A Mechanisms Perspective on Microvibration –
Good Practices and Lessons Learned

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Abstract

In September 2017, the ESA Mechanisms Section organized the first Advanced Mechanisms Design Course. The course focused on how to anticipate and avoid the most common problems encountered in several different fields of space mechanisms design. One of the topics addressed was ‘A Mechanisms Perspective on Microvibration’. This tutorial paper draws from the content of this well-received training, focusing on practical tips and good practices, complemented by lessons learned from operational missions and their on-orbit performance.

Introduction

The purpose of this paper is to make mechanisms engineers aware of the microvibration problem and offer practical knowledge and tools on how to deal with it. This paper will cover:

- What microvibration is
- What causes microvibration in mechanisms
- How microvibration is typically handled at the system level
- What a microvibration requirement for a mechanism looks like
- Which verification methodologies are appropriate in which circumstances
- How verification approaches can be used most effectively and which pitfalls to avoid
- Which approach can be used to minimize microvibration

This paper does not cover recovery actions to be undertaken in case a microvibration problem manifests on orbit. If possible, changing operational parameters of the mechanisms generating the noise is recommended. In certain cases, post-processing the data from the payload may be used to offset the effects of microvibration.

Microvibration and Mechanisms

What is microvibration?

Microvibration can be defined as a structure-borne vibration generated from equipment in the spacecraft that causes motion of the payload or other sensitive equipment that could cause degradation in performance. It is important to note that several terms are typically used interchangeably to discuss one phenomenon: microvibration, micro-vibration, microdisturbances, jitter or even simply noise. Microvibration disturbances are usually in the range of micro-g’s (μg) typically occurring at frequencies from as low as 0.1 Hz up to 1000 Hz. Mechanisms such as Reaction Wheels (RW), Control Moment Gyros, Antenna Pointing Mechanisms (APM), Cryocoolers, Solar Array Drive Mechanisms (SADM), scanners, and optical mechanisms are typically the main sources of mechanical noise on a spacecraft.

Microvibration is a significant technical challenge for the current generation of space missions due to the stringent stability requirements of the payloads. The current state of the art is ~0.1 μrad Line of Sight stability. This equates to motions in the order of only a few nanometres in payloads. A further order of magnitude improvement is required for future missions. Microvibration is a system-level problem and involves several disciplines, such as systems, mechanisms, mechanical systems & analysis, optical, attitude & orbital control systems, and spacecraft ops. This further complicates the mechanisms designer’s task.

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What causes microvibration in mechanisms?

Physical causes of microvibration can be anything generating forces in the mechanism. A non-exhaustive list of causes is rotor imbalance, mechanical bearing irregularity, bearing friction and imperfections, motor cogging, stepper motors, and gear meshing and contact. Knowledge and understanding of these causes is key to optimize a mechanism for low microvibration.

Several aspects complicate dealing with mechanisms as noise sources:

- Noise is generated in six degrees of freedom (DOF). Measurement or analysis of the mechanism needs to assess all six DOF, and not remain limited to the DOF most directly related to the mechanism motion, e.g. the rotation axis for a SADM.
- The phase of the six DOF of noise may be important but is often lost when multiple noise source data is combined for analysis. This is particularly relevant at spacecraft level, but could be of note to a mechanism designer in charge of delivering multiple mechanisms.
- The dynamic coupling of the noise source to the spacecraft affects the noise injected into the spacecraft. This aspect is typically handled at system level.
- Noise generation depends on operational parameters (for example APM noise is dependent on axis position as well as rotational speed). For mechanisms with multiple degrees of freedom, this could lead to a cumbersome verification campaign. From a design point of view, the modal design of mechanisms is typically aimed at surviving the launch. Structural modes of the mechanism will amplify noise generated internally to the mechanism. These modes can differ significantly for different configurations of the mechanism and may lead to additional design constraints.
- Some noise sources have varying noise performance over time. Mechanical wear of certain components can worsen the performance. In addition, some mechanisms may show intermittent periods of generating higher noise, for example if bearing cage instability occurs.
- There is unavoidable inherent variability between individual seemingly identical noise sources. Figure 1 shows how 8 identical RWs may vary in noise up to one order of magnitude in Power Spectral Density (PSD).
- The noise performance may be affected by vacuum, temperature, gravity effects, exposure to vibration and shock, and changes over life. Figure 1 shows how the noise of these RWs increases after vibration test. Figure 2 shows how different levels of pressure impact the modal behavior of another RW. This RW is evacuated. Removing the ambient pressure changes the shape of the thin walled pressure vessel, which in turn stiffens the main lateral mode.

These aspects have an impact on how the microvibration requirements are derived and need to be verified.

![Figure 1. RW noise for several identical units and impact of vibration tests. Image courtesy of SSTL.](image-url)
Case study: On ground versus on orbit noise behavior for a dry RW

For a European Space Agency (ESA) R&D study, Surrey Satellite Technology Ltd (SSTL) performed in-orbit microvibration measurements using an in-situ microvibration monitoring system [1]. Several different noise sources were measured, but the most surprising results appear on two reaction wheels that are identical except for the lubricant used. One wheel uses a synthetic oil, whereas the other uses dry lubricant in the form of a sacrificial bearing cage.

Figure 3 shows how the dry-lubricated RW becomes significantly noisier on orbit. In comparison, its oil-lubricated counterpart behaves the same in orbit as it did during on ground tests, as shown in Figure 4. The explanation put forward by SSTL theorizes particles generated by the sacrificial bearing cage are kept out of the bearing raceway on ground due to gravity effects but may impact the noise signature of the RW in absence of gravity. This example demonstrates how assessing microvibration generated by a mechanism can be significantly impacted by the conditions on ground.

Measurements for these reaction wheels and other noise sources were taken over a time period of 18 months. In that time, no clear degradation of the microvibration performance was recorded. However, in case there is a real concern regarding microvibration degradation performance for a specific mechanism, a monitor such as the one flown by SSTL can be used for in situ health monitoring. Early warning of changing performance gives the spacecraft operator the opportunity to take the necessary corrective action where possible.
Figure 3. Noise signature for the dry lubricated RW: in-orbit data (red), on-ground spacecraft data (green) and Kistler data (blue). Image courtesy of SSTL [1].

Figure 4. Noise signature for the oil lubricated RW: in-orbit data (red), on-ground spacecraft data (green) and Kistler data (blue). Image courtesy of SSTL [1].
How is microvibration handled at system level?

System-level microvibration assessments investigate the transmission of very low vibrations by the spacecraft structure from the disturbance source to the receiver location which might be a sensitive instrument or payload and, where necessary, to find adequate methods to attenuate the vibrations along the transmission path. The system-level responsible engineer needs to identify whether the performance requirements for the instrument or payload are fulfilled under the influence of the relevant disturbance sources.

System-level microvibration verification is not straightforward. Directly measuring microvibration susceptibility is difficult. The performances cannot be validated on ground in a representative on-orbit environment (e.g. zero gravity, in-vacuum, perfectly unconstrained “free-free” condition). In addition, the background noise, mechanical and/or electrical, may be too high to measure the actual performance. Therefore, the verification of the microvibration performances is usually based on a combination of analytical predictions and hardware tests to validate models. Different analysis methods, such as Finite Element Modeling (FEM), Stochastic Energy Analysis, or a combination, may be appropriate.

Microvibration generally occurs in the mid-frequency range where FEM is inaccurate. Therefore, several ESA R&D studies have been performed over the last years to further develop these methodologies [3] [4] [5]. For one of these methodologies, the on-orbit performance of the mission has later been reported [7].

Several challenges occur at system level that can have an influence on the mechanism development. For example, microvibration emissivity and susceptibility requirements need to be defined at an early stage in the project while the system-level modelling is still at an immature stage. Microvibration budgeting is notoriously difficult and over specification can drive the system-level design. In addition, contractual interfaces can lead to over specification. It is up to the system-level authority to manage these requirements between all parties as the design matures. However, as mechanism designers it is imperative to be critical towards the initial requirements and highlight its impact on the design in case it is a driving requirement as there may be scope for flexibility.

Another difficulty at system level is to appropriately combine the microvibration generated by different noise sources simultaneously. Generally, a satellite has different sources of microvibration. They all generate noise in 6 DOF and have varying modes of operation, which can lead to a large number of cases to simulate. Alternatively, enveloping cases can be devised, although they can in turn lead to additional, potentially unwanted, conservatism.

Lastly, coupling noise sources to the flexible spacecraft structure changes the dynamic behavior of both source and structure. This is notable, as microvibration requirements are typically defined on a clamped interface. Depending on the methodology used at system level, additional requirements can be imposed on the mechanism designer to accurately model this coupling, such as an accurate model of the mechanism or a dynamic mass measurement to obtain the accelerance matrix of the mechanism [3].

What does a mechanisms microvibration requirement look like?

Microvibration requirements will either be in force and torque (or PSD) versus frequency, or as a maximum instantaneous disturbance versus time.

Figure 5 shows an example of a force versus frequency requirement. It is important to note this requirement is applicable over the entire performance range of the mechanism, for example speed and position range, as well as for the entire set of potential environments. This requirement is specified for a clamped boundary condition. This particular requirement is challenging and may not be realistic, as it is specified over a very large frequency range. Verification of this requirement may be problematic, especially at the low and high end of the frequency range. The mechanism designer is encouraged to be critical of such a requirement, and of its prescribed verification approach, as either one may not be appropriate. This will be illustrated later in this paper when the verification approaches are discussed.
Figure 5 also shows a maximum instantaneous disturbance versus time requirement. This type of requirement is more appropriate for (but not limited to) mechanisms with short or intermittent duty cycle. The type of requirement used is often dictated by instrument needs. In order to verify this requirement, the time history signal (from analysis or test) needs to be split into different frequency contributions and to be compared to the requirements in each frequency band, as illustrated in Figure 5.

**Microvibration Verification**

*Which verification methodologies are appropriate?*
Verification by test and analysis or a combination of both approaches may be more suitable in different circumstances.

Verification by analysis can be very useful in the early stages of the design when there is no hardware available yet. In addition, in some cases performing a test on the complete system is not feasible. For example, assessing the induced microvibration by the coupled system of a solar array and a SADM is no possible by test. In this case, analysis or a combination with test data at SADM level is more appropriate. Lastly, verification by analysis may be required if no suitable test facility is available due to the required sensitivity, frequency range or physical size of the test subject.

Verification by test is advisable when representative hardware is available, as well as a suitable test facility. It can validate (part of) the analysis model. Testing is particularly useful to assess the impact of environmental tests or different environmental conditions on the microvibration performance of the mechanism.

*How to perform verification by analysis?*
Microvibration verification by analysis is typically performed in a two-step approach:
- mechanism level (source of disturbance)
- system level

The objective of the mechanism-level analysis is to estimate the expected exported torque/force between the mechanism and a hard-mounted interface during operation, represented by $F_{\text{EXPORTED}}$ in the diagram (Figure 6). $F_{\text{IN}}$ represents internal mechanism forces/torques such as electric motor torque.
The objective of the system-level analysis is to estimate the expected performance of the disturbance-affected equipment (e.g. pointing performance of optical equipment) when input mechanism disturbance is applied at the relevant mechanism to spacecraft interface point. For such an analysis, either a blocked force approach or coupled mechanism-spacecraft model can be used to simulate the input disturbance (Figure 7).

An example model developed in MATLAB/Simulink is shown in Figure 8. The standard building blocks of such a microvibration model may consist in:

- Motor drive electronics
  - Current control
  - Position control
  - Output voltage to be applied on motor
- Electric motor model
  - Stepper, Voice coil, brushless DC etc.
  - Coil dynamics (R, L, back-EMF, detent, eddy current losses)
  - Rotor dynamics
- Mechanism components
  - Gearbox (transmission error, backlash, friction)
  - Other non-linear force contributors: Slip-ring, Cable wrap
- Structural parts
  - Structural parts with significant modes in frequencies of interest represented as state space matrix of flexible body exported from FEM tool
  - Typical parts modeled as FEM: Doors, Solar array, Scanner etc.
Verification by analysis is an integral part of the overall verification process at unit level and especially important at system level, due to the complexity of performing system-level performance testing under gravity conditions. As such, an effective way to accurately assess system-level microvibration performance can be to perform simplified system-level tests, correlate the results with the simulation and perform the detailed performance assessment using the correlated analytical model.

This process can provide an extremely accurate prediction of in-flight performance, as shown by the example in Figure 9 of in-flight spacecraft jitter data versus analytical prediction performed during initial commissioning of a spacecraft.
How to perform verification by test?

Verification by test at mechanism level is typically performed on a dynamometer, often referred to as Kistler table (after the brand name of the predominant supplier). To illustrate the capabilities and limitations of this type of equipment, two facilities are discussed here: the Reaction Wheel Characterisation Facility (RCF) (Figure 10) and the 6-DOF microvibration test facility (6dMVMS) (Figure 11). Even though the RCF is named after RWs, it can be and has regularly been used for other mechanisms as well. Figure 12 shows the specification of both facilities. Test results using the relatively new 6dMVMS have already been reported elsewhere [10].

Figure 10. The RCF facility at ESA [8]

Figure 11. The 6dMVMS facility at ESA [9]
The RCF system is composed of the following subsystems [8]:
- Instrumentation of the facility and interconnection to the data handling system
- Test table providing a rigid interface between the specimen and the instrumentation
- Marble block acting as seismic reaction mass and hosting the test facility
- Pneumatic isolation system to decouple from disturbing environmental ground vibrations
- Vacuum bell equipped with a dry pumping system and a vacuum gauge
- Signal conditioning, data acquisition and processing system

The microvibration measurement system is composed of two platforms [9]:
- a measurement and excitation platform (lower platform)
- a vibration isolation platform (top platform)

Each platform is formed from a Minus-K passive isolation system and an array of sensors and actuators which provide 6 DOF control and measurement. The measurement platform is a bespoke design, and has two modes:
- measurement, where the platform measures the 6 DOF force/torque exerted on the platform;
- excitation, where the platform subjects a specimen to a controlled 6 DOF microvibration environment.

The platform is designed to allow measurements and excitation at low frequencies (< 0.03 Hz) and very low amplitudes (μN).

The facilities both have unique capabilities missing in the other facility. The RCF can be equipped with its vacuum bell to perform measurements in vacuum if required. The 6dMVMS can excite equipment and is therefore uniquely capable of verifying microvibration susceptibility requirements by test. The frequency range of both facilities is complementary, with only relatively small overlap, although an extension of the frequency range for the 6dMVMS is currently under investigation.

There are several good practices to take into account when verifying microvibration requirements by test:
- Modes of the test set-up can influence the data. This usually limits the frequency range and mass of the unit under test. For the RCF, the modes of the empty table are higher than 1250 Hz. With a payload, the unit under test and its MGSE, of 10 kg this drops to ~1000 Hz and even lower for
heavier payloads. This means the usable frequency range depends on the payload and varies on a case by case basis. The upper value of the usable frequency range is lower still than the natural frequency of the table with payload, as the upslope of this mode will skew results. For the RCF, it means the usable frequency range will be typically up to 900 Hz.

- Inappropriate modal design of mechanical ground support equipment (MGSE) can compromise data. The MGSE should be designed so its main modes are outside the measurement range of interest where possible. This may be challenging in certain cases as microvibration facilities have a limited mass capability. The combined mass of stiff MGSE and the unit under test may have an impact on the modes of the test facility itself as discussed above.

- Gravity offloading equipment may impact the microvibration measurement. For example, microvibration isolation systems can be designed to be very compliant. Therefore, they may require gravity offload systems to operate. These offloading devices themselves are usually also designed to be very compliant. Care needs to be taken not to influence the performance of the isolation system with the offload system. A second example of impact by gravity offload systems will be discussed in the case study below.

- Electrical ground support equipment (EGSE) can create electrical noise affecting the data. The EGSE used for the test facility itself are usually designed to avoid these effects, but the EGSE needed to run the mechanism may cause interference. If it is not possible to take this into account in the design stage of the EGSE, care should be taken when interpreting the results. It is common to see spikes at 50 Hz (in Europe) and its higher harmonics related to mains electrical noise.

- Careful selection of test durations and post-processing methods is required. Specifically, obtaining valid low frequency data leads to long test durations.

- Appropriate run-in of mechanisms may be required in order to measure stable performance, rather than start-up performance. For example, fluid lubricated mechanisms may require some time to clear out excess oil from the bearing races after a period of standstill and to reach a stable temperature which impacts the viscosity of the lubricant. On the other hand, mechanisms which are used intermittently may actually require testing after a long stand still.

- Plan for microvibration tests throughout the qualification campaign and after the life test prior to mechanism strip-down for sensitive applications. Where possible, it is even recommended to test in between different mechanical tests (sine vibration, random vibration, shock). In case a significant performance degradation is measured, it will be easier to trace it back to a specific test environment and potentially negotiate a relaxation of this requirement or design in specific protection for the mechanism.

- Assess other environmental impacts such as temperature and vacuum where possible. Often the impact is smaller than the impact of mechanical environmental tests. However, it is recommended to assess these effects on at least one unit.

- Test ALL units. Small build to build variability can lead to significant microvibration performance changes, as demonstrated in Figure 1.

Case study: Verification by test for a large rotating scanner

In order to demonstrate some of the issues with verification by test, one specific case study is discussed here. The force versus frequency requirement shown in Figure 5 is actually applicable on a large rotating scanning instrument. Verification by test is specified for this requirement. The scanner mass is 200-300 kg, with a rotating mass of more than half of the total mass. The scanner is designed to rotate at a constant speed of <1 Hz.

When comparing the requirement to the specification of state of the art test facilities (Figure 12), several observations can be made. Firstly, the instrument is too large for the entire instrument to be tested. A larger facility may need to be developed in order to test the complete instrument. However, the scan mechanism in the instrument is compatible with these two facilities.
Comparing the frequency range of the requirement to the test facility specifications shows that both facilities would be required to cover the entire range. Even then, the 6dMVMS can measure as low as 0.03 Hz, whereas the requirement goes lower than 0.001 Hz.

The sensitivity and measurement range of both facilities are also relevant. It seems the sensitivity and range of the RCF is only compatible with the requirement up to 150 Hz. At higher frequencies the requirement is below the sensitivity of the facility. The 6dMVMS can actually measure forces lower than the minimum force specified of 1 mN. However, it can only measure up to 1 N. For an instrument this large, rotating at <1 Hz, the exported force is unlikely to be as low as 1 N at the main rotating frequency.

The instrument requires gravity offloading to operate under a 1g environment, although it can also be operated for short periods of time without gravity offloading. However, a measurement in both of these configurations impacts the data in a different way. The offloading MGSE itself includes bearings as it needs to allow for the rotation. These can generate additional noise. Furthermore, the MGSE changes the inertia and the modal behavior of the instrument. On the other hand, operating without offloading significantly changes the preload of the bearings in the scan mechanism. This may in turn have a significant impact on the microvibration performance. Both potential test configurations have clear drawbacks.

Lastly, the scanner is not axisymmetric and has a large cut-out on one side. As a consequence, there are significant additional unbalance forces due to windage losses when operating in air. In order to make meaningful measurements, the test would need to take place in vacuum.

It is clear for this particular case that the specified requirement along with the specified verification method is very challenging to achieve. As mechanism designer, discussing these issues early during the development with the customer is strongly advised in order to avoid unnecessarily ambitious design constraints and to come up with a feasible verification approach.

**Which Approach can be Used to Minimize Microvibration?**

There are several potential approaches on how to minimize the microvibration generated by mechanisms. This includes potential design improvement methodologies, minimizing the impact of assembly, integration and test (AIT) on the microvibration performance as well as solutions external to the mechanism in case design optimization and other measures prove to be insufficient.

A mechanism designer can attempt to optimize a mechanism for low noise performance during the design phase. The following tactics can be used:

- Reduction of the amplitude of the noise generated by carefully selecting components, materials, surface finishes and lubricants. It is recommended to try out different options at breadboard stage for especially demanding applications.
- Screening of components and subassemblies during the manufacturing stage. As shown in the example in Figure 1, identical mechanisms can still differ significantly. Performance of key components or subassemblies can be screened prior to integration in the mechanism to minimize the spread of the noise performance and reduce it as much as possible. This approach is generally taken in case larger numbers of identical mechanisms need to be made, as setting up the screening process requires quite some effort.
- Improve the modal design. The main structural modes of the mechanism are likely to be excited by internally generated noise and therefore amplify the exported microvibration. This can be seen very clearly in Figure 2. Designing the mechanism structural modes in frequency ranges where higher microvibration is allowed by the specification will reduce the impact of these modes getting excited. The requirement in Figure 5 shows a clear frequency range allowing higher amplitudes of exported microvibration. If compatible with the structural requirements of the mechanism or instrument, this would be an obvious target area in terms of modal design.
• Control electronics can significantly impact performance. This is specifically the case for closed-loop controlled mechanisms. It is important to test these mechanisms with the real control electronics in order to assess this effect, or to include it in the microvibration model.
• Tune the operational parameters, e.g. restrict/tune the speed range. If certain speeds excite structural modes of the mechanism and it is possible to avoid these speeds without impacting the operations, this could be a valid approach to minimize the exported microvibration.
• More innovative design solutions, such as magnetic bearings or flexures instead of tribological contacts could be envisaged.

Noise source optimization does not necessarily end at the design stage, but can continue during AIT. Reducing the environmental loads on mechanisms generally reduces the final microvibration performance. If it is clear which (mechanical) environment has the largest impact on the performance, local reductions could potentially be negotiated. Alternatively, the mechanism can be protected using vibration isolation systems. In addition, the selected model philosophy can also have an impact. For protolflight/protoqual models, the higher qualification mechanical loads can lead to higher exported microvibration. Choosing a full qualification model (QM) means the flight models will only be exposed to the lower acceptance-level vibration environment.

Noise source isolation can be an effective approach to attenuate the exported microvibration. It may be more efficient and cost effective to isolate particular mechanisms than to design a low-noise mechanism. For certain very demanding requirements, a combination of both may be required [11]. Dedicated isolation systems can be used to reduce the exported microvibration, but it may even be possible to design isolation into the mechanism itself. Passive isolation systems based on visco-elastic isolators are used most often, although other, more performant/complex systems exist as well. Interestingly, isolation systems can be designed with a dual function to reduce the environmental loads on the mechanism, thereby protecting the mechanism and improving its performance, as well as reducing the exported microvibration.

Conclusion

Microvibration can be a design driver for mechanisms. This paper has collected a number of good practices and lessons learned on how to deal with microvibration when designing a mechanism. Appropriately understanding the impact of microvibration requirements and taking them into account in the early stages of a mechanism development can avoid many problems later during the project. A clear and feasible verification approach needs to be devised at the same time.

Further improvements in this area are key for future missions, both in terms of mechanism design and verification approaches which avoid unnecessary conservatism.

References

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