Microvibrations Modelling and Measurement on Sentinel 4 UVN Calibration Assembly using a Piezoelectric 6 Component Force Dynamometer

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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 relies on regular in-orbit re-calibrations using the Calibration Assembly (CAA). This CAA mechanism is comprised of a multi-functional wheel containing calibrated diffusers. Positioning is via a stepper motor and, as the instrument is mounted on the MTG-S platform, it is imperative that the resultant microvibrations and torques are controlled as the MTG IRS instrument is incredibly sensitive to them.

To this end, CSL has developed a Simulink model that inputs a motion profile to simulate the real-world mechanisms, generating the torques and microvibrations at the satellites center of gravity. To validate this prediction, a specially designed Kistler dynamometer allows the actual forces and torques exported by the CAA qualification model to be measured.

Measuring with Piezoelectric Dynamometers

Microvibrations 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 ideally suited for this purpose. Their incredibly high span-to-resolution ratio of greater than 100000 is a particular advantage. Thus, it is 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). In addition, the very high stiffness of piezoelectric force sensors permits natural frequencies of 1000 Hz or more.

To optimize the system, the measurement setup itself is also highly important. As can be seen in Fig. 1, the dynamometer needs to be mounted on a vibration-isolated table to prevent structure-borne sound and external vibrations affecting the results. These external influences can severely distort measurements as the dynamometer, and the mass of the object being measured, can generate a large acceleration themselves. With a correct set-up, the interference signal can reach levels below 0.01 N or 0.003 Nm (RMS; 3…350 Hz).

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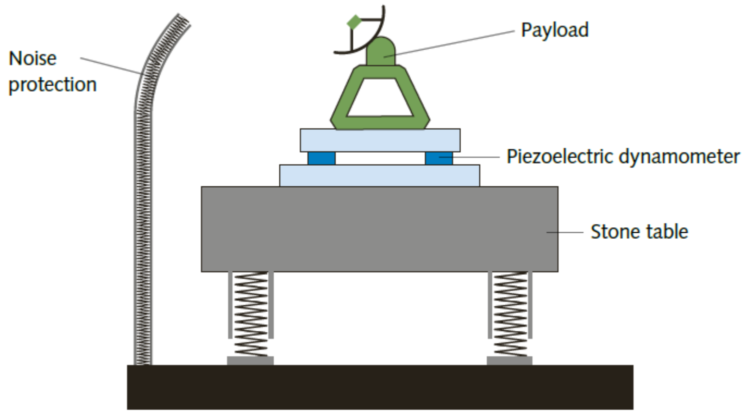


Figure 1. Microvibrations measurement setup: payload (green), piezoelectric dynamometer (dark blue), stone table (grey). An outer dome is used for noise protection.

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-insulated stone table, while the upper limit is determined by the natural frequency of the system consisting of the dynamometer itself together with the object being measured.

Correct mounting of the measured object to the dynamometer is critical in order to obtain a good measurement result. 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. Data recording is handled via a laptop and an analog-to-digital converter.

New Measuring Trends

As discussed previously, the maximum measurable frequency for microvibrations is currently in the range of about 350 Hz. However, higher cut-off frequencies are now increasingly required in order to allow for the measurement of larger objects. Unfortunately, the standard dynamometer design itself will be a limiting factor in trying to achieve these requirements. Recent standard dynamometers are comprised of four three axis force sensors sandwiched between a top and base plate, each made of steel (as shown in Fig. 2).

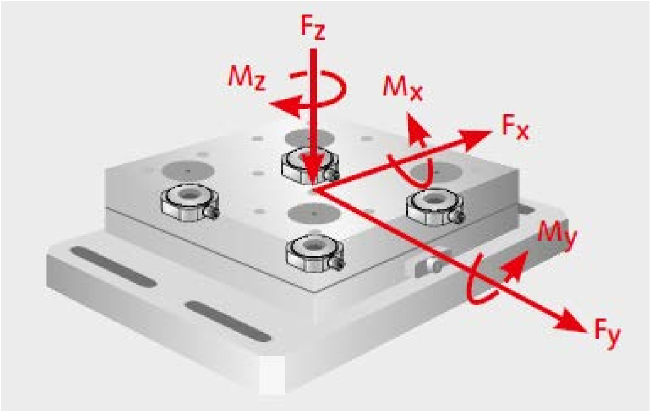


Figure 2. Structure of a piezoelectric dynamometer to measure microvibrations with four 3-component sensors

The dynamometer behaves like a second-order spring/mass system with a dominant natural frequency and so measurements must be taken well below this natural frequency. Addition of any further mass lowers the natural frequency even more. Therefore, if the dynamometer itself is small, simply mounting a heavy object to investigate it can itself have a major influence and lower the natural frequency of the system (as illustrated in Fig. 3).

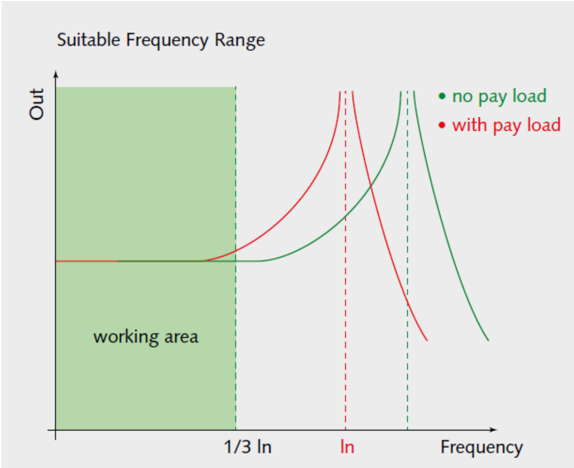


Figure 3. Natural frequency of dynamometer with and without additional mass

So, if measurements up to 500 Hz are required, the dynamometer should have a natural frequency of >1500 Hz, otherwise resonance will exert too much influence on the measurement signal. Therefore, a high natural frequency is a must.

The dynamometer's size and stiffness have a considerable effect on the natural frequency. The larger the dynamometer, the heavier the top plate will be – thereby reducing the natural frequency. This effect cannot, unfortunately, be entirely compensated for by increasing the stiffness of the sensors.

However, recent advancements in dynamometer design mean that higher natural frequencies are now possible. The consequence of this is that it becomes possible to easily isolate microvibrations and further reduce their causes.

In addition to this, new testing requirements are also demanding an increase in the size of the dynamometers in order to test complete subsystems and whole small satellites. Combined with the higher frequency requirement, this means, with known materials, the design limits have already been reached and any further improvements could only have been incremental while requiring enormous time and cost to achieve. Hence new materials for the dynamometer top plate were considered.

Ceramic Top Plate Dynamometer

As previously described, the dynamometer size has a critical impact on natural frequency of the unit, and while they help add stiffness; heavy top plates are especially unfavorable. A search for new materials to be considered for the dynamometer top plate showed that ceramics offer highly advantageous properties (see Table 1).

Table 1. Steel and ceramic – material properties

	Steel 17-4 PH	**Ceramic (Al_2O_3)**
Specific gravity	7.8	3.84
Modulus of elasticity (Young´s modulus)	190,000 MPa	370,000 MPa
Tensile strength	1200 MPa	300 MPa
Thermal expansion	10.8 µm/m-K	5.7 µm/m-K

The low specific gravity and a high modulus of elasticity offered by ceramics show a clear benefit, however, the low tensile strength and low thermal expansion would be drawbacks.

As seen in Fig. 4, finite element method (FEM) calculations showed that natural frequencies can be increased by 40% if ceramic top plates with similar dimensions to steel were used. This would lead to significant improvements in microvibration detection.

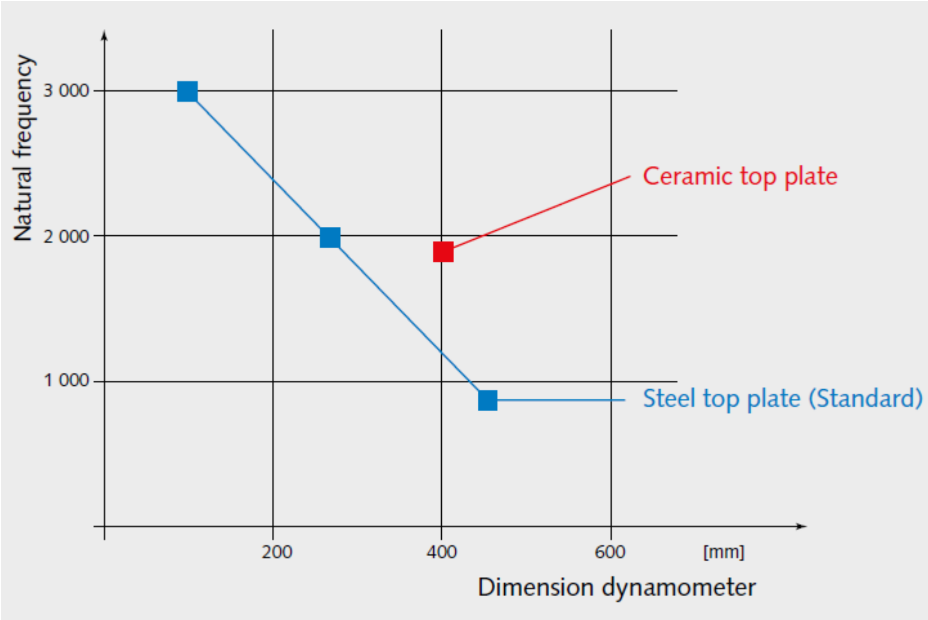


Figure 4. Natural frequency $F_{x,y}$ direction in relation to dynamometer size

In such a case, lower strength could be acceptable considering the very small forces and loads involved in microvibration measurements. In order to still allow for a correct mounting of the dynamometer, the steel base plate was retained, as it has no effect on the natural frequency of the dynamometer.

Measurements of the natural frequency in the z-direction showed a very well-defined peak at about 2570 Hz (Fig. 5). In the shear directions (Fx,y), the natural frequency was about 1950 Hz. For comparison, dynamometers with steel top plates reach about 1400 Hz in the shear direction.

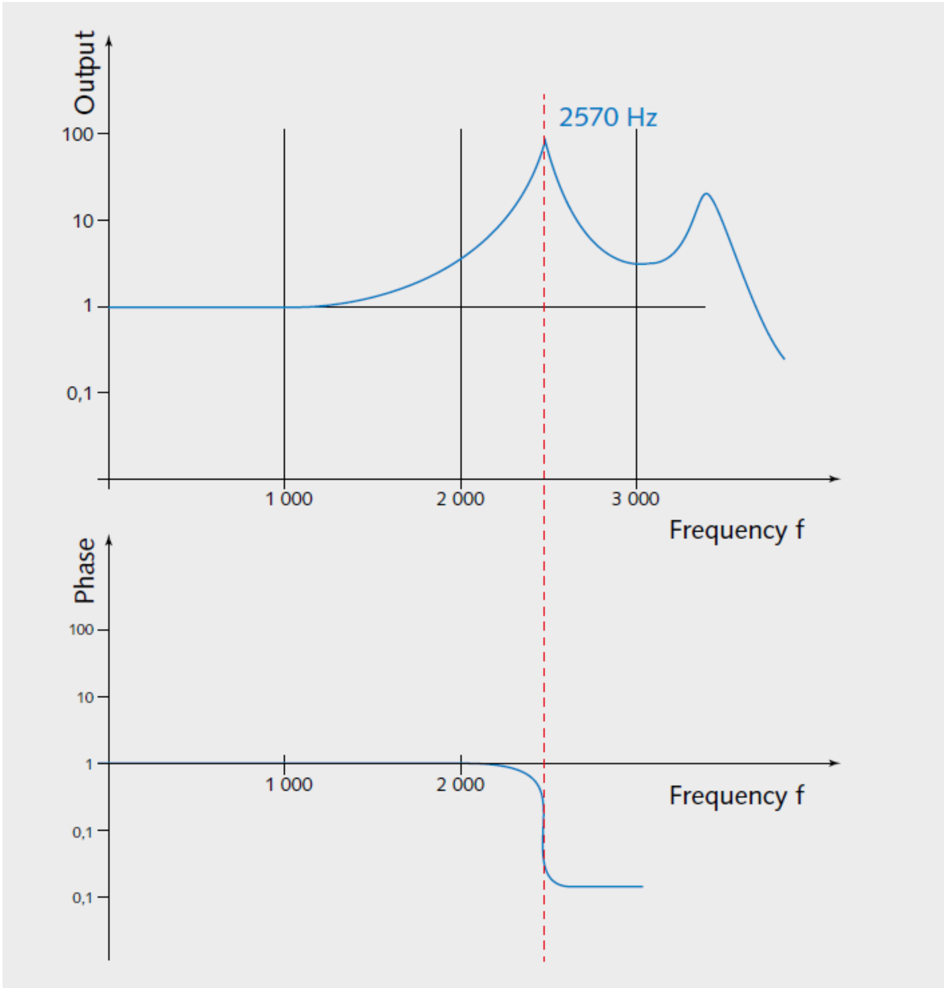


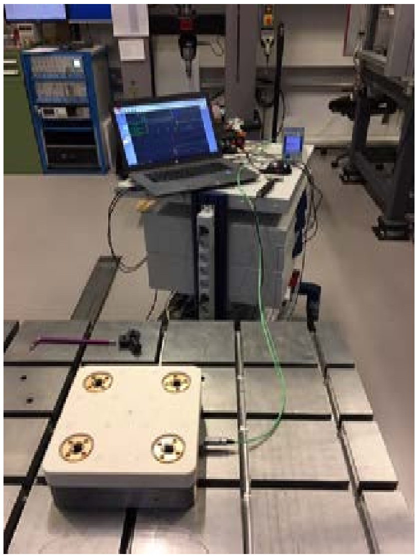
Figure 5. Natural frequency in F_z direction, Ceramic top plate dynamometer type Z21492

However, after further investigation, the low thermal expansion proved to be a problem; despite the FEM calculation, a full validation of this behavior was not possible. So, an extended investigation with experimental specimens was undertaken to ensure that the difference in thermal expansion, between a steel base plate and an Al_2O_3 top plate, would not lead to fractures in the latter because of its special structural design.

Effects of Dynamometer mounting

The dynamometer must be mounted on a stiff base, ideally a stone table or steel table (min 10x more mass than dynamometer with test object).

Essential is also proper mounting. The dynamometer must be screwed with four screws on the stiff, flat and clean base. Incorrect mounting affects natural frequency heavily. The effect of different incorrect mounting was measured at Kistler in our test lab. The dynamometer was mounted on a stiff base plate and excited with an impulse hammer in Z–direction.



Figures 6 and 7. Test set up for natural frequency measurements

Table 2. Configurations for natural frequency measurements

1	Placed on base
1a	Placed on foam
3	Mounted with 1 screw (120Nm)
4	Mounted with 2 screws diagonal (120Nm)
5	Mounted with 4 screws (120Nm)
6	Mounted with 4 screws (20Nm)
7	Mounted with 4 screws (20Nm),50µm steel strip beneath one edge
8	Mounted with 4 screws (20Nm),paper beneath one edge

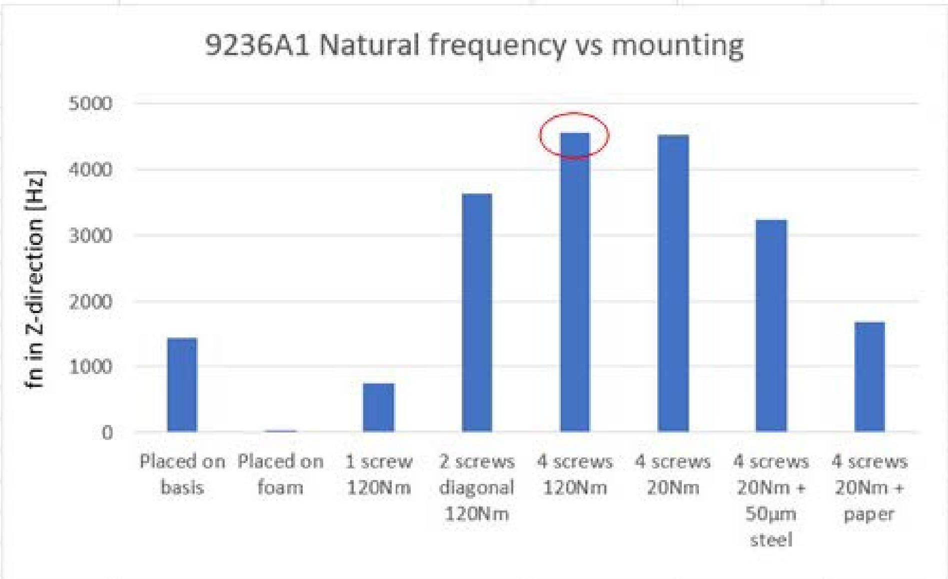


Figure 8: Configuration 5 is recommended. In the summary below, it clearly shows the highest natural frequency.

Characterization of the Optical Calibration System for Sentinel 4 UVN Satellite

The CSL required a natural frequency greater than 1500 Hz to characterize the optical calibration system of the Sentinel 4 UVN satellite. Kistler's dynamometer type Z21492, with a ceramic top plate, was selected due to its large dimensions and high natural resonance frequency.

The dynamometer was tested on an insulated stone table and in a sound-insulated area by Kistler. The next step was the validation measurements of subassemblies for the Sentinel 4 satellite. After completion of this validation, CSL will perform further calibration measurements so that they will be able to offer the space community a superior test facility for characterization of microvibration measurements, down to a noise floor of 0.01 mN (Narrow band noise ΔF=1 Hz).

S4/UVN Calibration Assembly

The Sentinel 4 mission covers the needs for continuous monitoring of Earth atmospheric composition and air pollution using a high-resolution Ultraviolet/Visible/Near-Infrared (UVN) sounder instrument to be deployed on two geostationary MTG-S satellites. The radiometric accuracy of the UVN instrument relies on periodic in-orbit re-calibrations using the UVN Calibration Assembly (UVN CAA). This mechanism has been designed, built and qualified by CSL. The mechanism is composed of a multi-functional wheel with optical diffusers and a mirror that are successively placed in front of the camera during the calibration. The rotation is activated by a stepper motor and controlled by a resolver.

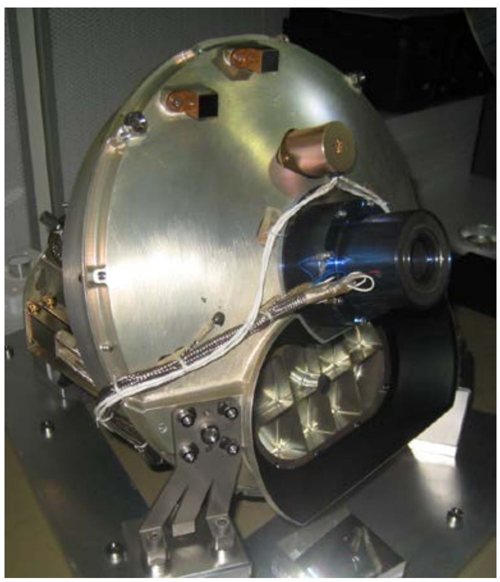


Figure 9. S4/UVN CAA

MTG-S being an Earth observation satellite with accurate pointing requirements, the exported torques and micro-vibrations that are generated by subsystems can degrade the performance of the MTG instruments. Therefore, the micro-vibrations emitted by the Calibration Assembly during the motion of the mechanism shall be reduced to the minimum achievable.

In this goal, the micro-vibrations and exported torques of the Calibration Assembly were estimated using a model and then characterized using the Kistler micro-vibrations dynamometer.

Micro-Vibrations Modelling

To evaluate the micro-vibration levels in the moving mechanism a Simulink model has been created that incorporated the elements that generate the vibrations as well as the main components that influence the transmission of vibrations in the mechanism. The elements that generate the micro-vibrations are:

- The stepper motor
- The bearing
- The friction

The main elements that influence the transmission of the 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 Center of Gravity (CoG).

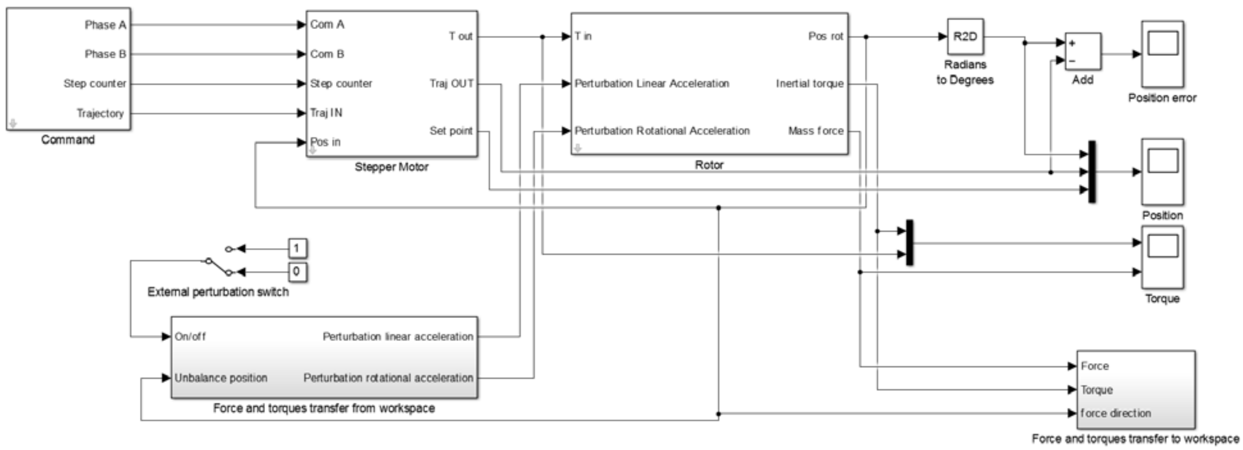


Figure 10. Micro-vibrations Simulink model

The stepper motor controller is a Simulink block that takes in input the motion that the motor should follow as well as the micro-stepping parameters and transforms it into the sine wave that will be the current input of the stepper motor. The stepper motor is another Simulink block that takes in input the current of the two phases and that generates the output torque of the motor. The modelling also takes into account the detent torque of the stepper motor.

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

The last block is the exportation of the results in the MATLAB workspace. The results of the Simulink computation are composed of the torques and forces generated by the assembly at the motor location. After the simulation, a Matlab script is ran in the workspace to take into account for 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 carried out to identify the exported torques and micro-vibrations in different frequency bands. The final result of the analysis is a temporal response of the injected micro-vibrations at the spacecraft CoG.

Micro-Vibrations Optimization

Using the produced model, an optimization analysis was carried out to reduce the micro-vibrations exported to the spacecraft. The driving of the stepper motor can be tuned by multiple parameters. The main parameters are the maximum current injected in the motor and the motion profile. These parameters have been analyzed to reduce the micro-vibrations to the minimum achievable.

The first optimization performed was determining the impact of the input current as well as the sensitivity to the detent torque of the stepper motor. It was found that the micro-vibrations created by the stepper motor were primarily affected by the ratio between the holding torque (proportional to input current) and the detent torque. The higher the ratio, the lower the micro-vibrations level.

The second analysis performed was determining the impact of the driving profile on the generated micro-vibrations. A micro-stepping strategy was introduced to reduce the exported micro-vibrations but even with a perfect input signal, the micro-vibrations induced by the stepper motor cannot be erased. It was evaluated that having more than 64 µsteps / step does not improve the micro-vibrations behavior.

A specific input current profile was also suggested to, in theory; remove the non-uniformity of the output torque and so to provide a constant output torque during the motion. This profile was working well in simulations even in open-loop conditions with external perturbations. But it was evaluated incompatible with the actual electronic control system due to cross use of table lookup with other subsystems. Following the rejection of an advanced current profile, more common profiles were evaluated including a constant velocity profile, a constant acceleration profile and a jerk profile.

For a jerk-based profile, a full motion is divided in 7 parts: 4 transitions 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 exported micro-vibrations during a complete motion. It was found that the best profile to reduce the micro-vibrations is a jerk profile that tends to a constant velocity profile. Tuning the acceleration part of the jerk profile allowed reducing the micro-vibrations during the transient part of the curve.

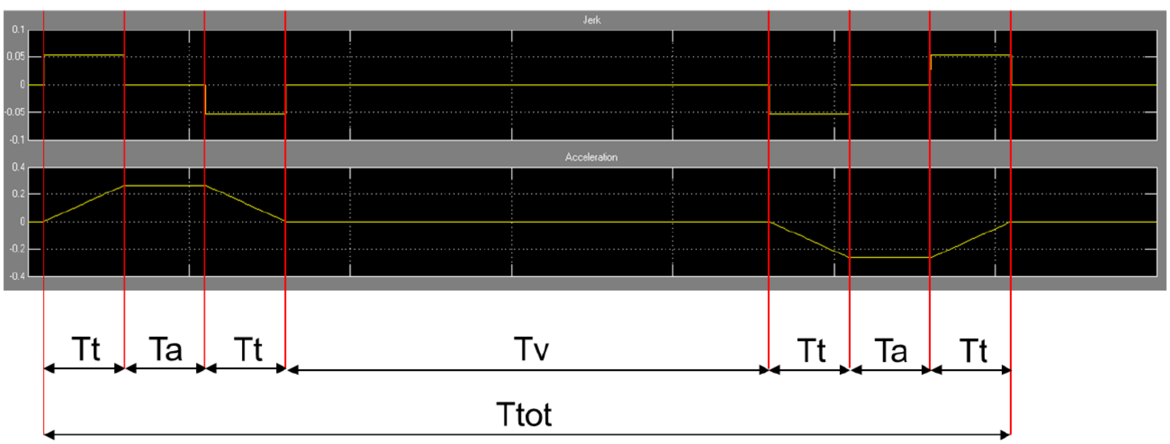


Figure 11. Jerk and Acceleration definition

Micro-Vibrations Setup

Once the sensitivity analysis and optimization performed on the Simulink model was complete, it was required to compare the results with physical measurements. Therefore, a test campaign has been performed using the Kistler dynamometer developed for this application. Fig. 12 shows the CAA mounted on the micro-vibrations table.

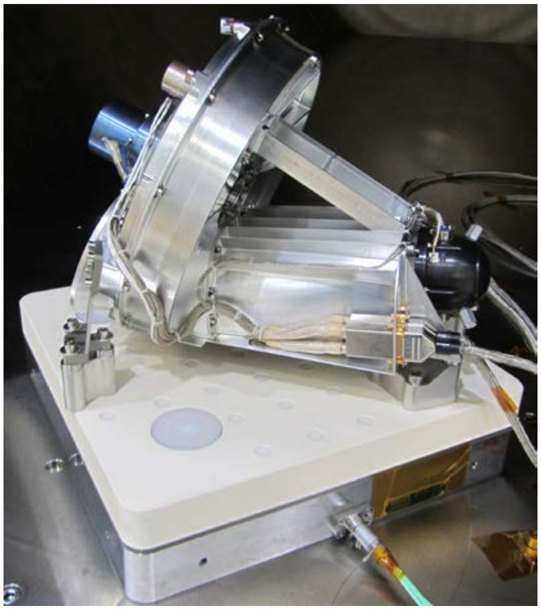


Figure 12. UVN CAA mounted on µVib table

The table is capable of recording the forces in three axes as well as the torques around the three axes with a high sensitivity as described in the first part of this article.

Being very sensitive, a favorable environment is required to avoid impacting the measurements. The two main noise contributors are the acoustic and the seismic environment. Since a characterization of Flight Models was foreseen, it required working in ISO5 environment which creates additional acoustic noise due to continuous airflow. However, CSL is equipped with vacuum chambers located in ISO5 environment which allows reducing the acoustic noise by closing the chamber during the measurement. Furthermore, each vacuum chamber is equipped with a very stable optical bench that is decoupled from environmental vibrations thanks to a heavy seismic mass.

The environment noises shown in Tables 3 and 4 were reached, with the instrument installed on the dynamometer, in Focal 5 and Focal 2 that are two vacuum chambers at CSL. The measurements are from 0 to 500Hz.

Table 3. RMS Noise in Focal 2

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 4. RMS Noise in Focal 5

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

Fig. 13 shows an example of the spectral signature of the noise for the Mz axis.

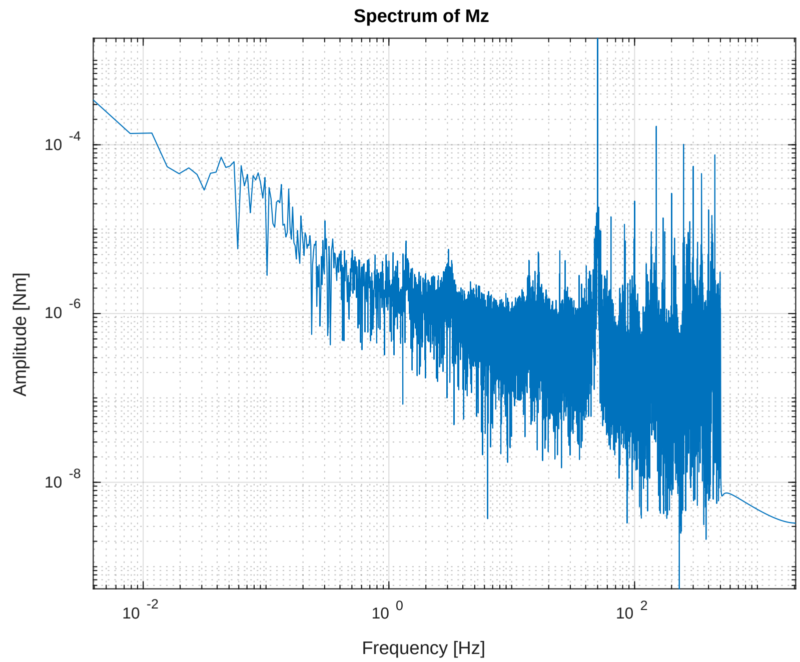


Figure 13. Noise spectral signature for Mz

It can be seen from the noise level that the goal of 0.01 N is not reached. This is attributed to the noisy environment in the cleanrooms. Furthermore, the local ISO5 airflows were activated during the test in Focal 5 hence the higher noise level seen. On the spectral signature, a peak at 50 Hz is present as well as harmonics. This peak has limited impact on the measurement regarding the UVN mechanism because its amplitude is much lower than the measured microvibrations.

Micro-Vibrations Characterization

Three models were characterized using the dynamometer. The first model to be tested was the Life Test Model on which an extensive campaign was done to check the impact of the optimization parameters identified during the modelling of the system. Later, two Flight Models were characterized to check that the behavior is repeatable between the different models.

The characterization is performed at the interface of the dynamometer by 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 CoG of the spacecraft is determined. While the forces at the injection point should be used to compute the torques at the CoG, they are discarded in the computation because the levels are within the noise of the dynamometer and when multiplied by the lever arm, it becomes the main contributor to the torques seen at the spacecraft CoG which is unrealistic.

In Figures 14, 15 and 16, a comparison between the model and the measurement is shown for the torque around the Z axis of the mechanism. The measurement is shown for three frequency bands from 1.2 to 500 Hz. The measurements appeared to be pretty well correlated with the simulation results. The simulation allows getting more accurate data at frequencies that cannot be measured, e.g., very low frequency range.

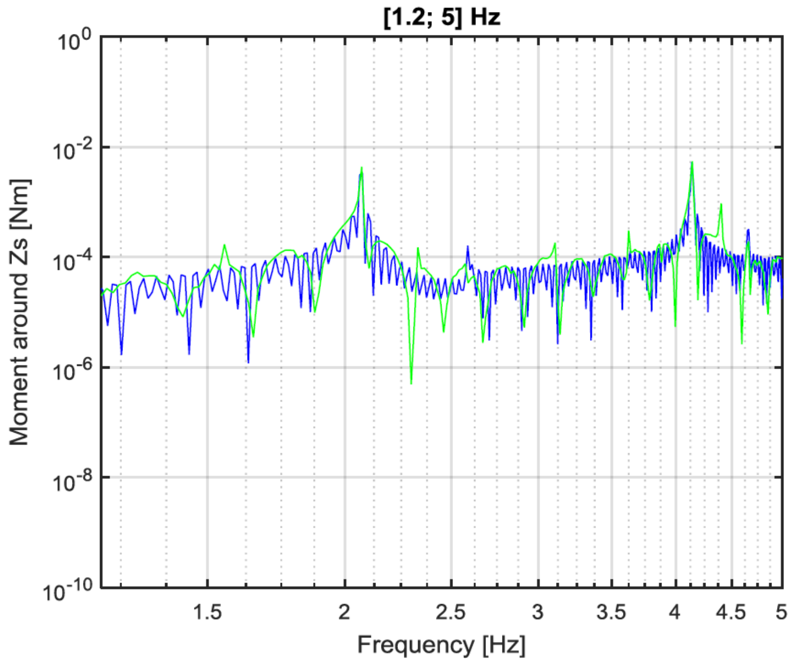


Figure 14. Simulated (blue) vs measured (green) µVib

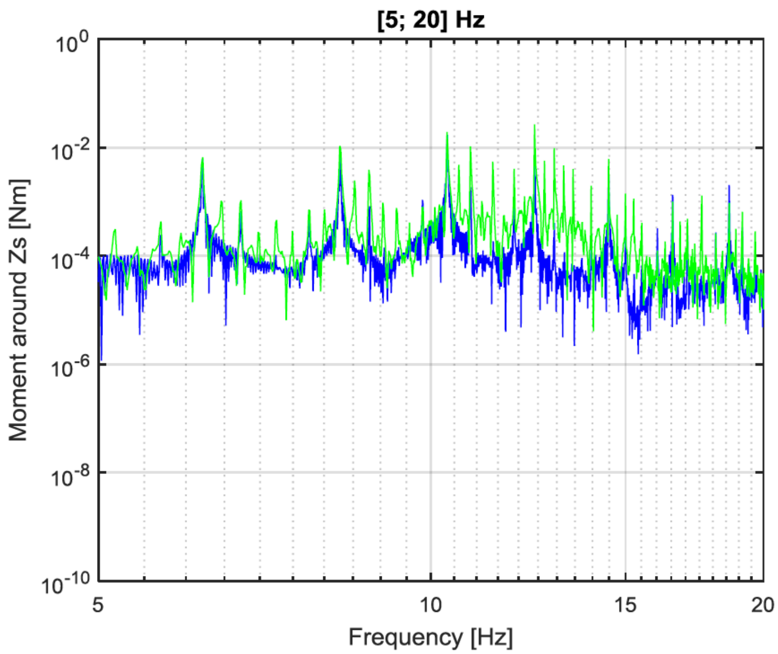


Figure 15. Simulated (blue) vs measured (green) µVib

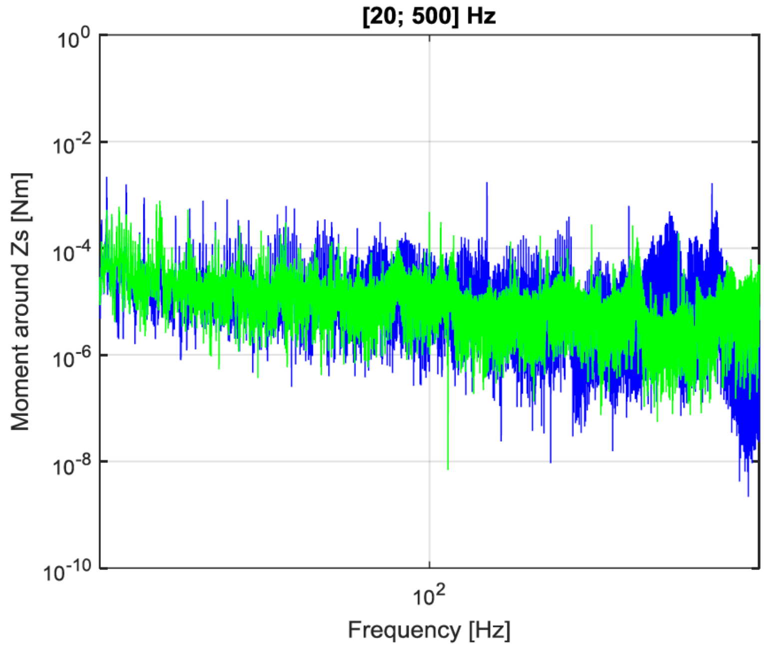


Figure 16. Simulated (blue) vs measured (green) µVib

The Life Test Model measurements showed that the Simulink model conclusions in terms of reduction of microvibrations and exported torques were correct except for the impact of the holding torque to detent torque ratio. It was observed that changing the drive current (to vary the holding torque) didn't visibly change the emitted perturbations of the mechanism.

Conclusion

The dynamometer developed by Kistler for CSL's UVN calibration mechanism is of an innovative design that includes a ceramic top table in order to increase the global Eigen frequency of the system and by this way allows measurements into a larger bandwidth.

The measurements performed by CSL for the UVN project showed that the actual microvibrations and exported torques have been correctly modelled by the Simulink model and it will allow using the model to extrapolate the predications towards the very low frequencies (< 1 Hz).

While the measured noise levels were sufficient for the current project, it is expected to reach a better performance with the micro-vibrations dynamometer. Indeed, the environment of the measurement set-up could not be efficiently optimized because of the stringent cleanliness requirements for UVN and therefore additional measurements will be performed inside and outside cleanrooms with improved acoustic environments in order to reduce the noise level to the minimum achievable.

Acknowledgement

This activity has been performed for a contract between CSL and OHB-M for the design and development of the UVN calibration assembly.