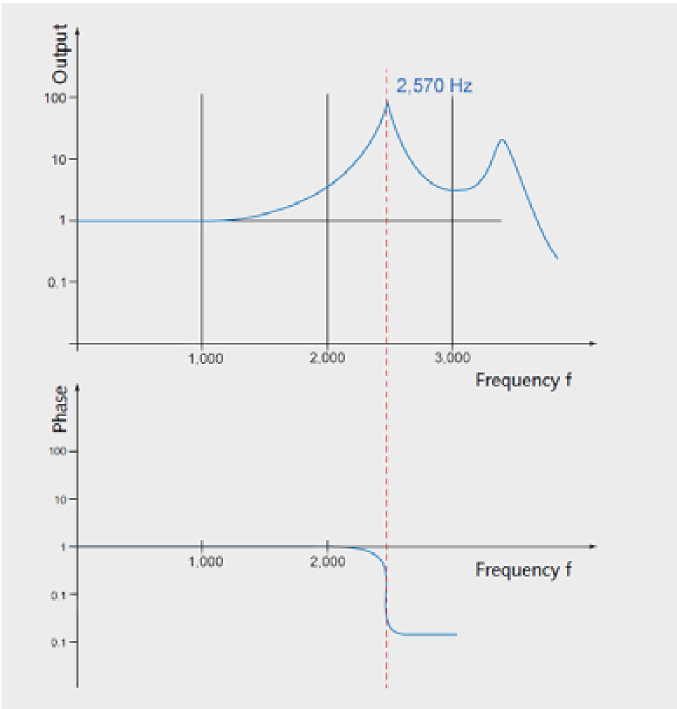

Figure 5: Natural frequency in Fz direction, ceramic top plate dynamometer Type 9236A2

The benefit, therefore, is that the suitable frequency range (see figure 3) can be increased from 350 Hz to over 500 Hz. However, further investigation revealed that low thermal expansion presents a problem: despite the FEM calculation, full validation of this behavior was impossible. An extended investigation with experimental specimens was therefore undertaken to ensure that the difference in thermal expansion between a steel base plate and an Al2O3 top plate would not cause fractures in the top plate due to its special structural design.

4. Characterization of the optical calibration system for the Sentinel 4 UVN satellite

CSL required a natural frequency greater than 1,500 Hz to characterize the optical calibration system for the Sentinel 4 UVN satellite. Kistler's type 9236A2 dynamometer with a ceramic top plate was selected thanks to its large dimensions and high natural resonance frequency.

The dynamometer was tested by Kistler on an isolated stone table and in a sound-insulated area. The next step comprises validation measurements of the subassemblies for the Sentinel 4 satellite. Once this validation has been completed, CSL will perform further calibration measurements that will enable it to offer the space community a superior test facility for characterization of micro-vibration measurements, down to a noise floor of 0.01 mN (narrow band noise $\Delta F=1$ Hz).

5. S4/UVN calibration assembly

The Sentinel 4 mission meets the needs for continuous monitoring of the Earth's atmospheric composition and air pollution; to do so, it uses a high-resolution Ultraviolet/Visible/Near-Infrared (UVN) sounder instrument deployed on two geostationary MTG-S satellites. The radiometric accuracy of the UVN instrument relies on periodic in-orbit recalibrations using the UVN Calibration Assembly (UVN CAA). This mechanism was designed, built and qualified by CSL. The mechanism consists of a multifunctional wheel with optical diffusers and a mirror that are successively placed in front of the camera during the calibration. Rotation is activated by a stepper motor and controlled by a resolver.

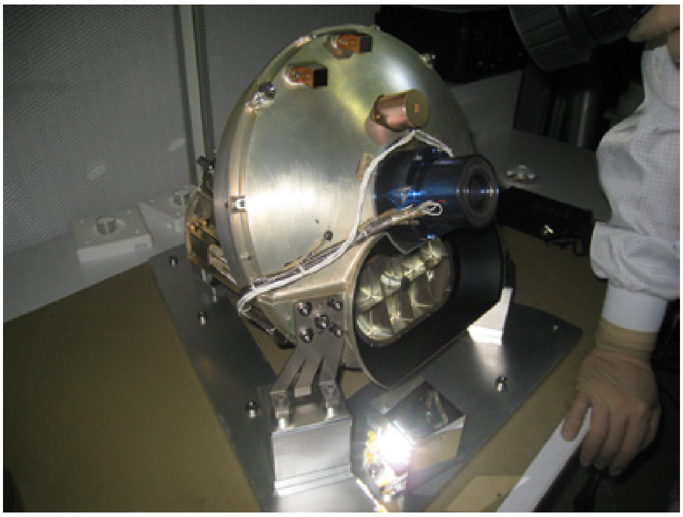

Figure 6: S4/UVN CAA

Since MTG-S is an Earth observation satellite with accurate pointing requirements, the exported torques and micro-vibrations generated by subsystems can degrade the performance of the MTG instruments. The micro-vibrations emitted by the Calibration Assembly during the motion of the mechanism should therefore be reduced to the minimum achievable.

To attain this objective, the micro-vibrations and exported torques of the Calibration Assembly were estimated with the help of a model, followed by characterization using the micro-vibration dynamometer from Kistler.

6. Micro-vibration modeling

A Simulink model was created to evaluate micro-vibration levels in the moving mechanism. This model incorporates the elements that generate vibrations as well as the main components that influence the transmission of vibrations in the mechanism.

The elements that generate micro-vibrations are:
- The stepper motor
- The bearing
- The friction

The main elements that influence the transmission of vibrations are:
- The stepper motor controller
- The transfer function from the motor to the spacecraft interface
- The lever effect from the spacecraft interface to the spacecraft's CoG (Centre of Gravity)

The stepper motor controller is a Simulink block; as inputs, it receives the motion that the motor should follow as well as the micro-stepping parameters, and it transforms this data into the sine wave that will be the current input for the stepper motor. The stepper motor is another Simulink block that receives the current of the two phases as input and generates the output torque for the motor. The modeling also takes account of the stepper motor's detent torque.

The next simulation block is the output shaft, which simulates the behavior of the driving shaft by modeling the resistive torque on the shaft. This includes the friction in the bearing and the rotation inertia of the multi-functional wheel. This block can also take account of some cyclic resistive torque generated by imperfect ball-bearing balls.

The last block handles export of the results to the Matlab workspace. The results of the Simulink computation comprise the torques and forces generated by the assembly at the motor location. After the simulation, a Matlab script is run in the workspace to take account of the mechanical transfer function from the motor interface to the Calibration Assembly interface.

The input transfer functions were previously recovered from the FEM analysis. Once the temporal results are obtained in Matlab, a frequency analysis is performed to identify the exported torques and micro-vibrations in different frequency bands. The final result of the analysis is a temporal response to the injected micro-vibrations at the spacecraft's CoG.

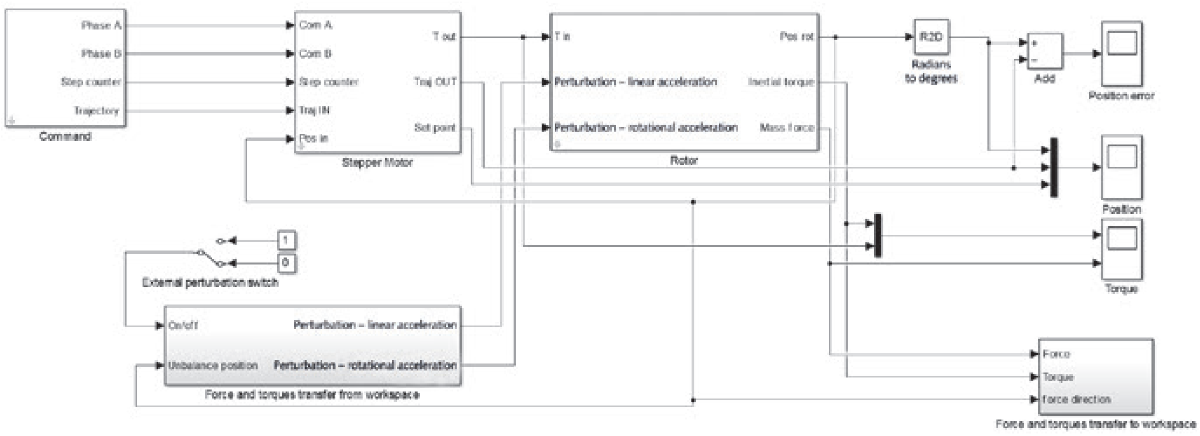

Figure 7: Simulink micro-vibration model

7. Micro-vibration optimization

The completed model was used to perform an optimization analysis aimed at reducing the micro-vibrations exported to the spacecraft. Multiple parameters of the stepper motor can be tuned to minimize the exported micro-vibrations. The main parameters are the maximum current injected into the motor and the motion profile. These parameters were analyzed to reduce micro-vibrations to the minimum achievable.

The first stage of optimization involved determining the impact of the input current and the stepper motor's sensitivity to the detent torque. It was found that the micro-vibrations generated by the stepper motor were primarily affected by the ratio between the holding torque (proportional to input current) and the detent torque. As the ratio increased, the micro-vibration level decreased.

A second analysis was performed to determine the impact of the driving profile on the generated micro-vibrations. A micro-stepping strategy was introduced to reduce the exported micro-vibrations; even with a perfect input signal, however, the micro-vibrations induced by the stepper motor cannot be eliminated. The evaluation showed that a ratio of more than 64 µsteps / step does not improve micro-vibration behavior.

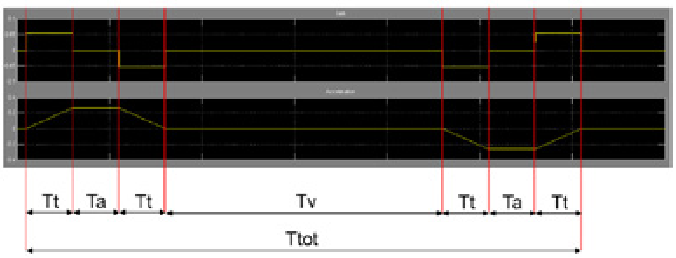

Figure 8: Definition of jerk and acceleration

A specific input current profile was also suggested: in theory, this would eliminate the non-uniformity of the output torque so as to provide constant output torque during motion. This profile performed well in simulations, even under open-loop conditions with external perturbations. However, it was evaluated as incompatible with the existing electronic control system due to cross-use of table lookup with other subsystems. After an advanced current profile was rejected, more common profiles were evaluated: these included a constant velocity profile, a constant acceleration profile and a jerk profile.

For a jerk-based profile, a full motion is divided into 7 components: 4 transition phases (Tt), 2 constant acceleration phases (Ta), and 1 constant velocity phase (Tv). By tweaking the transition and acceleration phases, the motion profile could be tuned and optimized to reduce the micro-vibrations exported during a complete motion. It was found that the best profile to reduce the micro-vibrations is a jerk profile that tends towards a constant velocity profile. Tuning the acceleration component of the jerk profile made it possible to reduce the micro-vibrations during the transient part of the curve.

8. Micro-vibration setup

Following the sensitivity analysis and optimization of the Simulink model, a comparison of the results with physical measurements was required. For this purpose, a test campaign was performed using the Kistler dynamometer developed for this application. Figure 9 shows the CAA mounted on the micro-vibration table.

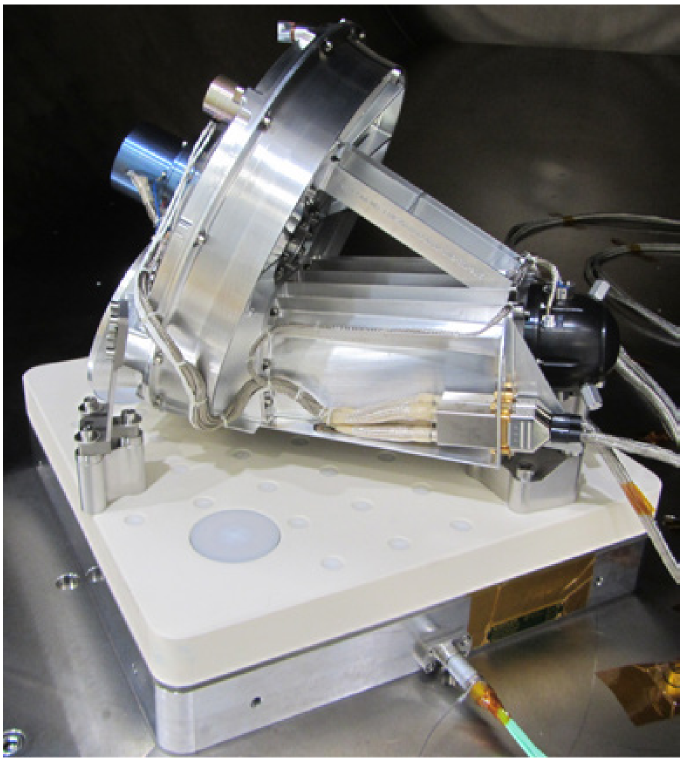

Figure 9: UVN CAA mounted on micro-vibration dynamometer Type 9236A2

As described in the first section of this article, this is a highly sensitive dynamometer that can record forces in three axes as well as the torques around the three axes.

Due to its high sensitivity, the dynamometer requires a favorable environment to ensure that measurements are not impacted. The two main noise contributors are the acoustic and seismic environments. Because characterization of Flight Models (FMs) was foreseen, there was a requirement to work in an ISO 5 environment where additional acoustic noise is created due to the continuous airflow. However, CSL is equipped with vacuum chambers located in an ISO 5 environment, so acoustic noise can be reduced by closing the chamber during the measurement. Additionally, each vacuum chamber is equipped with a very stable optical bench that is decoupled from environmental vibrations thanks to its heavy seismic mass.

The following environmental noise levels were recorded by the instrument installed on the dynamometer in two vacuum chambers at CSL, named Focal 5 and Focal 2. The measurements range from 0 to 500 Hz.

Axis	Noise Focal 2
Fx	2.9E-2 N rms
Fy	2.9E-2 N rms
Fz	3.7E-2 N rms
Mx	3.8E-3 Nm rms
My	3.2E-3 Nm rms
Mz	1.2E-3 Nm rms

Table 2: RMS noise in Focal 2

Axis	Noise Focal 5
Fx	3.5E-2 N rms
Fy	4.9E-2 N rms
Fz	1.7E-1 N rms
Mx	4.4E-3 Nm rms
My	2.1E-3 Nm rms
Mz	2.2E-3 Nm rms

Table 3: RMS noise in Focal 5

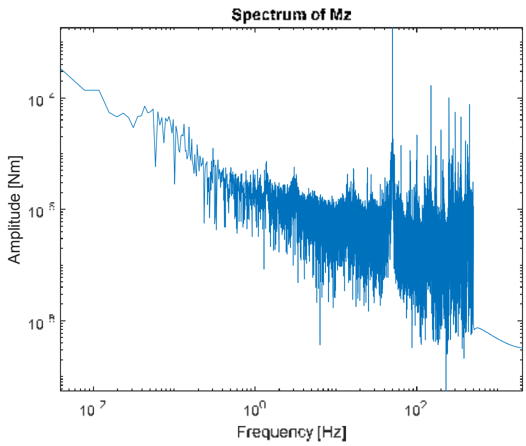

Figure 10: Shows an example of the spectral signature of the noise for the Mz axis.

From the noise levels, it can be seen that the goal of 0.01N is not reached. This is attributed to the noisy environment in the cleanrooms. Furthermore, the local ISO 5 airflows were activated during the test in Focal 5, accounting for the higher noise level observed there. The spectral signature shows the presence of a peak at 50 Hz, as well as harmonics. This peak has a limited impact on the measurement in the frame of the UVN mechanism because its amplitude is much lower than that of the measured micro-vibrations.

9. Micro-vibration characterization

The dynamometer was used to characterize three models, of which the first to be tested was the LTM (Life Test Model). An extensive test campaign was rolled out on this model to check the impact of the optimization parameters identified during modeling of the system. At a later stage, two FMs were characterized to verify that the behavior is repeatable between the different models.

The characterization is performed at the interface of the dynamometer, with frequency bands for the six degrees of freedom. Once the results are obtained, the response is rotated and translated to the theoretical injection point of the mechanism. From this injection point, the impact of the mechanism on the spacecraft's CoG is determined. The forces at the injection point should be used to compute the torques at the CoG; however, they are discarded in the computation because their levels are within the dynamometer's noise levels and, when multiplied by the lever arms, they would become the main contributor to the torques observed at the spacecraft's CoG – and this is unrealistic.

Figures 11, 12 and 13 show a comparison between the model and the measurement of the torque around the Z axis of the mechanism. The measurement is shown for three frequency bands from 1.2 to 500 Hz. There appeared to be fairly good correlation between the measurements and the simulation results. The simulation makes it possible to acquire more accurate data at frequencies that cannot be measured, e.g. in a very low frequency range.

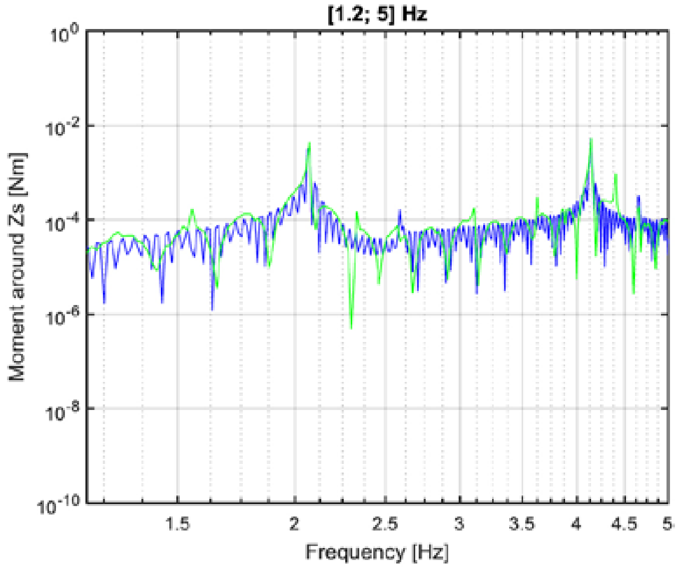

Figure 11: Simulated (blue) vs measured (green) μVib

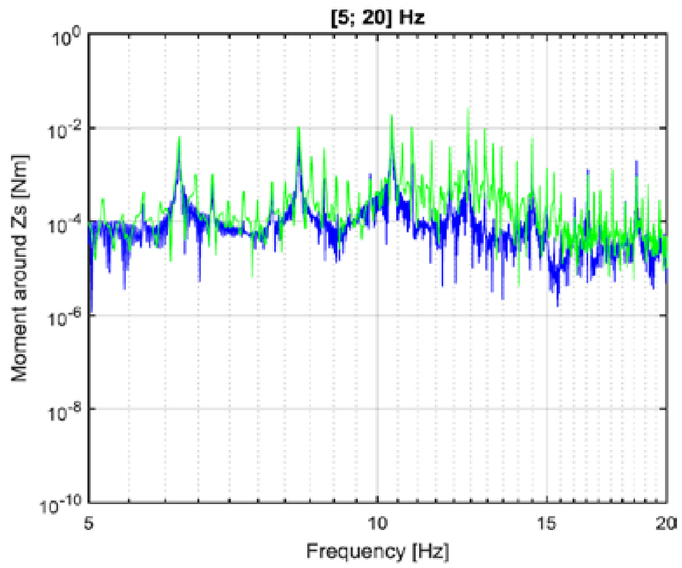

Figure 12: Simulated (blue) vs measured (green) μVib.

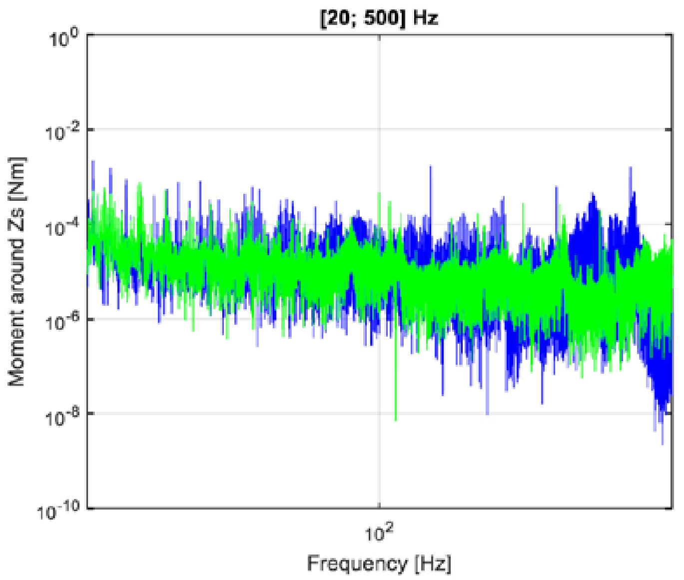

Figure 13: Simulated (blue) vs measured (green) μVib.

Based on the LTM measurements, it could be demonstrated that the conclusions from the Simulink model regarding reduction of micro-vibrations and exported torques were correct, except for the impact of the ratio between holding torque and detent torque. It was observed that changing the drive current (to vary the holding torque) did not visibly change the perturbations emitted by the mechanism.

10. Conclusion

The dynamometer developed by Kistler for CSL's UVN calibration mechanism features an innovative design that includes a ceramic top plate to increase the system's global natural frequency, thus permitting measurements across a wider bandwidth. The measurements performed by CSL in connection with the UVN project demonstrated that the actual micro-vibrations and exported torques were correctly replicated by the Simulink model, and that the model can be used to extrapolate the predictions to very low frequencies (< 1 Hz).

While the measured noise levels were sufficient for the current project, it is expected that better performance will be achieved with the micro-vibration dynamometer. In fact, the environment of the measurement setup could not be efficiently optimized due to the stringent cleanliness requirements for UVN; consequently, additional measurements will be performed with improved acoustic environments, both inside and outside cleanrooms, so that the noise level can be reduced to the achievable minimum.

Acknowledgment
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