

Isolating Components from UAV Vibration

By Howard Loewen

Introduction

Performing analysis and generating solutions for vibration problems in the aerospace industry is often a task fraught with misery. In most cases, the complex nature of vibration and data collection prevents any rigorous mathematical analysis. Trial and error is the more common approach for smaller applications where an engineer is not available or not otherwise required. Without a reasonable starting point, frustration can set in as the time needed to acquire acceptable results can be substantial and those results will be far from optimized. UAV technology has become very accessible and dealing with vibration is now the problem for a large range of people with varying levels of expertise.



Problem

Vibration causes problems for many reasons. The most obvious problem is mechanical fatigue, which can wear out fragile parts and electrical components prematurely. Blurred pictures and shaky video from optical equipment are problems for surveying or surveillance applications. There are many other situations you can come across, but the most critical reason for UAVs is that the sensing equipment used for inertial flight navigation can be negatively affected by vibration. Violent or high-frequency resonance vibration can cause immediate sensor reading errors. Even if there are no immediate sensor errors, sensor drift can also occur over the duration of a flight if there is significant coning or sculling vibration. Reaching acceptable results requires time and experimentation, but a better understanding of the fundamentals can speed up the process and improve the final system.

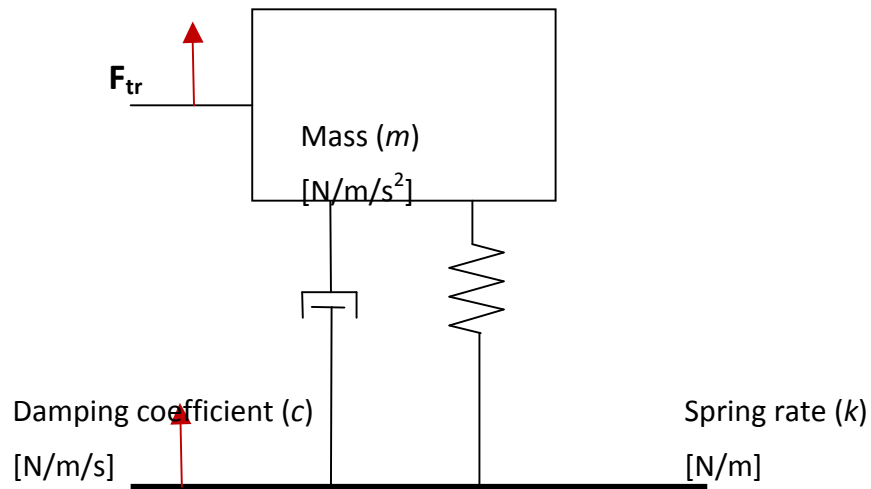
Shock vs Vibration

While shock absorbers are designed for protecting from mechanical shock, the components used for isolating against vibration are usually referred to as isolators or dampers. Vibration differs from shock mainly by its periodic (and usually harmonic) nature and the implied lower force amplitude. Sensitive equipment may be able to withstand hundreds or thousands of g 's during a very brief shock impulse, but are not usually expected to continue normal operation while experiencing this shock. Vibration forces are usually many orders of magnitude smaller in intensity and larger in pulse duration. The periodic nature of the vibration, along with the requirement that electronic equipment operate properly in the presence of these vibrations is the primary challenge.

Some common nomenclature used:

m	[kg]	Mass of the isolated system.
k	[N/m]	Total spring rate supporting the isolated system. Usually specified by isolator's manufacturer.
c	[N/m/s]	Damping coefficient of the springs supporting the isolated system.
ζ	[unitless]	Damping ratio, a function of c .
f	[Hz]	Source vibration frequency(s).
fn	[Hz]	Natural frequency, a function of mass and spring rates.
F_0	[N]	Force applied by vibrating source.
F_{tr}	[N]	Force transmitted to isolated system.

The following figure shows a schematic of a simple 1-degree-of-freedom system with a mass mounted to a vertically vibrating plane. The source vibration force (F_0), and the transmitted force (F_{tr}) are both continuously alternating in direction and changing in magnitude, but minimizing the amplitude of (F_{tr}) is the goal. The damping coefficient and spring rate are properties of the isolator.



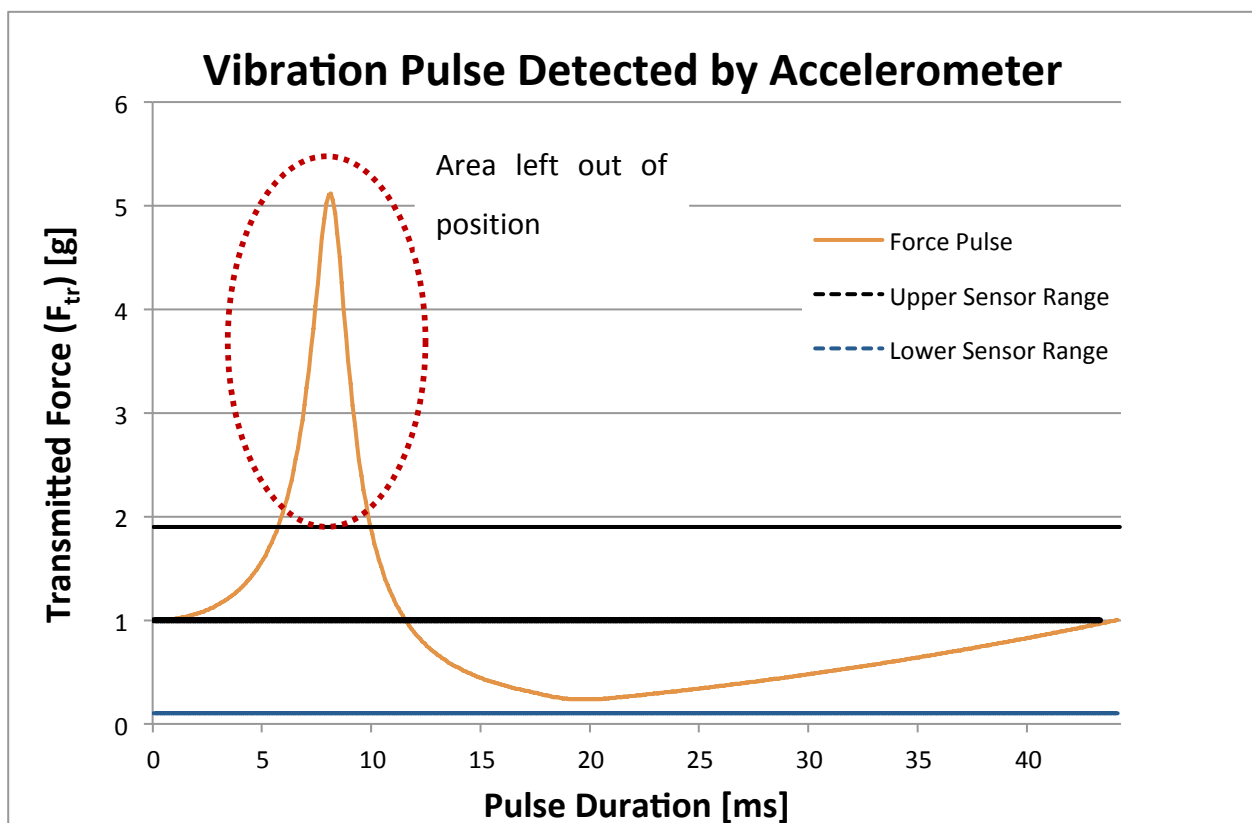
Shock Protection vs Vibration Protection

A shock absorber works by protecting against the high amplitude of a shock impulse and therefore the large forces generated. This is accomplished by separating the targeted equipment from the source of shock using a high spring rate and damping the motion to zero over time thus absorbing the shock force. Shock absorbers rarely need to deal with a harmonic force or protect from resonance scenarios.

Protecting against vibration requires a different approach called “isolation”. The goal is to reduce the force magnitude while also protecting against the periodic nature of vibration. In this case a high spring rate would transfer most of the force that is applied and would not be suitable. An understanding of how and when vibration amplification and resonance situations occur is important when isolating your system.

Problem Example

An accelerometer used for flight navigation to help determine aircraft position provides a good example of why isolating against vibration is necessary. In the first scenario, a portion of the vibration exceeds the maximum limits of the accelerometer. The graph below shows one period of a simplified force pulse generated by an internal combustion engine. The large peak occurs during the power stroke and the amplitude is greater than the maximum threshold of the sensor. Everything within the sensor's range is used in calculating position. Forces beyond this range, such as the area outlined in red in the graph below, are left out and generate inaccuracies. These inaccuracies accumulate from each period and can create very large discrepancies between calculated position and actual position.



The second scenario is more complex to understand, but easier to prevent. A vibration of a certain frequency (usually in the kHz range) can come close to that of the sensor's internal resonance frequency. This would effectively "rattle" the sensor to the point where it no longer operates correctly, even though it looks stable externally. Luckily, in a similar mechanic that

makes it easy to suppress treble sound compared with bass, high frequency vibration is much easier to isolate from than low frequency. Almost any isolation system can effectively suppress high frequency vibration. On the downside, it makes it more difficult to protect against low frequency vibration such as those created by piston engines and prop blades.

Sensor Drift

Inertial navigation utilizes sensors to measure gyroscopic and acceleration forces to determine position. Sensor drift describes the condition where the output detected by a gyroscope or accelerometer gradually gets more inaccurate over the time of operation. This can happen due to coning and sculling motion.

Coning motion occurs when two perpendicular axes (say the *x-axis* and *y-axis*) experience oscillating, angular vibrations of the same frequency. A false, non-oscillating angular motion will be detected by a gyroscope triad in the third axis (the *z-axis* in this case).

Sculling motion occurs when an oscillating, angular vibration occurs in one axis, and an oscillating, linear vibration of the same frequency occurs in a second, perpendicular axis. A false, non-oscillating linear motion will be detected by an accelerometer triad in the third axis.

The error in the output of the gyroscope and accelerometer triads will accumulate over time during a flight due to the coning and sculling errors. Large errors that accumulate quickly cannot always be corrected for by the autopilot. Suppressing high frequency vibration will greatly help reduce coning and sculling motion.

Resonance and Amplification

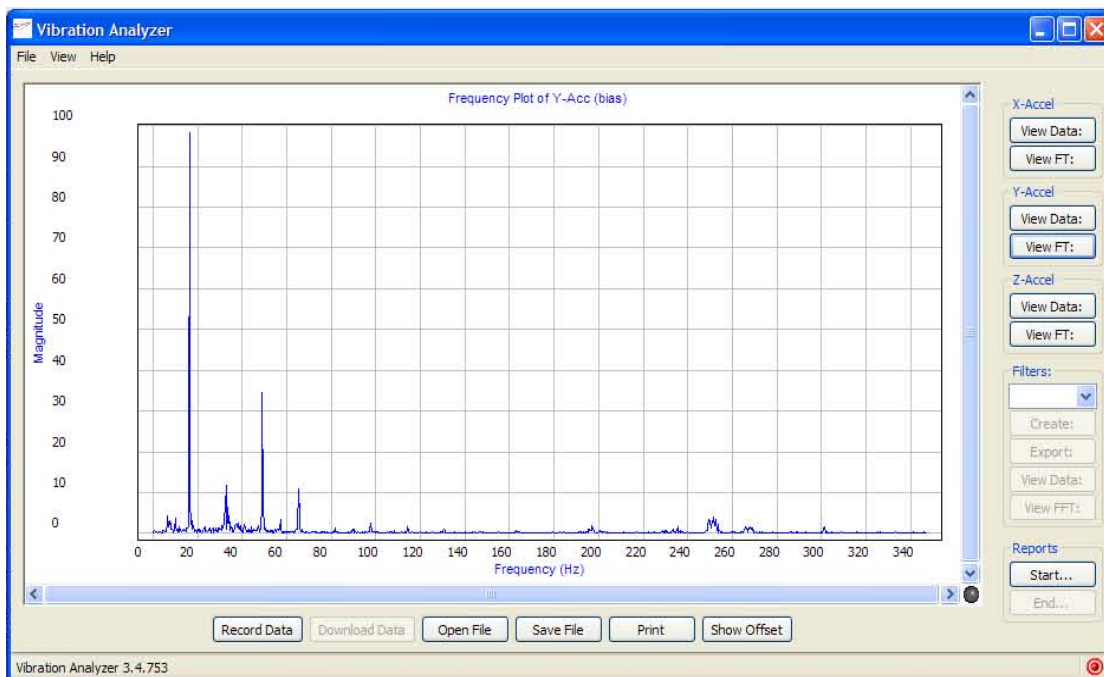
It's a common misconception that any spring/damping system will be better than a rigid mounting system for protecting against vibration. Although this may be true when isolating very high frequencies, it's very easy to inadvertently amplify low frequency vibrations. Most people have heard of resonance and know that mysterious (and usually bad) things happen under these conditions. When a suspended mass is displaced, it will tend to oscillate at some frequency until the motion is damped to zero. This frequency is called the natural frequency and resonance occurs when the natural frequency matches the vibration frequency. When this happens, the only thing that limits the force amplification is the damping ratio. Preventing or minimizing amplification has to be accomplished by increasing the damping ratio or lowering the natural frequency of your suspended platform.

Where to Start

Vibration suppression requires tuning compromises to best suit your needs. Is the equipment you're isolating more sensitive to high or low frequency vibration? What sort of source vibration can you expect from your UAV? What's the worst case scenario (blurry video or crashing your UAV)? How much are you limited by weight restrictions? These are important things to consider because you'll likely need to make compromises somewhere. The source vibration is most likely the least flexible thing you have to work with so it's a good place to start.

Testing a UAV for vibration frequencies can be done with MicroPilot's Vibration Analyzer. The vibration analyzer works by recording accelerometer and gyro data in raw units at a high sampling rate and applying a Fourier transform to calculate frequency response. Although the units for magnitude are all relative, it provides information about absolute frequencies and relative magnitudes between each axis. Experiments can also be done to calibrate the relative units to absolute units if so desired.

A helicopter, for example, will likely vibrate with equal frequencies and magnitudes in the X and Y directions because of the main rotor, but very differently in the Z direction. The following image is a capture from an isolated system mounted to a large R/C helicopter idling on the ground at 1000 rpm (~17 Hz). The spikes show the transmitted vibration frequencies and relative amplitudes.



The higher frequency vibrations in this example will probably be much less likely to affect equipment than the large spike at 17 Hz. Any system aimed at reducing low frequency vibration should do an even better job at reducing high frequency vibration.

The Other Variables

The damping coefficient provides a force similar to spring element, but the force exerted depends on motion instead of displacement. Energy is absorbed by the damping medium, reducing motion but not necessarily transmitted force, depending on frequency. The damping coefficient, damping ratio, and loss factor are all different ways of expressing the same thing. Isolator manufacturers will often specify the damping ratio of an isolator, but this number is relative to the mass used and only applies for the manufacturer's rated mass. As long as you stay near the rated mass load for that isolator then it will be fairly accurate. If a manufacturer provides the damping coefficient instead, or if you load an isolator with a different mass than it was rated, the following correlation may be useful:

$$\zeta = \frac{c}{4\pi\sqrt{km}}$$

The mass to be isolated and the spring rate suspending it are combined to determine the natural frequency of the system through the following equation:

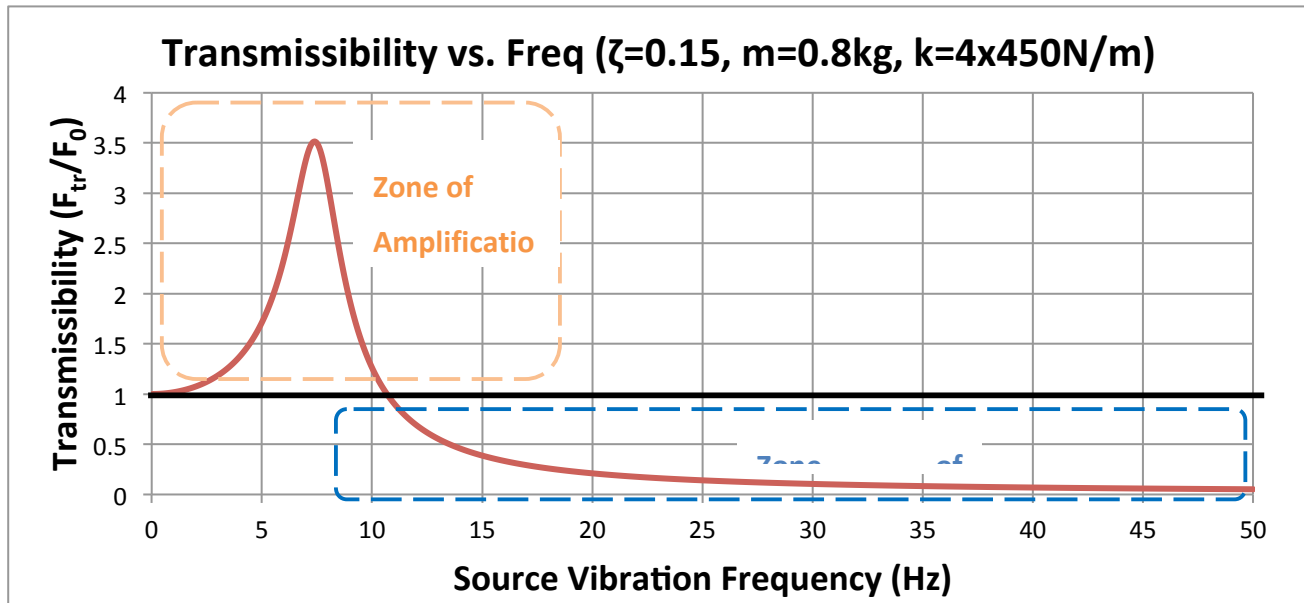
$$f_n = \frac{\sqrt{\frac{k}{m}}}{2\pi} \text{ [Hz]}$$

The damped natural frequency should be used instead if absolute accuracy is desired, but for damping ratios below 0.4 (they're commonly between 0.05 and 0.20 for most isolators) this equation is much simpler and will be within 92% accuracy. Also, remember to multiply the number of springs by their spring-rates when mounted in parallel. Lower spring rates can be achieved by mounting them in series, doubling the length of the spring. This effectively reduces the spring-rate (and damping coefficient) by half.

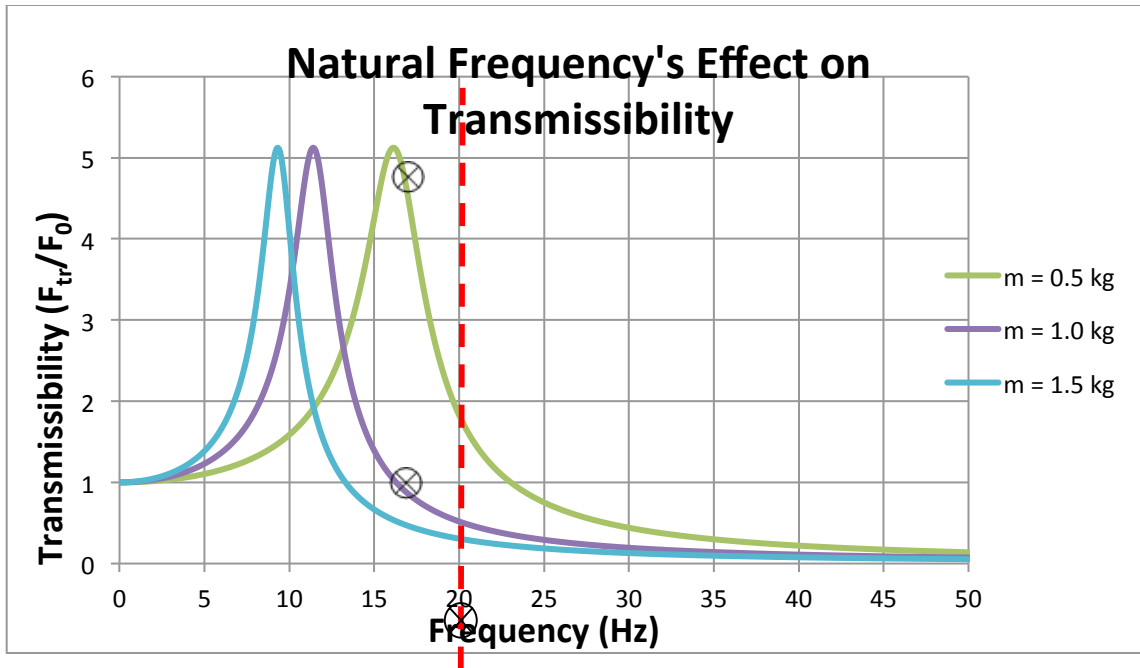
Transmissibility, Achieving Vibration Isolation

The ratio of natural frequency to source vibration frequency, along with the damping ratio, is used to determine the transmissibility. This is defined as the ratio of force transmitted through the suspension apparatus to force applied by vibration. Minimizing this ratio for a specific frequency range is the goal of vibration isolation and the equation is shown and plotted below:

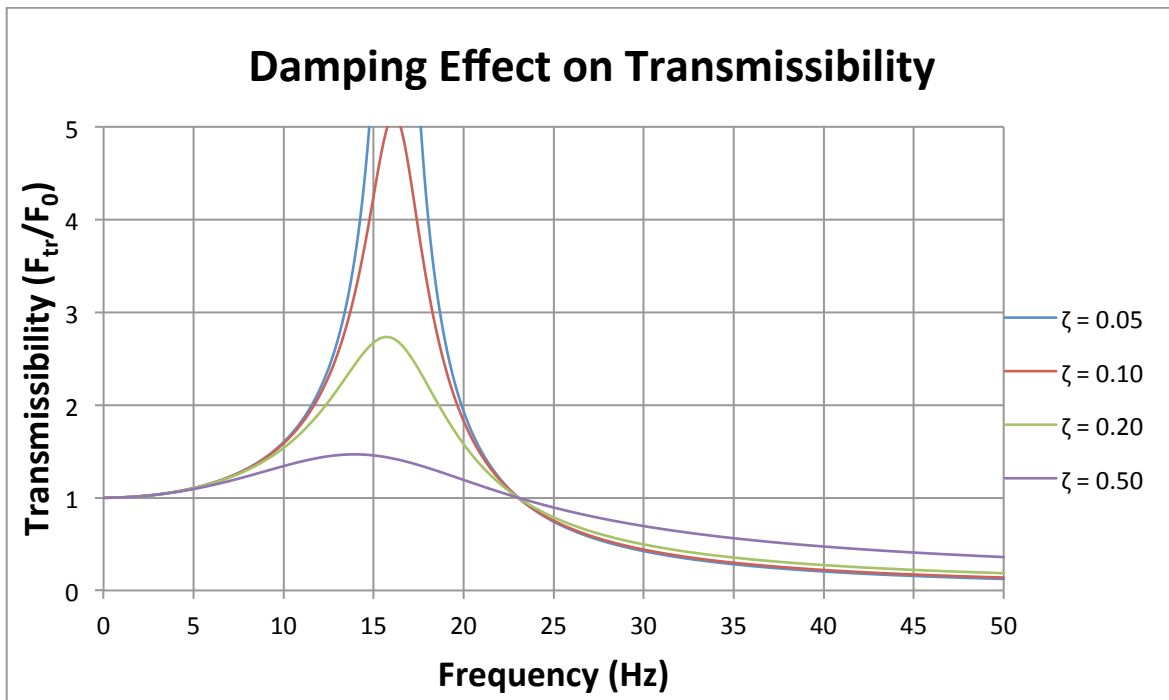
$$\frac{F_{tr}}{F_0} = \sqrt{\frac{1 + (2\zeta \frac{f}{f_n})^2}{(1 - (\frac{f}{f_n})^2)^2 + (2\zeta \frac{f}{f_n})^2}}$$



To get any isolation and prevent any amplification from occurring, your natural frequency needs to satisfy the correlation $f_n < 0.71f$. On the follow graph, the natural frequencies corresponding to each mass system are approximately 9 Hz, 12 Hz, and 16 Hz (occurring at each peak). For the source vibration shown by the red dashed line at 17 Hz, it's clear that the 1.5kg mass system has the best isolation at $f_n = \frac{9}{17}f = 0.53f$. The transmissibility = 0.5, meaning that only half the vibration force applied is transmitted to the mass. The 1.0kg mass system is neutral to the vibration (transmissibility = 1 so no amplification or isolation) at $f_n = \frac{12}{17}f = 0.71f$. The 0.5kg mass system is actually experiencing significant amplification (almost 5 x) at $f_n = \frac{16}{17}f = 0.94f$. An identical graph can be made with decreasing spring-rates instead of increasing mass since the ratio of spring-rate to mass is what determines natural frequency.



Since damping does not appreciably change any frequencies of the system, its effect is not as important as mass and spring rate. It becomes important when resonance and amplification is unavoidable, such as in a low mass, low vibration frequency system. Larger damping ratios will limit both amplification and isolation as shown in the graph below. This will help prevent large spikes at resonance, but isolation at greater frequencies won't be as effective.

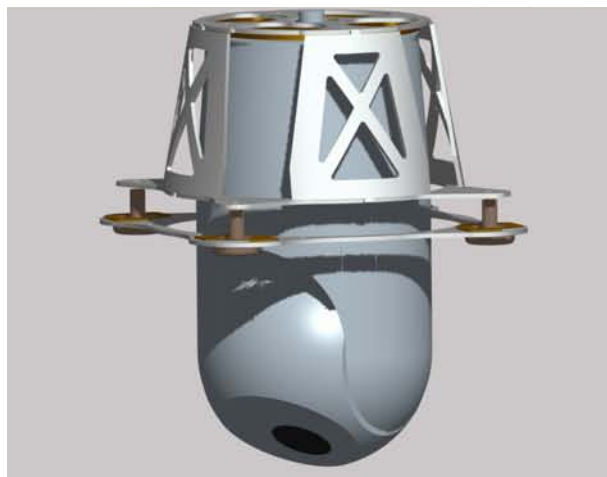


Isolating a very light mass can be problematic. Adding otherwise needless mass to an isolated platform usually isn't feasible for aerospace applications. Displacing mass (batteries are often suitable) from other parts of the aircraft is usually the best option. Anything above 500 grams or so can usually be isolated by 80% to frequencies above 20 Hz (1200 rpm) with little difficulty.

Mounting Orientation

A real-world vibration problem is not nearly as simple as the 1-degree-of-freedom system. It's a good idea to find isolators that move in all three directions with equal spring rates. [LORD Corporation](#) and [Tech Products Corporation](#) are good sources for this type of isolator. With mass loads less than 500 grams, compact wire rope isolators may provide a good solution. They can have extremely low spring rates (and therefore resonance frequencies) in shear. This comes at the expense of large compression spring-rates and resonance frequencies often well above 20 Hz. [Enidine's CR1 series](#) have provided good results in helicopter applications.

The final consideration is the orientation of the isolated platform. Placing the center of mass an equal distance from all isolators will give the best result. The center of mass should also be vertically in line with the isolators, as opposed to sitting above or hanging below, either of which will create a rotating force. Cameras are especially vulnerable to rotating motion because their focus will sweep across the intended target. A common mounting orientation of MicroPilot's Dayview camera system is shown below. Very tall, narrow masses may tend to easily oscillate in a rotational manner. If you find this to be the case, this motion can be reduced by attaching isolators in a wider stance, or experimenting with vertical mounting orientations that better keep the mass closer to the isolator plane.



Vibration While in Contact with the Ground

While in flight, a UAV can be thought of a mass vibrating freely in the air. The forces applied by vibration are transferred to this mass, causing it to oscillate. So far, reducing the transfer of this oscillation to mounted equipment has been the main topic. Other problems, however, can arise for a UAV sitting on the ground. For example, fixing a helicopter to the ground rigidly and applying power to the rotor is likely going to damage the helicopter. The vibration forces cannot cause the mass of the helicopter to oscillate freely because its position is fixed. This means that vibration forces will be applied in the form of mechanical stress instead of free motion. The mechanical components, especially within the drive-train, are unlikely to withstand significant stress forces, resulting in the failure of those components.

For this reason, it's also important to consider vibration when changing or altering landing gear. Much like the chassis of the helicopter, the landing gear can be thought of as a very stiff spring/damper system that can transmit and amplify vibration. This system, however, is allowed to slide against the ground. Altering landing gear in such a way that either prevents sliding, or causes vibration amplification can have catastrophic results. The analysis of this type of system is beyond the scope of this article, but careful testing is the best way to ensure that modified landing gear will not cause problems.

Conclusion

This article is intended to give an overview of the vibration phenomenon as well as a starting point for experimentation. Entire university courses are dedicated to exploring vibration and cover far more material than this article ever could. Meticulous analysis requires a lot of time, skill and advanced mathematics but this may not be necessary for satisfactory results. A simplified understanding and some experimentation will likely satisfy the needs of most UAV applications.

About MicroPilot

With 750 clients in 65 countries, MicroPilot is the world leader in miniature autopilots for UAVs and MAVs. MicroPilot is the first UAV autopilot manufacturer to bring to market a sub 30 gram autopilot, triple redundant autopilot, and full-function general purpose autopilot. MicroPilot offers a family of lightweight UAV autopilots that can fly fixed-wing, transitional, helicopter, and Multi Rotor UAVs. MicroPilot also provides complementary products such as the XTENDER^{mp} SDK, trueHWIL, payloads, and catapults.