APN-112

Inertial Navigation Systems and Vibration

Contents

Introduction

In many systems, platform vibration does not significantly degrade Inertial Navigation System (INS) performance. However, when vibration is severe, or when vibration is less severe but under poor INS conditions, there is often a dramatic degradation in the INS solution quality. This document introduces platform vibration in the context of an INS and why it should be considered early in the system design cycle. Several common errors due to platform vibration are discussed, as are the impacts of vibration on Inertial Measurement Unit (IMU) performance and INS solution outputs. Basic methods to measure and mitigate vibration in these contexts are briefly noted. This document is not meant to be a comprehensive guide on vibration theory or related topics like digital signal processing.

Vibration is oscillatory motion in the mechanical domain that may be periodic or random in nature. While in general the kinematic mean remains constant in a system exposed to vibration, perturbations occur in position, velocity, and acceleration due to the vibration.

These states are exactly what an Inertial Navigation System is trying to estimate. However, the goal is typically to measure motion or dynamics of interest ("platform motion"), not the oscillatory motion due to vibration. Vibration is essentially injecting unwanted signal or noise and reduces the effective signal to noise ratio (SNR) of the inertial sensors that compose the IMU. Additional factors usually related to the physical design and implementation of the sensors introduce or aggravate inherent IMU measurement errors. On the downstream side of the system, the INS solution output may also be impacted by vibration, resulting in a user experiencing increased noise or measurement aliasing in the state estimates. Extra challenges exist when platform motion approaches or overlaps with vibration in the frequency domain, or when the scale of platform motion is overwhelmed by that of vibration.

Mitigating vibration poses a challenging design problem dependent on the characteristics of a full system within the operating environment. It requires consideration throughout the system design process to introduce appropriate types of mitigation to different stages and subsystems. Iterative design spanning multiple engineering domains should be considered. If vibration does cause problems, it is unlikely a solution can be found within a single domain. For example, it is generally not possible to implement software changes that provide a reliable and robust fix to compensate for insufficient mechanical platform isolation in the IMU mount design. Solutions closer to the source of the vibration (i.e., in the mechanical domain) are likely to be most effective, even though mechanical design improvements can be challenging and have ripple effects throughout a system. A holistic approach will help a system operate effectively across the range of intended conditions. For these reasons it is very important to consider potential vibration throughout the entirety of your system design process.

Applicable Products

This application note is applicable to any Hexagon | NovAtel OEM7 receiver product, including enclosure products and OEM receivers, where SPAN or Terrain Compensation is enabled or where IMU data is collected.

Technical Overview

An IMU exposed to vibration undergoes unwanted oscillatory motion that may introduce noise to or mask the measurement of platform motion of the system on which the IMU is mounted, which will degrade the INS solution output quality. Mitigating vibration is a system design problem with solutions likely to be most successful close to the source of the vibration in the mechanical domain, as illustrated in Figure 1.

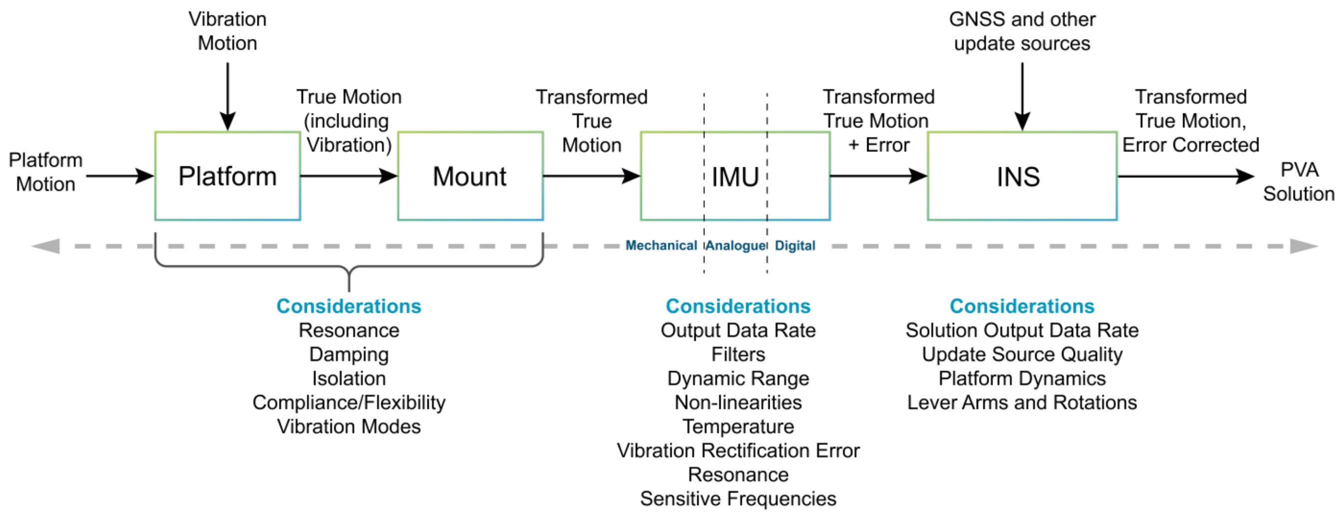


Figure 1: Motion information flow from platform through IMU and INS

Measurement Errors Due to Vibration

Vibration will always be detrimental to the performance of an INS. System motion signals as measured by an IMU exposed to vibration are at risk for clipping, aliasing, or vibration rectification errors. Properly tracked system motion that contains vibration signals requires careful consideration of the INS solution output characteristics. These concepts will be explored in depth in this section.

Aliasing

Aliasing occurs in digital signals when there is any frequency content present in the measured signal that is greater than half of the sampling frequency (i.e. the Nyquist Frequency) according to the Nyquist-Shannon sampling theorem. An aliased signal erroneously appears to the observer as being at a lower frequency than the original signal. Specifically, any frequency content of the original signal that is above the Nyquist frequency folds back into the range from zero to the Nyquist frequency. This is illustrated in Figure 2 and Figure 3. As a result, an INS may mechanise slow moving signals that look like real, low dynamics motion, but are in fact aliased from fast moving sources caused by vibration. In the worst case, when the fast-moving oscillations are close to or at the sampling frequency (or a multiple thereof), the aliased signal is close to or at 0 Hz, as shown in Figure 4. This can introduce a static or slow-moving bias error to inertial measurements with an amplitude equivalent to the original vibration. When this error is integrated in the INS mechanisation process, it is amplified and results in an error in the navigation trajectory produced by the system.

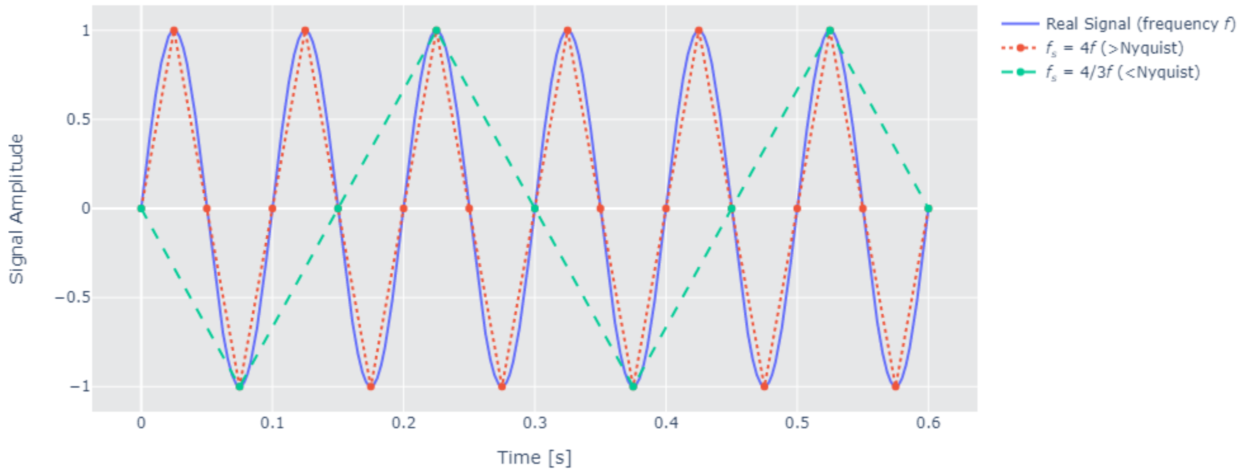


Figure 2: Aliasing in time domain - sampling above and below the Nyquist frequency

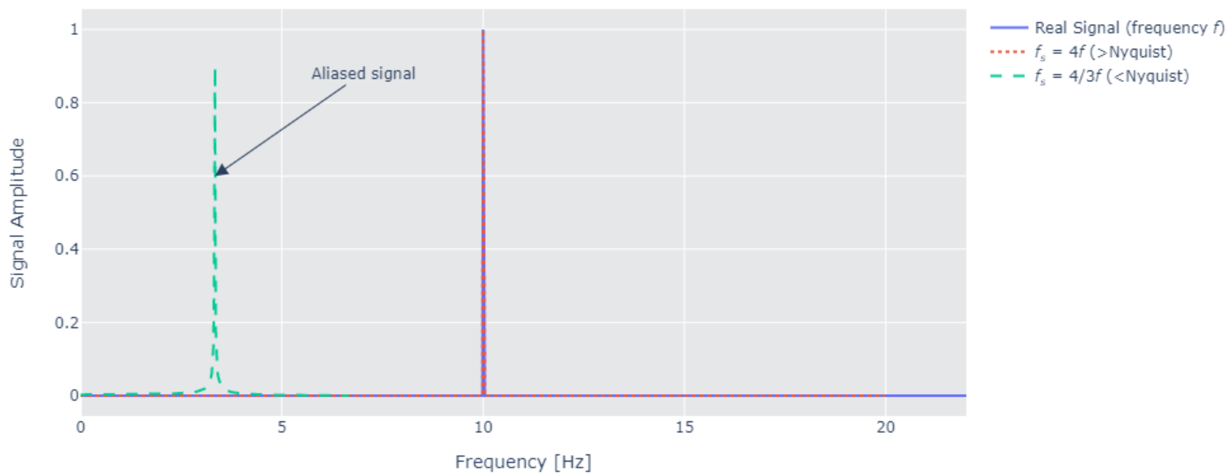


Figure 3: Aliasing in frequency domain - sampling above and below the Nyquist frequency

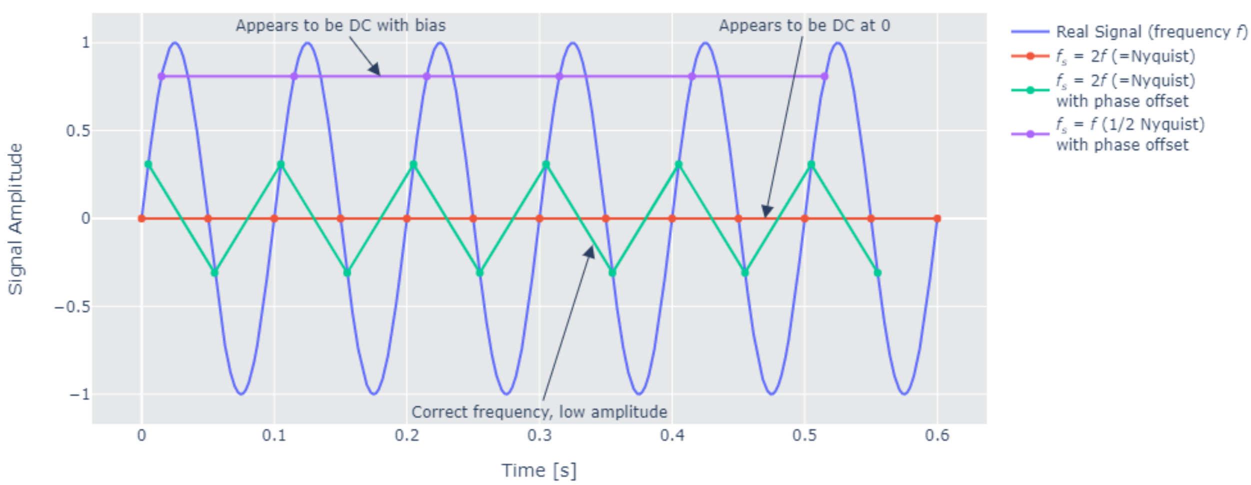


Figure 4: Aliasing in time domain - sampling at Nyquist frequency or signal frequency with phase offset

A simple fix for aliasing is to increase the sampling frequency to at least twice the highest frequency present in the signal. However, this can prove difficult due to processing load, bandwidth limitations, or limited design flexibility, especially since frequency content may exist well into the kilohertz range.

Other than increasing the sampling frequency, aliasing can be minimised by applying an anti-aliasing low pass filter early in the signal chain to remove frequency content above the Nyquist frequency, before the sampling occurs. This may be in the mechanical domain in the form of vibration isolators or in the analogue domain before the analogue to digital converter (ADC). If a signal in the digital domain is downsampled, a digital anti-aliasing filter can be used beforehand to the same effect, as in Figure 5. The key is to apply a low pass filter prior to sampling, as once an aliased signal is present in a digital signal, it cannot be filtered out if there is no way to distinguish a low frequency aliased signal from real low frequency motion. A low pass filter applied to this sampled signal will remove both the aliasing and real signals.

Even if an anti-aliasing filter is applied to high frequency signal content prior to sampling, a balance must be struck between the filter characteristics and the system response. As a result, no filter is ideal, and there may be points in the filter response between the nulls that correspond to a particularly high amplitude, high frequency vibration. Some of this vibration signal may then present as a very low amplitude aliased signal that introduces small error into the INS, as demonstrated in Figure 6 and Figure 7.

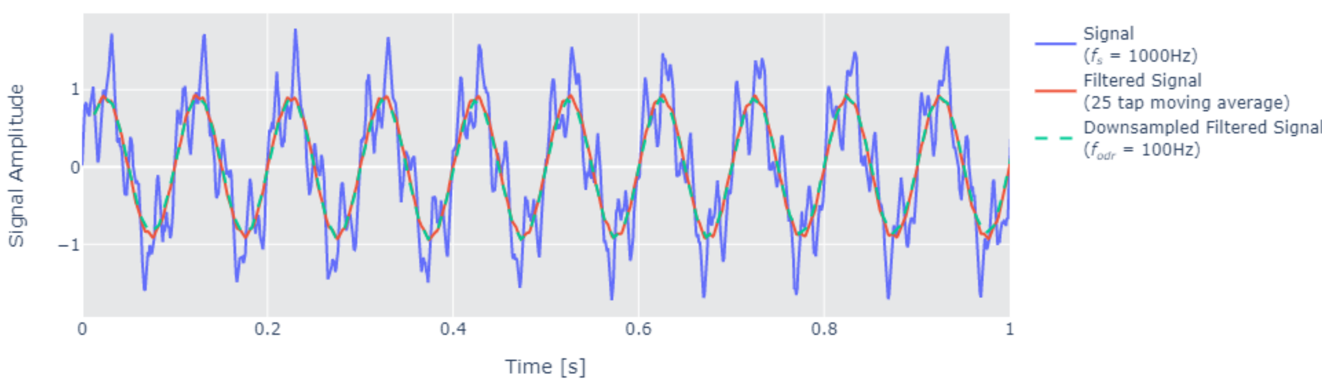


Figure 5: Filtering effects in time domain

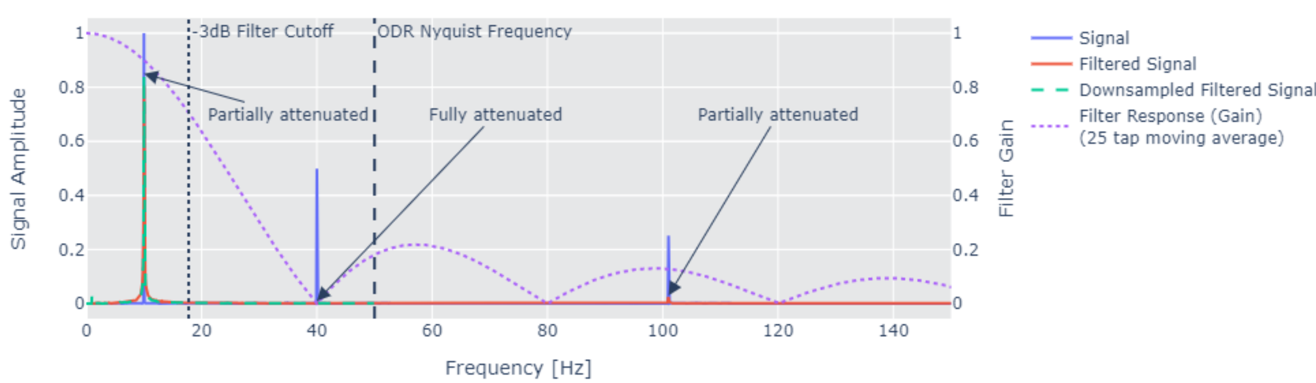


Figure 6: Filtering effects in frequency domain

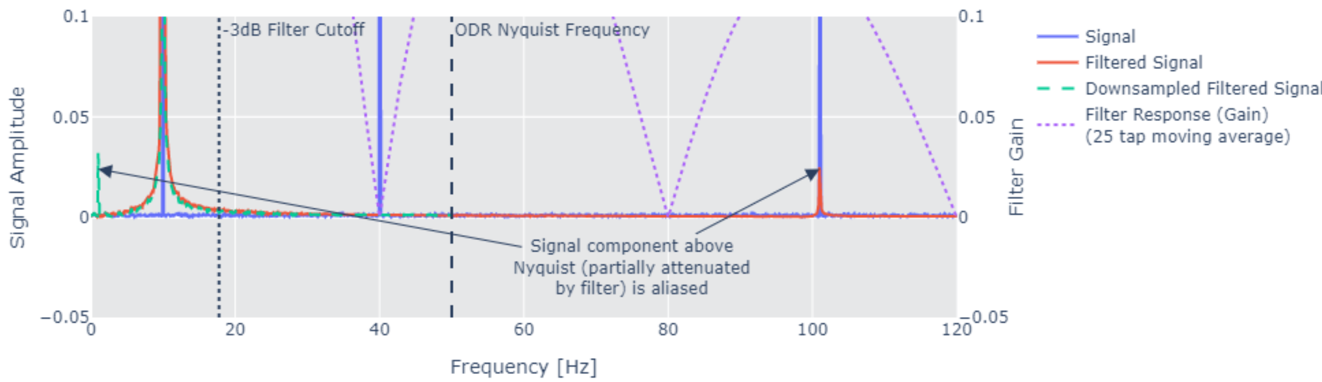


Figure 7: Filtering effects in frequency domain - aliasing

Preventing aliasing may require a cascade of anti-aliasing filter designs in different domains (different domains are illustrated in Figure 7). Minimising vibration at the IMU reduces the reliance on anti-aliasing filters which will improve system response and reduce any aliased signals “leaking” into the IMU measurements used by the INS.

Clipping

Signal clipping occurs when the dynamics of the motion exceeds the measurement range of the inertial sensor, resulting in a distorted signal. If an IMU can measure +/-10g and the system undergoes 11g acceleration, the IMU may provide a wrong measurement of 10g, or otherwise malfunction. Clipping is more likely to occur when vibration is present because the motion due to vibration is superimposed on top of the platform motion, and the combined signal is measured by the IMU. When the platform motion is well below the dynamic range of the IMU, a high vibration environment may still cause clipping to occur. If the high frequency vibration content is subsequently removed with a low pass filter (e.g. when the INS mechanises the IMU measurements), the resulting low frequency signal will have an error. This is illustrated in Figure 8. Even if clipping is avoided, approaching the limits of the sensor measurement range may increase the effects of non-linearities in the sensor behaviour, introducing further error.

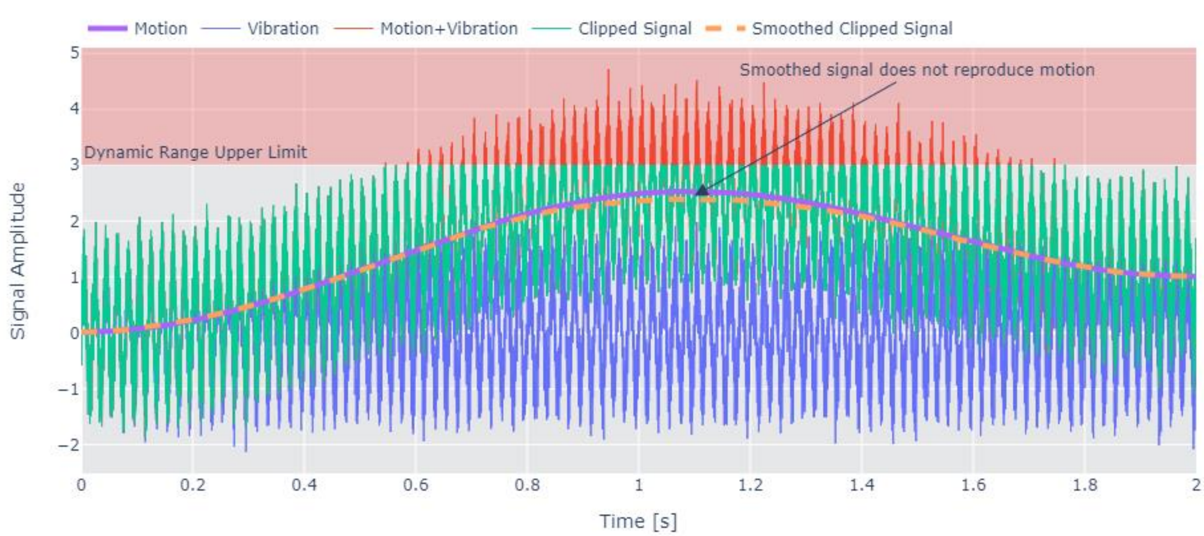


Figure 8: Clipping effect in time domain

Minimising vibration at the IMU leaves greater dynamic range for measuring platform motion and dynamics of interest to improve INS performance.

Vibration Rectification Error

Vibration rectification error (VRE) describes systemic measurement error or bias error in IMU measurements that is dependent on the frequency and amplitude characteristics of the vibration the IMU is experiencing. There may be a variety of actual mechanisms driving this error based on the physical construction and operational principles of the IMU technology, and the specific vibration profile experienced by the sensors. Two key contributors to VRE are scale factor non-linearities and clipping. The measurement error will be present even if the output signal from the IMU does not contain the frequency driving the VRE due to sensor frequency response or anti-aliasing filters. Therefore, the error cannot be easily removed or estimated as there is no observability into the state causing the error.

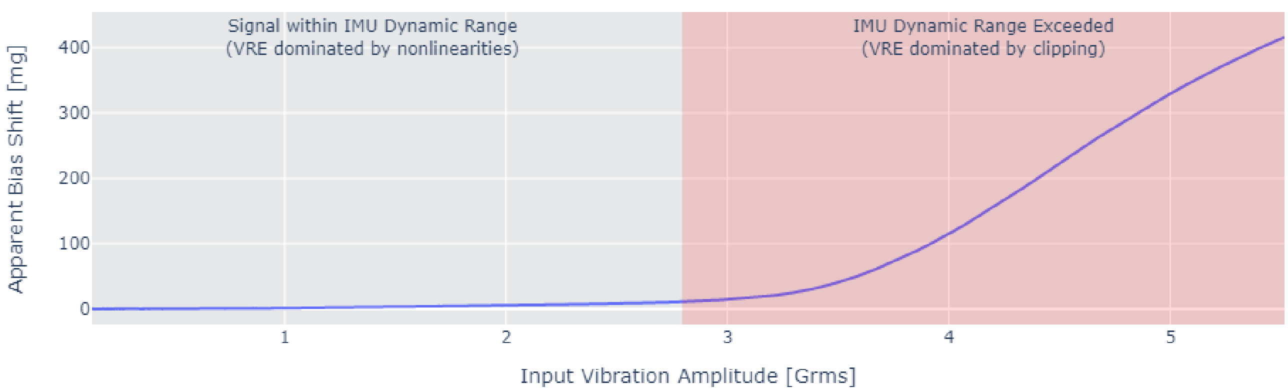


Figure 9: Accelerometer vibration rectification error in vertical axis with 100 Hz sinusoidal input vibration

Very few IMU manufacturers provide comprehensive VRE specifications that can be used to quantify impact under specific vibration conditions. Minimising VRE is best tackled by minimising vibration experienced by the IMU.

Other IMU Errors

Vibration may cause a much broader distribution of measurements to be made by an IMU than a unit experiencing only platform motion. One may then postulate that any measurement errors due to non-linearities or time-dependent variation in sensor characteristics will be amplified. Furthermore, vibration, while often modelled as either random or a single sine wave, is probably composed of a combination of random and periodic signals and is likely to be dependent on various time dependent system states, like velocity or temperature. Minimising vibration at the IMU will only be beneficial in minimising the effects on these errors.

In fact, any of the specific error sources noted above may be dependent on the operating point of the system as the frequency or vibration profile changes. In a typical system the frequency changes won't have Gaussian characteristics, making it hard to estimate with a Kalman filter designed with the assumptions of these processes. Finally, each level of system integration will be constrained by design decisions in the layer below, so careful specification design may be necessary early to avoid incompatible constraints.

INS Lever Arm Rigidity

Another source of performance degradation in an INS due to vibration is when the vibration experienced by the IMU results in different motion relative to the GNSS antenna(s). This difference in motion violates the rigid body assumption of the lever arm(s) between IMU centre of navigation and the GNSS antenna phase centre(s). While small displacements are of little consequence in pseudorange only positioning modes where GNSS position error is much larger than the scale of the displacement, they will become relevant when GNSS position error is measured in millimetres, as in corrected GNSS operational modes (e.g. Real Time Kinematic (RTK) or Precise Point Positioning (PPP)).

Improving structural rigidity between the IMU and the antenna(s) and minimising vibration in this part of the system help to avoid these errors.

If the INS solution is used in conjunction with external sensors or systems (like a LiDAR), the same principle applies. Minimising any potential deviation in motion between the IMU and the external sensor will improve performance when using the INS solution to estimate the external sensor position. Conversely, introducing compliance between the IMU and external sensors, for example by using soft vibration isolators in between, will potentially introduce unwanted errors.

INS Solution Output

The above sources of error focus on the IMU measurements and the inputs to the INS. Even if the motion and vibration are perfectly captured and the INS internal state estimates are assumed to have zero error, the INS solution output as requested by the user may show evidence of aliasing. This is because requesting a periodic output of the INS solution is equivalent to sampling a signal digitally, and the same sampling rate considerations relating to the IMU measurements must be applied to the INS output solution. If platform motion in the system is guaranteed to have frequency content of less than 5 Hz, then a solution output rate of 10Hz (twice the Nyquist frequency of 5Hz) is sufficient (i.e., requesting the INSPVAX log ONTIME 0.1). If vibration is present and the resulting vibration-induced motion is being tracked by the INS, this motion may appear as aliased when looking at the time history of the INS position, velocity, and attitude (PVA) solution (see Figure 10).

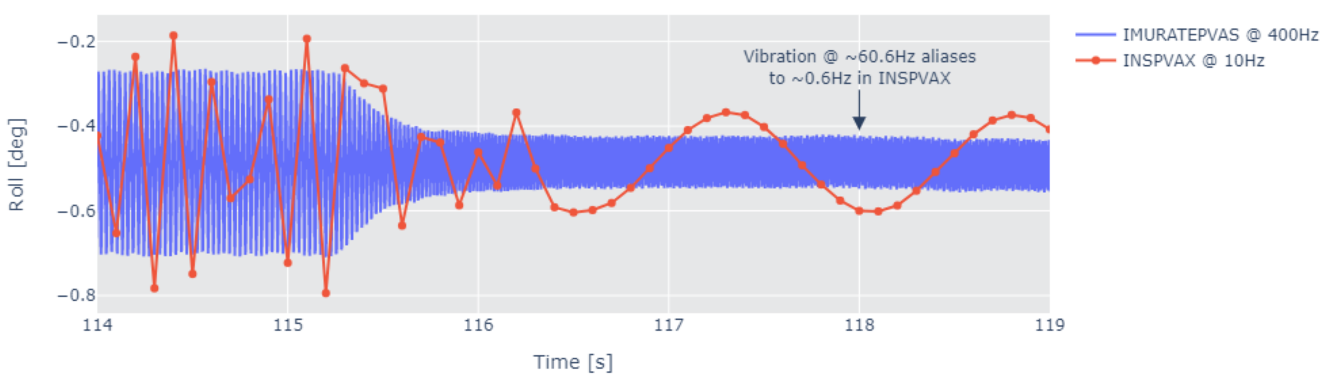


Figure 10: INS solution output aliasing due to log rate

As discussed above in the IMU measurement aliasing section, if the frequency of vibration is close to or coincides with the solution output rate, then a very slow moving or static bias may be present in the output signal with an amplitude within the bounds of the vibrational motion, introducing additional error to the final solution from a user's perspective.

Finally, NovAtel's SPAN technology has a feature by which the INS solution can be translated to a different location relative to the IMU centre of navigation (centre of nav) using a user defined offset lever arm configured via the

SETINSTRANSLATION command. As demonstrated in Figure 11, this lever arm will amplify any effects of vibration because small angular perturbations in the attitude result in large position and velocity perturbations as the solution output is translated further away from the INS centre of navigation. This amplification is due entirely to the geometric transformation, and not an error in the PVA solution.

Combined, these two phenomena can result in a large slow-moving or static bias error that has real impact on the total system error budget and can be especially problematic when the INS solution is used as part of a feedback control system. INS solution output error can be managed by properly selecting a solution output sampling rate and by minimising vibration at the IMU to prevent the resulting cascade of error through the system.

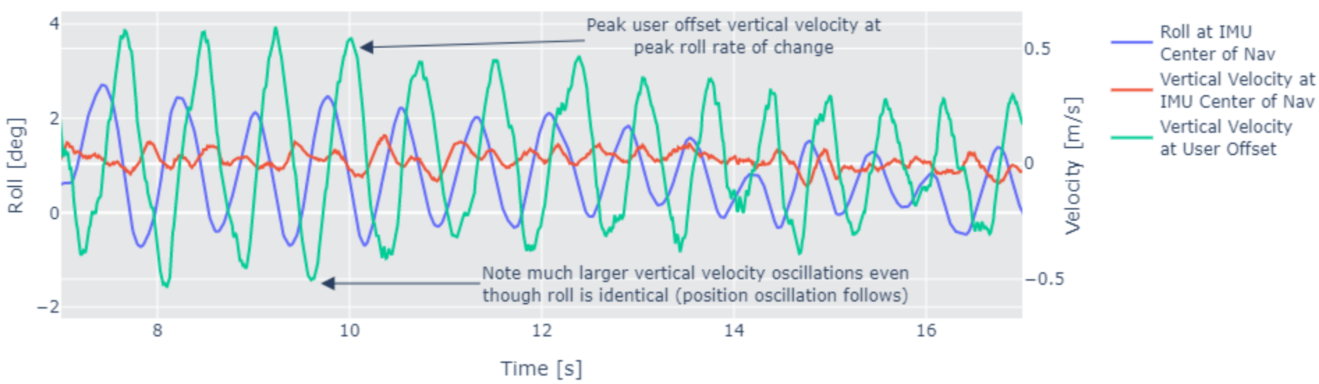


Figure 11: Roll perturbations amplifying vertical velocity oscillations due to user output lever arm

How Much Vibration Is Too Much?

The short answer is: “it depends”. The ability of an INS to reject sensor error is dependent on the quality of the sensor measurements, the quality of complementary updates, and the stochastic characteristics of the error sources. Cases with high quality, reliable external updates (i.e., excellent GNSS availability, regular zero velocity updates, valid non-holonomic constraints) and good initial conditions (i.e., starts with low vibration, sufficient time to estimate sensor biases, following system alignment best practices) will tolerate higher vibration (and poorer inertial measurements). Furthermore, use cases with high dynamics provide better signal to noise ratio and observability for the inertial sensors than use cases with low dynamics. It follows that an INS solution for a vehicle making regular turns and stops in a suburban or highway environment will always outperform a slow-moving vehicle traveling in straight lines when exposed to the same vibration profile (other conditions being similarly equivalent). The vibration characteristics which cause minimal impact in one use case, may be much more detrimental in another based on the factors described. Early characterisation of an INS for the intended use case will help a system operate effectively across the range of intended conditions.

Mitigating Impacts of Vibration on Inertial Navigation Systems

As mentioned repeatedly in the previous section, the best way to mitigate the impact of vibration on an INS is to minimise the vibration experienced by the IMU (and the GNSS antennas). The first step in mitigation is to identify and characterise potential sources of vibration in the system. Next, a combination of subsystem separation, vibration isolation, specification design, and filtering can be used to minimise the effects of vibration. Vibration can be difficult to model in complex systems, and so iterative empirical methods may be required to achieve appropriate levels of mitigation and desired system performance. Furthermore, vibration should be considered very early in the design process to help guide various system and subsystem design decisions.

Sources of Vibration

In most systems, periodic vibration is derived from rotating or oscillating equipment and associated subsystems. Electric motors, internal combustion engines, hydraulic pumps, compressors, fans, drivetrains, wheels, tracks, propellers, rotors, gearboxes, hard drives, and LiDARs are all typical examples of rotating equipment where potential eccentricities or unbalanced components drive vibration. Carefully balanced rotating elements will reduce vibration and increase overall system lifetime. Oscillations may arise from pistons, hammer mechanisms, linkages, or linear electric drives like voice coils. Consequences and analysis are similar for both, and rotating equipment will refer to both for the remainder of this document. Secondary vibration sources may occur as rotating or oscillating equipment interacts with other parts of system. For example, a vaned fluid motor or pump or a gearbox will have periodic changes in pressure or forces as each vane passes inlets/outlets or as gear teeth make and break contact. Another example is when track or tire treads repeatedly impact the traction surface. This can introduce vibration at frequencies higher than expected.

Rotating equipment typically drive periodic vibrations at a frequency equal to the period of the rotation (fundamental frequency) or a multiple (harmonic) thereof. In some cases, the frequency of vibration with the highest power is not the fundamental frequency due to equipment characteristics or structural resonances. For example, some internal combustion engine configurations will show the most vibrational power at a frequency equivalent to twice the engine RPM.

Random or broadband vibration is more likely due to vehicle interactions with surfaces or surrounding fluids. Special vibration sources like rocket engines are also possible. Shock and pyroshock can generally be ignored if the duration of the disturbance is assumed to be short and very intermittent, even if energy magnitudes are high. Survivability must be considered, but the intermittence is less likely to cause continuous INS performance degradation.

High frequency vibrations can also propagate through the air as sound. If this method of transmission is suspected, sound damping methods may be relevant to minimising vibration in the IMU.

All parts of a system will react differently to the forces or displacements due to vibration. Resonance or damping characteristics will allow power at different frequencies to be transmitted with varying effectiveness from the source to the surrounding structure and subsystems. Sometimes a seemingly insignificant source of vibration dominates the impact on an IMU due to a structural resonance close to the frequency of that vibration. The same can also be true, where a very high energy vibration source has little impact on the IMU because the vibration has been damped by the system before reaching the IMU. In fact, this is leveraged when effectively isolating vibration.

As an initial exercise, it is useful to identify key pieces of rotating equipment in a system and determine the rotational rates expected in this subsystem. This can inform IMU selection and the potential need for isolating different subsystems. Remember that the RPM of a piece of equipment can be used to determine the expected frequency by dividing by 60, so an engine running at 1500 RPM will be expected to be a source of vibration at 25 Hz, with power also present at higher harmonics like 50 Hz, 75 Hz, 100 Hz, etc. Measuring vibration at the IMU and other points in the system can help confirm the source, frequency, and amplitude of vibration. An example of this exercise with a sample system is illustrated in Figure 12, Table 1, and Figure 13.

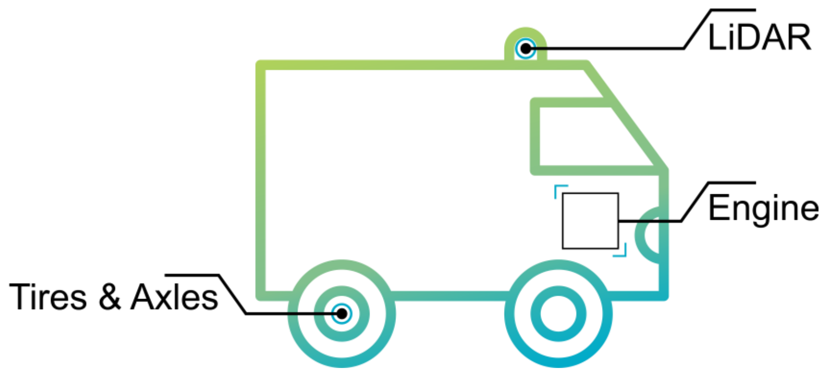


Figure 12: Sample system with key pieces of rotating equipment identified.

Table 1: Sample system expected vibrational frequency content from rotating equipment at two operating points

Subsystem	Typical RPM	Fundamental Frequency (Hz)	1st Harmonic Frequency (Hz)	2nd Harmonic Frequency (Hz)	3rd Harmonic Frequency (Hz)	*n*th Harmonic Frequency (Hz)
Engine (Idle, 0 km/hr)	750	12.5	25.0	37.5	50.0	12.5*(*n*+1)
Engine (Highway, 100 km/hr)	2100	35.0	70.0	105.0	140.0	35.0*(n+1)
Tires (Idle, 0 km/hr)	0	-	-	-	-	-
Tires* (Highway, 100 km/hr)	834	13.9	27.8	41.7	55.6	13.9*(n+1)
LiDAR	1200	20.0	40.0	60.0	80.0	20.0*(n+1)

** Note that tires on roadways will also introduce random vibration in addition to sinusoidal vibration.*

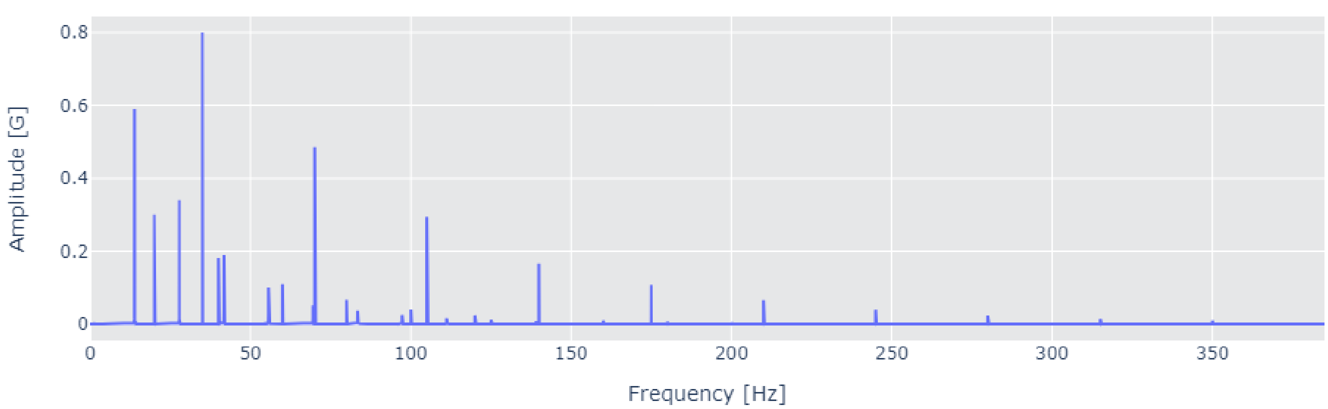


Figure 13: FFT of simulated sample system vibration at 100 km/hr, with 9 harmonics

Measuring Vibration

In an existing system where vibration is suspected of causing INS performance degradation, it may be best to measure the vibration profile at the location of the IMU with a wide bandwidth accelerometer (and gyrometer if available). The sensor should be mounted securely, rigidly, and as close to the IMU as possible to ensure measurements are representative of the vibration experienced by the IMU. Be aware that mounting this extra sensor can change the vibration characteristics if the mass or rigidity of the IMU portion of the system changes appreciably. It may be enlightening to take measurements at other points in the system to understand where vibration is damped or amplified by the system.

Where the IMU is mounted in a secondary enclosure as part of a subsystem, be aware the enclosure may exhibit its own transmissibility characteristics. This changes the vibration environment the IMU experiences relative to where the enclosure is mounted. The stiffness, mass and fastening methods of the enclosure or printed circuit boards will all impact the enclosure transmissibility.

Measuring the vibration at the IMU helps provide a baseline to evaluate the effects of design changes in the mechanical domain. Design changes should be made in small, incremental steps to help characterise improvements or regressions more easily, with additional measurements taken at each small change. Vibration measurements should be made across the full operating range and during different use cases. Different subsystems should be enabled and disabled to help understand the impact on the overall vibration profile.

Once vibration data is collected, analysis can be carried out to summarise data in both time and frequency domain and calculate key metrics. Visualising data with FFT (Fast Fourier Transform) calculations, PSD or ASD (Power or Acceleration Spectral Density) calculations, and spectrograms can help identify dominant vibration frequency, power levels, harmonics, and distribution. Correlating small steady state sections of time domain and frequency domain metrics with different operating points or use cases provides excellent insight into system behaviour. An example of comparing vehicle speed to vertical acceleration spectral density is shown in Figure 14.

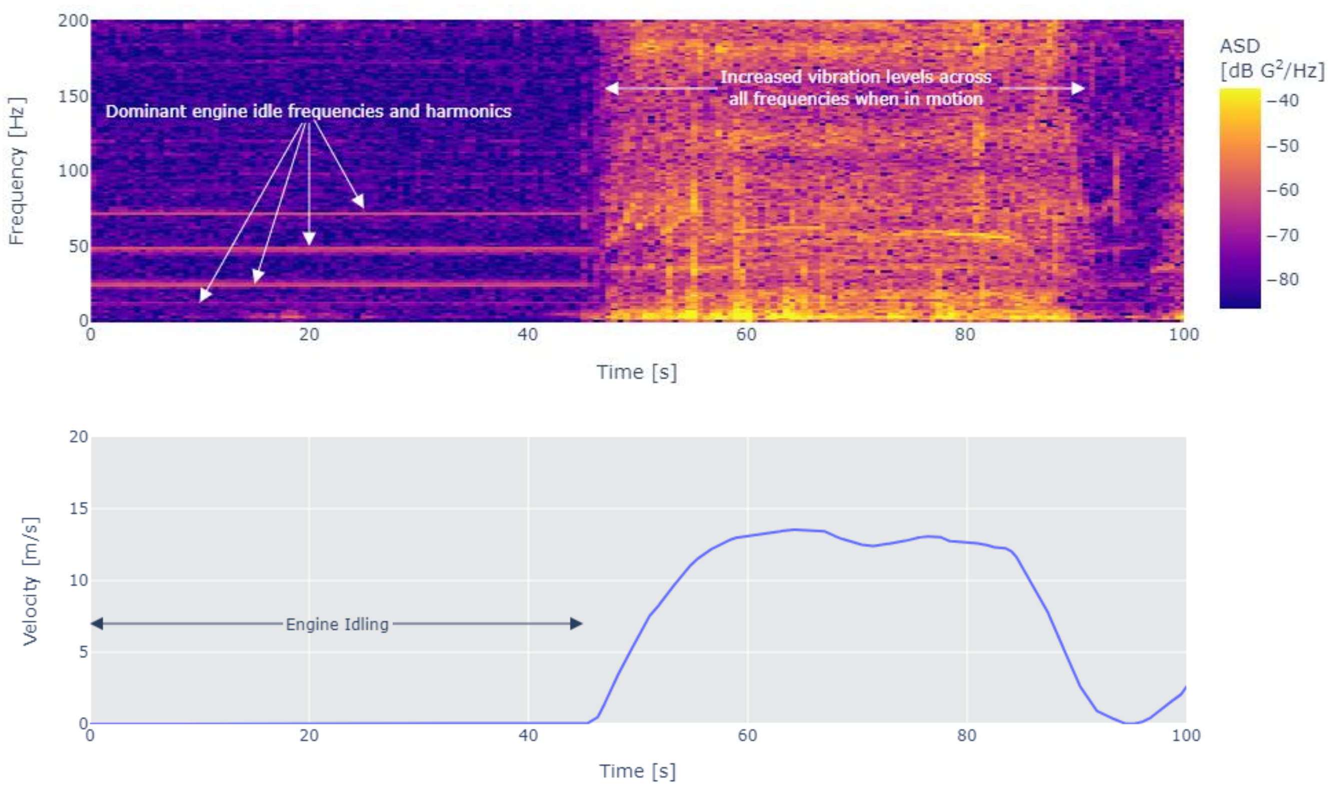


Figure 14: Vertical vibration spectrogram and vehicle velocity correlation example in ground vehicle

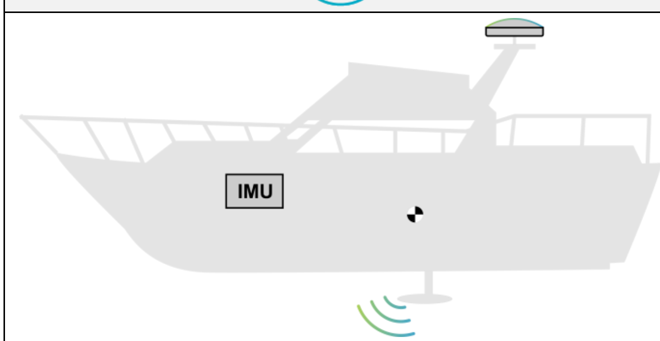
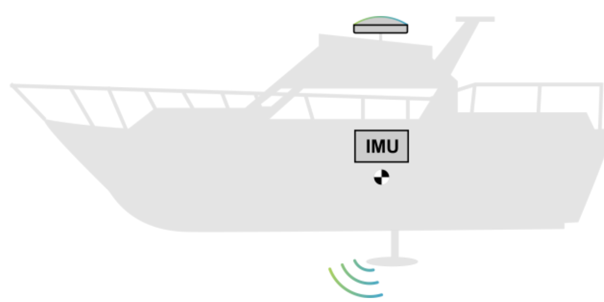
Root cause analysis techniques and experimental design will also help a team successfully diagnose and mitigate vibration problems. Detailed vibration measurement and analysis techniques are beyond the scope of this document.

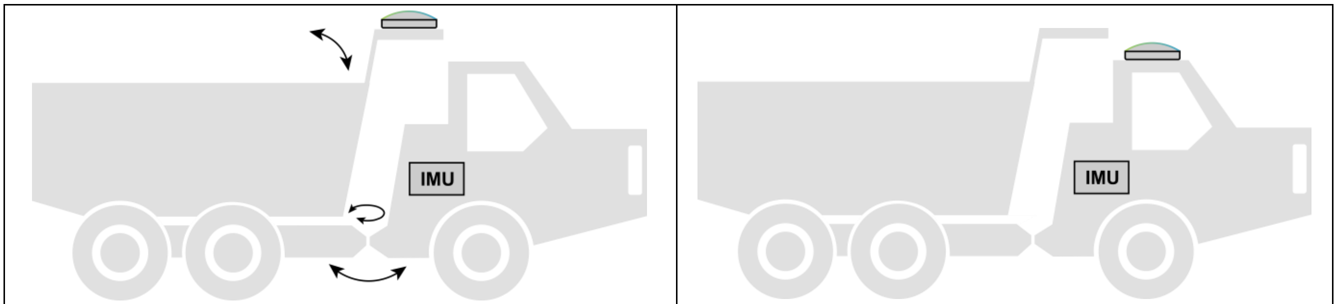
Subsystem Separation

Subsystem separation helps to minimise vibration at the IMU and decouple subsystems that should be independent. In general, it is a good idea to physically separate the mounting location of an IMU from any sources of vibration. Mounting solutions should be implemented for both sources of vibration and sensors to minimise transmission from source to system structure to sensor. Physical separation requires trade-offs between several potentially competing design goals:

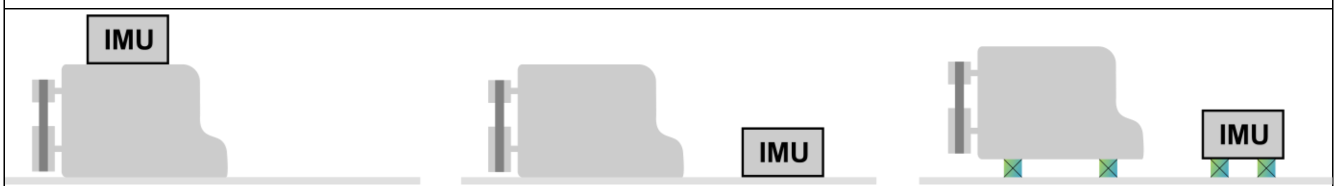
- Minimise the lever arm between the IMU and primary GNSS antenna.
  - Reduces INS solution error.
- Minimise the lever arm between the IMU and the USER output location.
- Mount the IMU at a location representative of the system motion (e.g. centre of gravity or inertia).
  - Some systems do not have a rigid structure, which may violate rigid body assumptions of lever arms. For example, air-ride cabs, articulated steering, suspension systems, adjustable components, or flexibility in structures.
- Mount the GNSS antenna(s) with a clear view of the sky away from sources of interference or multipath.
  - This may be some distance away from the rest of a system or on a less rigid mount.
- Mount the IMU at a location isolated from vibration.
- Mount the IMU in a sufficiently stiff location to minimise unwanted vibration or motion.
- Mount the IMU with appropriate hardware.
- Ensure the structure between the IMU and GNSS antenna(s) is very rigid.
  - Longer lever arms require greater rigidity but rigid structures may transmit vibration well.
- Ensure the structure between the IMU and the user output location is truly rigid.
- Ensure the lever arms are measurable with sufficient accuracy.
- Optimise overall system size, weight, power, and cost (compact, lightweight, low cost, minimal cabling, simplicity for manufacturing and maintenance, etc.).

Table 2: Subsystem separation and mounting examples

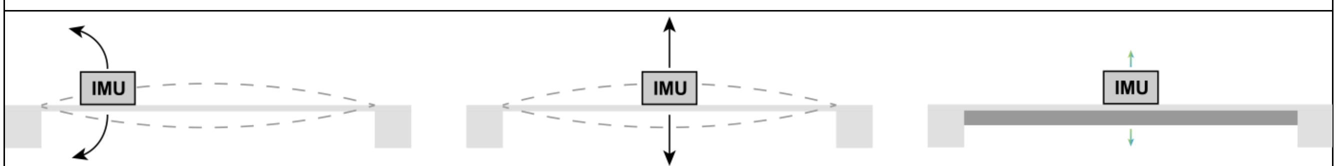
	
	
Both the IMU to antenna and IMU to sensor lever arms should be minimised and the IMU mounted close to the centre of gravity of the vessel. The shorter antenna mast improves lever arm rigidity.	



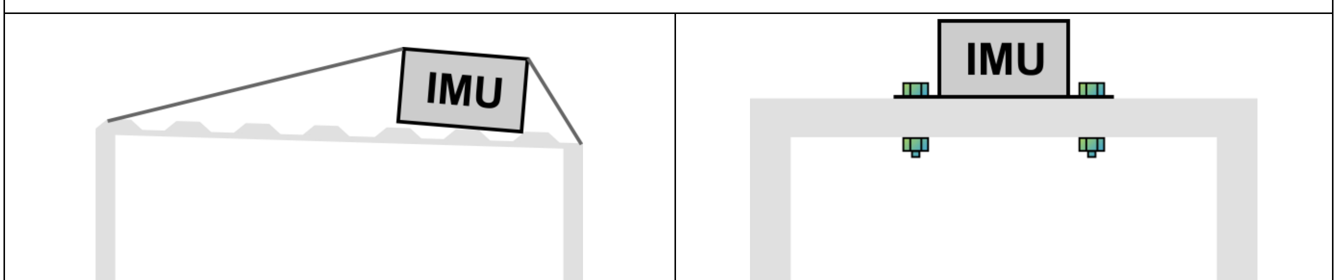
The IMU and antenna should be mounted rigidly relative to one another to ensure a constant lever arm. Avoid cantilevered mounting locations but ensure the antenna has a clear view of the sky.



Mount the IMU away from sources of vibration like engines. Ideally isolate either the source, the IMU, or both.



Mount the IMU to have only linear motion, not both rotational and linear motion. Stiffen the mounting location to minimise the motion. This also applies to IMUs mounted on printed circuit boards.



Mount the IMU rigidly with appropriate fasteners to a stiff, square, and flat structure. Avoid temporary mounting methods like tape, hook and loop, or zip ties. Avoid uneven or flexible surfaces.

Where possible, it is likely more effective that the source of vibration be isolated from the rest of a system's structure through mount design. Carefully balancing rotating equipment will help to minimise vibration amplitude.

Vibration Isolation and Mount Design

Introduction to Vibration Theory

A system experiencing vibration can be modelled as one or more mass-spring-dampers with different forcing functions and initial conditions. The simplest cases are modelled with a single degree of freedom mass-spring-damper (Figure 15) and can grow in complexity to improve fidelity. Vibration isolator design also relies on this type of modelling. This section of the document assumes that the source of excitation of the mass-spring-damper system is the base and the mass is the inertial sensor to be isolated. Detailed vibration theory is beyond the scope of this document but there are many good references available (for example, see Steinberg [1]). However, it is beneficial to consider a few properties of a mass-spring-damper model:

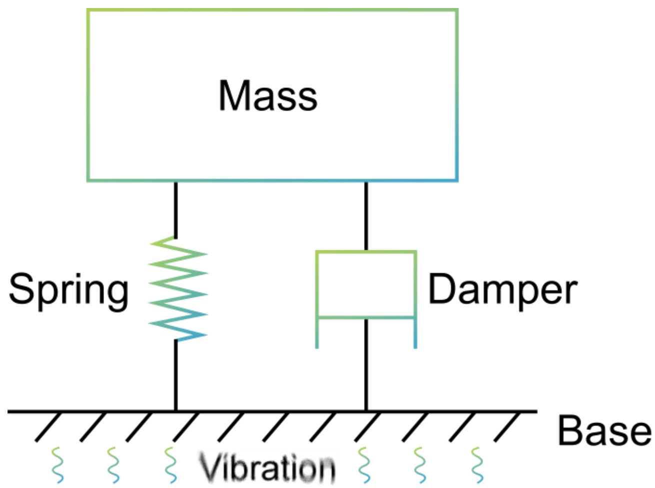


Figure 15: Schematic of a mass-spring-damper system

- A mass-spring-damper system has a natural frequency and a damping ratio.
- When a system is excited by a periodic input at the natural frequency it will resonate and amplify the input, i.e. the displacement of the mass will be larger than the displacement of the mass for base excitation.
- When a system has a lower damping ratio, the amplitude when resonating will be comparably high, but isolation will be more effective.
- The undamped natural frequency is given as $\omega_n = \sqrt{k/m}$, where k is the spring constant and m is the mass. Note that the natural frequency increases with increasing spring constant and decreases with increasing mass.

The ratio of output force or motion to the input in a mass-spring-damper system over different input frequencies is the system frequency response or the transmissibility of the system. A typical frequency response is illustrated in Figure 16.

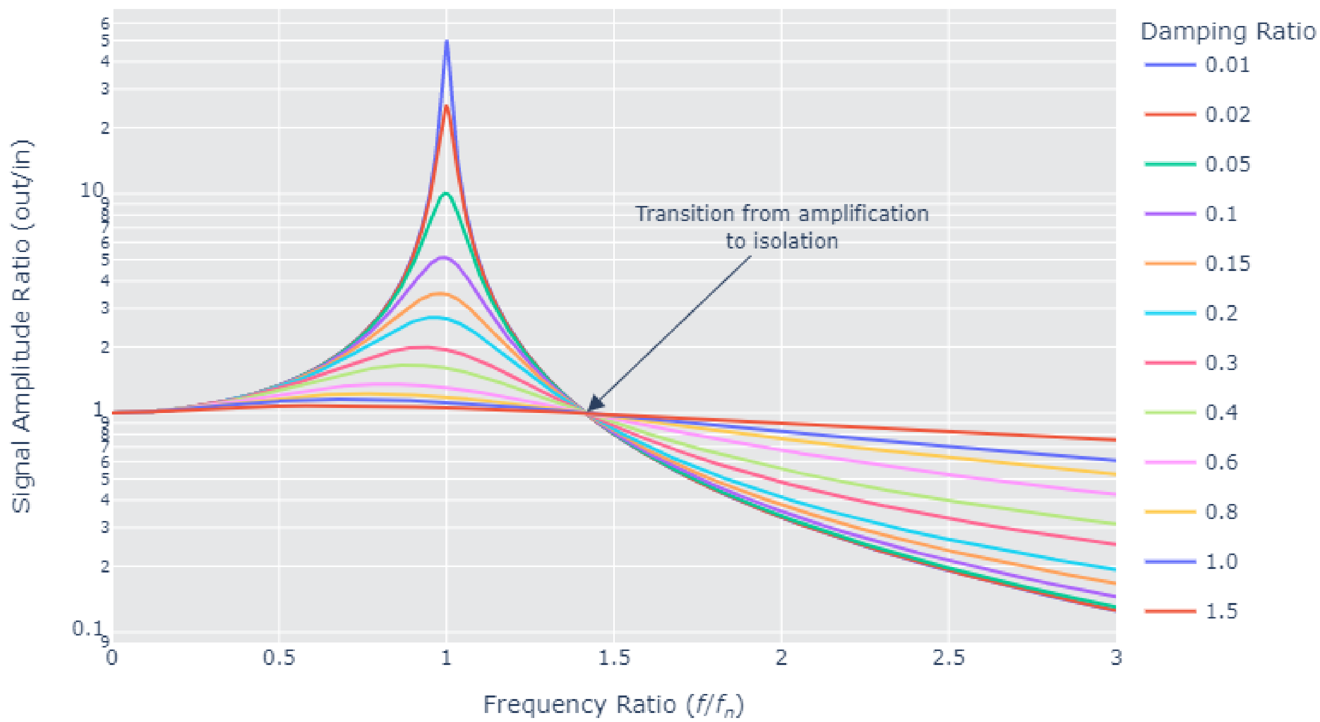


Figure 16: Frequency response of Mass Spring Damper with base excitation

- The damped natural frequency is where the peak amplitude occurs, and this frequency drops slightly as the damping ratio increases.
- A critically damped or over damped system minimises the resonant peak, but this is challenging to achieve across a range of real operating conditions.
- When the input frequency is less than the damped natural frequency, the output is amplified relative to the input as frequency increases, until the resonant peak occurs.
- When the input frequency is greater than the damped natural frequency, the output amplification starts at the resonant peak and decreases with increasing frequency.
- When the output to input ratio (amplification ratio) drops below 1.0, isolation begins (this occurs at $\sqrt{2}\omega_n$).
- When a system has a low damping ratio, the amplitude when resonating will be comparably high, but isolation will be more effective, while a high damping ratio will minimise the resonant amplitude peak but isolation will be less effective.

When designing an isolation mount to isolate the source of vibration from the rest of the system, the solution for external forcing or rotor excitation should be reviewed. This is beyond the scope of this document.

Mount Design

When designing a mount that can isolate base vibration, common design goals include:

- Isolate vibration above a certain frequency.
- Manage the impact of resonance close to the natural frequency of the mounting system.
- Ensure performance across the full operating range of the system – not just specific operating points, but also the transition between operating points. This includes not only input frequency ranges, but also temperature ranges, which can have a large impact on the spring constant and damping ratio of the system.
- Minimise size, weight, cost, and maintenance requirements.

The simple solution is to design a mount that can be modelled as a single mass-spring-damper where the mass is a combination of the IMU and the mount hardware. The natural frequency of the mount is selected so sufficient isolation is achieved at the Nyquist frequency of the IMU (to avoid aliasing), while staying well above the highest expected frequency of normal system dynamics (to avoid any significant amplification and the risk of clipping). This becomes complicated as vibration may occur at frequencies between normal system dynamics and the IMU Nyquist frequency, which will be amplified, perhaps to dangerously high levels. These vibration frequencies may shift around with system operation (e.g. the RPM of a motor in a vehicle changes).

Furthermore, the mount natural frequency and damping ratio will change as temperature changes and material properties change. Material aging effects may also have an impact on mount transmissibility and drive the need for regular maintenance. This is more of a concern when elastomeric materials are used in the mount.

In some situations, an existing mount may just require some adjustment to shift natural frequencies away from vibrational forcing frequencies. This can be done by stiffening the mount to shift the natural frequency higher or increasing the mass of the mount to shift the natural frequency lower (or vice versa). For example, an extra steel plate may be placed between the IMU and the existing mount to increase mass, or the hardness of a rubber isolator mount can be changed. A typical case is when the structure to which the IMU is mounted exhibits resonant frequencies excited by system sources of vibration. The amplified vibration is readily passed to the IMU. A good initial strategy in such a case is to stiffen the underlying mounting structure to shift the natural frequency of the structure higher away from the forcing frequencies, and then add isolation hardware between the structure and the IMU as needed.

Changing or combining materials to increase the damping ratio will help reduce the peak amplification, which may be necessary to stay within the dynamic range of the inertial sensors. For example, changing from natural rubber to an engineered elastomer for part of the mount may give the desired result.

Adjusting the geometry of the active parts of a mount will also help adjust the natural frequency and damping ratio of the mount. For example, the diameter of a rubber isolator mount can be changed to achieve a different spring constant.

It is easy to discuss mount designs in a single dimension. However, in a real system, the vibrational modes can be complex, consisting of linear motion and angular motion in multiple axes. This impacts both accelerometers and gyrometers. These complexities should be considered in all mount designs, where different sources of vibration will affect the IMU and the mount in different ways. Most mount designs will also exhibit different transmissibility and natural frequencies in at least one of three of each translational and rotational axes. An excellent example of this is the typical vibration mode of unbalanced shaft as in an electric motor or internal combustion engine: the system will experience periodic angular rotation perturbations along the axis of the shaft rotation, while simultaneously experiencing periodic linear acceleration perturbations in both axes forming the plane perpendicular to the axis of the shaft rotation. This is illustrated in Figure 17.

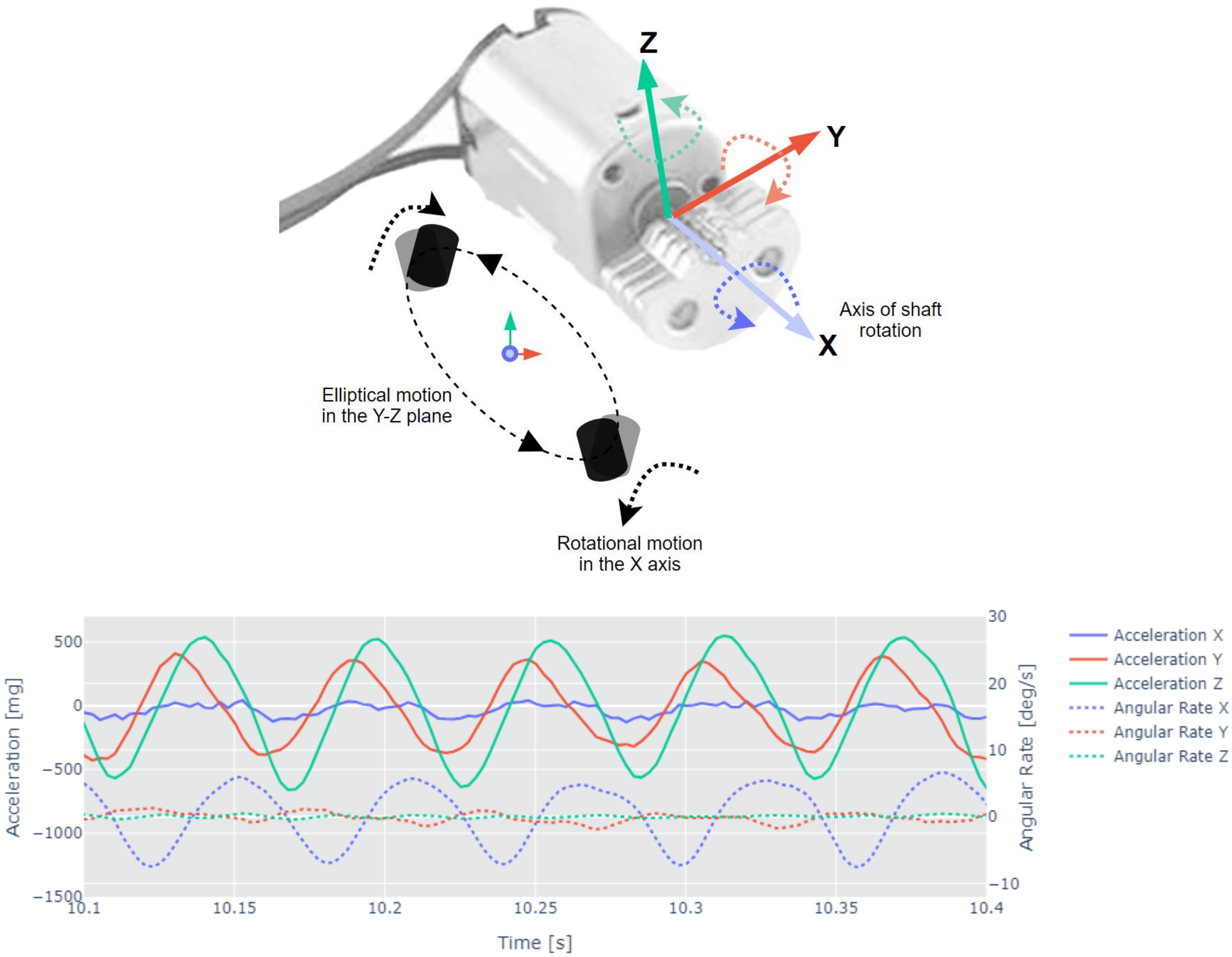
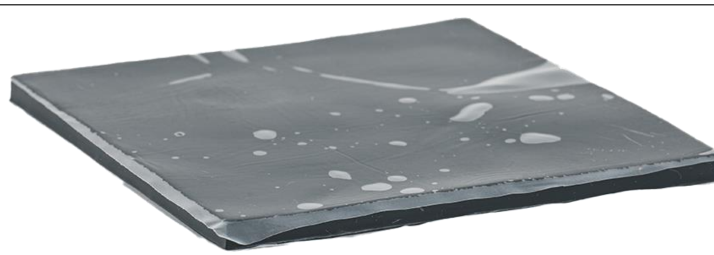
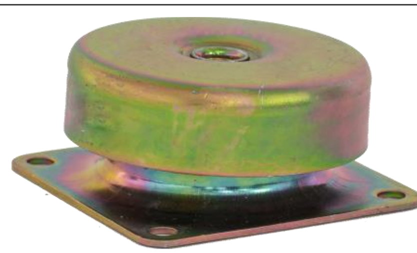


Figure 17: Example of correlated motion due to vibration in an unbalanced motor. Dominant motion in Y and Z linear axes, and X rotational axis.

Challenging situations may necessitate multi-stage vibration isolation at either the location of the vibration source or at the IMU, or both. Analysis and frequency response becomes more complex.

A variety of vendors offer different vibration damping isolators or components in different materials. Some examples are illustrated in Table 3. Different geometries vary how isotropic the isolator behaviour is, while different materials or styles provide varying spring rates, damping ratios and environmental compatibility.

Table 3: Examples of different vibration isolators

Isolator Description	Sample Images
Wire Rope Isolator	 
Sandwich or Stud Mount	
Multi-plane or Plate Style Mount	 
Damping Pad	
Cup Style Isolator	

Common pitfalls when introducing a vibration isolation mount design include:

- Unexpected resonant frequency amplification, either at a different vibration frequency or through incorrect design.
- Insufficient mount rigidity resulting in excessive displacements due to platform motion.
- Insufficient mount lifetime due to isolator material strength or aging effects, resulting in higher maintenance costs.
- Unexpected changes in mount characteristics across the full operating range (forcing frequencies, non-linear material response, temperature).
- Unexpected vibration modes.
- Using a complex mounting solution when another solution like subsystem separation or specification design is more appropriate.
- Introducing a path by which vibration can bypass the isolation mount (e.g. cables transmitting vibration, bolts through the isolator).

Mount design should be complemented with iterative vibration measurements to properly compare performance before and after specific changes. Shaker table testing or modal testing with an impact hammer may also aid in understanding mount performance, but these techniques are beyond the scope of this document.

IMU Specification Design

In conjunction with subsystem separation and appropriate vibration isolation, appropriate specification of the IMU is necessary to achieve the desired INS performance. Further, IMU specifications are heavily constrained by cost, so IMU specification design will drive vibration isolation specifications and subsystem separation design. In general, a more expensive, higher grade IMU will deliver better performance under high vibration environments. Certain specifications will offer a trade-off between IMU cost and subsystem vibration isolation complexity. Some key specifications to consider during design for vibration include sample rates, measurement ranges, and filter configurations. Vibration rectification error should also be considered if information is available from the IMU manufacturer.

Sampling Rates and Bandwidth

As discussed previously, the sampling rate should be at least twice the highest frequency content of the motion signals to avoid aliasing. The IMU output data rate should be considered first. The internal sampling rate of the IMU may be used to meet this criterion if the signal processing chain is appropriate (e.g. anti-aliasing filters), however this requires deeper knowledge of the IMU theory of operation. In addition, reasonable reproduction of the platform motion profile in the time domain requires the sampling rate to be 10 times higher or more than the highest frequency content of interest in the system dynamics (this is usually much lower than the highest vibration frequency content). Alongside sample rates, the bandwidth of the sensors should be considered when determining if platform motion can be tracked reliably.

If vibration frequency content is present above the IMU Nyquist frequency that is not filtered by the IMU, a vibration isolation mount should be used to filter out this frequency content in the mechanical domain.

Measurement Range

The measurement range of the IMU should be selected to avoid signal clipping when considering the sum of the maximum amplitudes of platform motion profile and the worst-case vibration, across all use cases and operating points of the system.

If the total maximum amplitude exceeds the measurement range of the IMU, a vibration isolation mount can be used to bring the total motion experienced by the IMU within the acceptable range. Care must be taken to avoid amplifying the signals as per the previous discussion about transmissibility to avoid making the problem worse instead of better.

INS Interface Design

When an INS system is integrated into a larger system, the interface and data output is specified. Vibration should be considered at this stage to ensure sufficient data output bandwidth is available to avoid any output signal distortion (see Figure 10) and meet control system requirements, if any. As discussed previously, the same sampling rate requirements apply: the solution output rate should be twice any output data frequency content to avoid aliased signals and ten times any platform motion that should be reproduced in the time domain.

Conclusion

INS performance can be degraded when vibration is severe and when inertial filter conditions are unfavourable (low dynamics, poor GNSS reception, etc.). The vibration environment in which an INS is expected to operate must be considered early in the overall system design to optimise performance and manage errors due to aliasing, clipping, VRE, filtering, and sampling rates. Vibration is most readily addressed in the mechanical domain, while solutions in software are difficult to implement and limited in capability.

The first step to mitigation is to identify potential sources of vibration in the overall system. This can be done by inspection and analysis and aided by quantitative vibration measurements at different points in the structure. These measurements establish a baseline for comparison after design changes, IMU location changes, or isolation mounts are introduced to verify improvements are being made. It is important to remember that successful vibration mitigation is an iterative process due to the complexity of the problem.

When designing an isolation mount, the properties of a mass-spring-damper should be considered. A good starting point is to stiffen the structure to which the IMU is mounted to increase resonant frequencies and reduce displacements, and then introducing an isolator to damp high frequencies passed to the IMU. The mounting location of the IMU may need to be re-evaluated to minimise vibration exposure through subsystem separation.

During overall system design, important INS requirements should be identified (e.g. overall IMU and INS performance, IMU and INS output data rates, IMU dynamic range, bandwidth, latency, etc.). Performance error budget development and vibration environment evaluation will help drive these requirements, while managing vibration in the mechanical domain will ease the stringency of the requirements. For example, output sampling rates should be sufficient to capture both motion and vibration, and error budgets for position or velocity should account for vibration and lever arm offsets.

References

[1] D. S. Steinberg, *Vibration Analysis for Electronic Equipment*, 3rd ed., Hoboken, NJ: Wiley, 2000.

Support

To help answer questions and/or diagnose any technical issues that may occur, the NovAtel Support website is a first resource.

Remaining questions or issues, including requests for test subscriptions or activation resends, can be directed to NovAtel Support.

Before contacting Support, it is helpful to collect data from the receiver to help investigate and diagnose any performance-related issues. A list of appropriate troubleshooting logs can be found on the OEM7 Documentation Portal (the LOG command with the recommended trigger and data rate is included with each log).

The data can also be collected using NovAtel Application Suite.

Documentation

For any questions on logs and commands, please visit the OEM7 Documentation Portal.

Contact Hexagon | NovAtel

support.novatel@hexagon.com 1-800-NOVATEL (U.S. and Canada) or 1-403-295-4900

For more contact information, please visit novatel.com/contact-us