

SMOOTH OPERATOR

Jitter characterization during reaction wheel operation can help minimize the impact of vibration on satellites

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Reaction wheels are used for attitude control of satellites without the need to use thrusters and propellant, which is in limited supply. The operation of a reaction wheel uses an electrical motor to rotate a flywheel at various rotational speeds, causing the satellite to counter-rotate proportionately due to the conservation of angular momentum. This operation rotates the satellite around its center of mass but does not reposition the satellite, as can be done with a thruster.

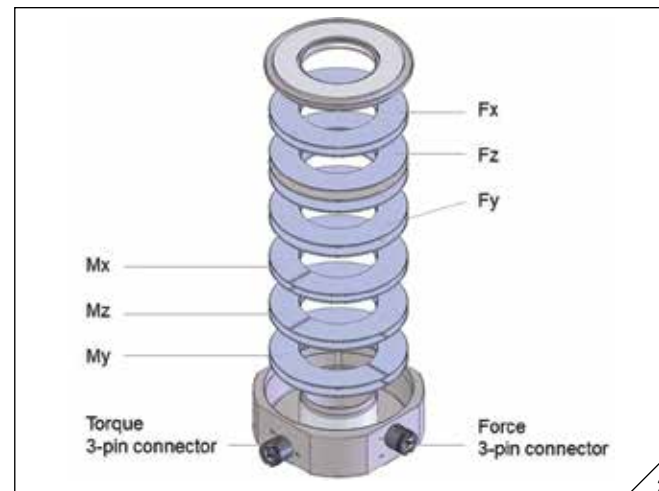
As the flywheels rotate there are small fluctuations, called jitter, that are directly coupled into the satellite and can affect mission operation. For example, if a satellite is imaging and pointing at a specific location, jitter can blur or distort the image.

A reaction wheel can also be operated as a momentum wheel, using near-constant rotational speed to influence a satellite's attitude by creating angular motion to

stabilize the satellite's axis to point in a nearly fixed direction.

Characterizing the unwanted vibration or jitter during reaction wheel operation supports balancing operations to optimize unwanted disturbances. Balancing applies masses on parts of the wheel, which is essential to reduce residual forces and moments during operation. It is becoming increasingly common for satellite manufacturers to request jitter characterization.

Satellites with low mass and size, usually under 500kg are becoming more common because they are cheaper. Using many small satellites could be more useful than fewer larger ones in certain applications, such as scientific data collection and university research. Smaller sizes and a diversity of missions require a variety of reaction wheel sizes and performance. For small satellites, resolution of forces and moments lower than 5mN and 0.5mNm



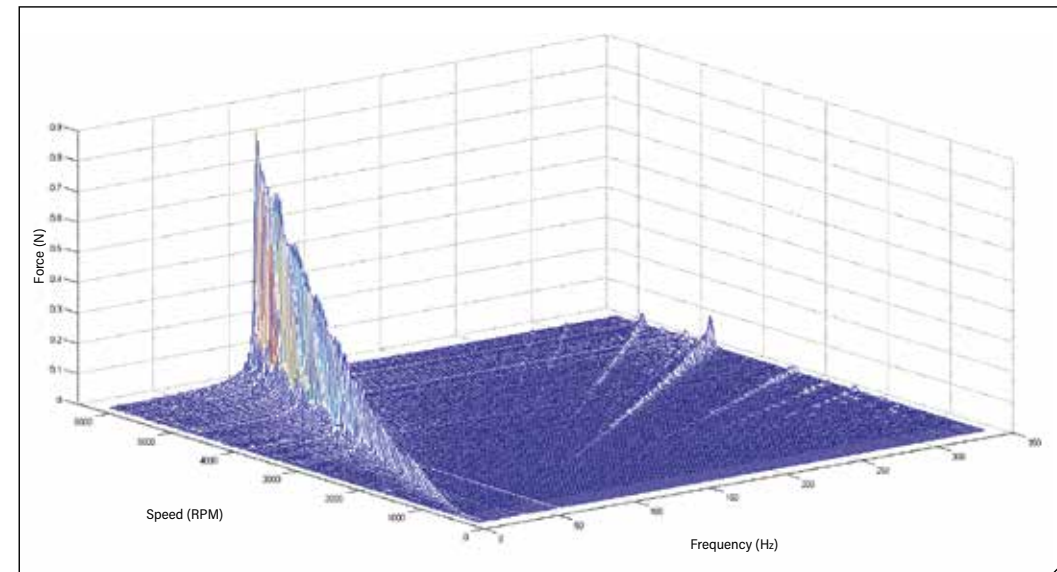
1 // Small satellite reaction wheel investigations using the 9306A six-component force sensor on a vibration isolation table

2 // Internal design of a piezoelectric six-component force sensor

can be significant to the mission. Various rotational speeds can be used, resulting in the need to measure a range of vibrational orders and resonances.

Recent years have seen advances in terrestrial observation accompanied by an increase in the need to measure Earth's surface and atmosphere with greater precision. For example, cameras on the latest Earth observation satellites feature resolution on the order of 0.5m. We can quickly get a perspective of commercial

"JITTER CHARACTERIZATION IS BEING REQUESTED BY MANUFACTURERS"



3 // Waterfall plot showing the radial force output from a candidate reaction wheel plotted against speed versus frequency

image quality with Google Earth. The reduction of reaction wheel jitter contributes to the improvement in image quality.

PIEZOELECTRIC TECHNOLOGY

A six-component piezoelectric sensor, such as the Kistler 9306A, is ideally suited for jitter characterization of small reaction wheels. Such a solution provides very high measurement resolution as well as direct measurement forces and moments. This makes it possible to measure dynamic force changes greater 0.5mN, and moments changes greater than 0.02mNm, depending on the signal bandwidth and assuming optimal measuring configurations with optimal charge amplifier (type 5080A recommended). A static weight can be 'eliminated' by resetting the charge amplifier (similar to a tare function). This allows the measurement range to be based on the magnitude of the dynamic signals of interest while increasing the signal-to-noise ratio. Piezoelectric sensors deliver a rigid measurement platform, achieving very high natural frequencies of 6.9kHz in force and 6.3kHz once mounted.

The design uses six pairs of quartz discs cut in different orientations to measure the

six components of interest. The resulting charge sensitivity is up to 73pC/N and moment sensitivity up to 255pC/Nm. The sensor output uses a laboratory grade, low-noise, quasi-static charge amplifier to deliver the high resolution previously mentioned.

The measuring chain for performing reaction wheel jitter investigations starts at the six-component sensor output. This is converted to a low-noise voltage by the charge amplifier. The voltage output is input to a six-channel DAQ with a noise level at least as good as the charge amplifier, to allow for the lowest possible measured signal.

Time domain, FFT and waterfall representations are usually of interest for such investigations and are correlated to the rotational speed of the wheel.

COMPONENT CALIBRATION

With mechanism testing and jitter characterization, it is of great importance to calibrate the measurement instrument accurately. The application demands the ability to resolve low-level measurements, where the effects of such jitter on the mechanism design and spacecraft system and subsystems makes it a critical success

factor. The smaller the satellite, the smaller the jitter level under investigation, so accurate calibration is even more critical.

A hexapod six-component calibration system has been developed by Kistler (Figure 4). The advantage of this system is that it can automatically calibrate the 9306A for full-scale operational range in positive and negative directions. Parameters evaluated included sensitivity, linearity and cross-talk of the multicomponent sensor. As microvibration uses only a fraction of the measuring range, an additional partial range calibration for low full-scale forces and moments is performed on request, using a conventional hydraulic press with reference standards and fixtures.

LOW BACKGROUND NOISE

To measure low-level, high-resolution forces and moments, the test environment should be constructed to minimize environmental noise from sources such as airflow and seismic inputs. Typical considerations include a vibration isolation table with resonances outside the frequency of interest, such as is shown in Figures 1 and 5.

This will isolate the force sensor from external vibration from sources such as compressors, machinery, people walking and road traffic. In an area with high environmental induced vibration, testing should preferably be performed very early in the morning or at night when activity is low. Even airflow from an air-conditioning system can create unwanted input to the sensor and may require the use of a box over the test article. In short, an evaluation of the environment when taking low-level measurements will ensure that external influences are minimized to optimize measurement of the jitter. Electrical noise from the signal-conditioning system can sometimes be improved by using battery power instead of AC mains power. Some signal conditioners offer DC and AC input.

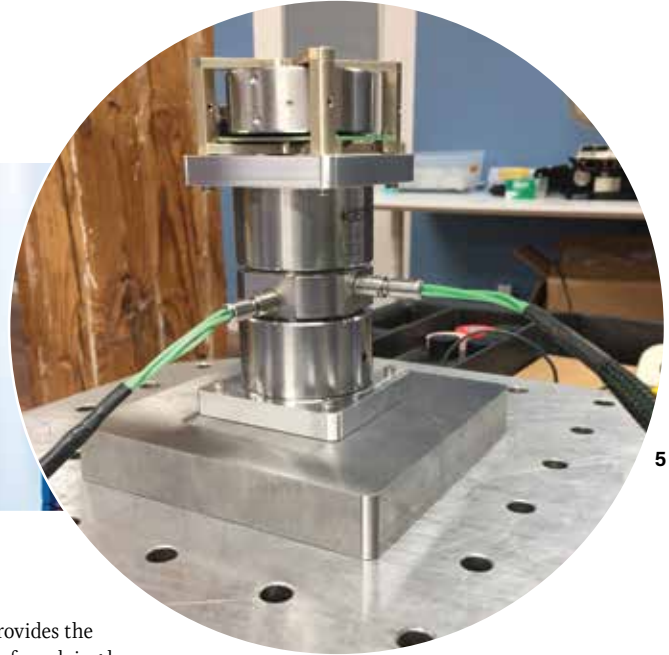
HIGH-FREQUENCY RESPONSE

A piezoelectric sensor can be modeled as a lightly damped second-order system. As



4 // Automatic calibration on hydraulic hexapod at Kistler

5 // The reaction wheel jitter investigations used a 9306A force sensor with vibration isolation table and an airflow insulation box



5

such, the natural frequency (f_n) can be used to estimate the amplitude response tolerance using different frequencies.

Most piezoelectric sensors follow the high-frequency response rule. For example, a 5% amplitude response means that over a frequency range, the amplitude can vary $\pm 5\%$, which is a tight tolerance. The test engineer should decide on the amplitude response tolerance of interest and the frequency range of interest based on the lightly damped second-order approximation. For a natural frequency of 6.9kHz, the 5% amplitude response is up to 6.9kHz/5, or 1.4kHz. The 10% amplitude response has a frequency within a range of up to 6.9kHz/3, or 2.3kHz. For higher frequency measurements, the trade-off

improved and rangeability provides the added benefit of resolving low-level signals. The maximum noise of the DAQ used for the investigation should also be in the same range or even lower to allow for the best resolution possible.

THE IMPORTANCE OF SIGNAL SYNCHRONIZATION

It is crucial that measurement signals are synchronized, or results may be interpreted completely incorrectly. Synchronization can be performed in two ways. The classic solution is to have a separate line, where a system clock is routed to each device to ensure that the measured values are recorded at the same time. The other option is to equip each device with a precise clock and periodically adjust it as is used in the precision time protocol (PTP).

PTP, as described in IEEE 1588-2008, is a procedure whereby the clocks of local network components can be

adjusted to achieve accuracy in the sub-microsecond range – without extra cables.

Kistler LabAmp 5165A and 5167A devices have two network connections and integrated PTP switch functionality. They synchronize themselves via the normal network cables. Depending on the required data rate and number of channels, several devices can be connected in series without the need for an external PTP switch.

PTP recognizes two clock types – master and slave. A slave synchronizes itself to its corresponding master. The most precise clock in a network is determined by the automatic 'best master clock' algorithm. Once this 'grand master' is selected, the synchronization of the next slave takes

place, which may in turn act as master for the next iteration. After a successful initialization, synchronicity is checked at regular intervals and the clocks are adjusted if necessary

TYPICAL MEASUREMENT RESULTS

Figure 3 is a waterfall plot showing the radial force output from a candidate reaction wheel and how the force output from the wheel varies with speed versus frequency. The primary ridge on the graph is created from the static imbalance of the rotor, where the force shown is equal to $F = m \cdot r \cdot \omega^2$ and the $m \cdot r$ term in that equation is the rotor's static imbalance.

The smaller ridges showing in the higher frequencies tend to be running harmonics of the bearing/rotor system. Spacecraft designers use this information to create mathematical models of the disturbance output from the reaction wheels to evaluate the effects of jitter on their instruments.

The six-component piezoelectric measurement chain provides robust measurement capability to accommodate various reaction wheels. The result is the measurement of low-level jitter with high precision to enable the balancing and characterization of the reaction wheel.

Other benefits of the jitter measurement system includes six-component calibrated operation, a high-sensitivity sensor, rangeable operation, high-frequency operation and synchronized digital six-component data. \

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“REDUCTION OF THE REACTION WHEEL JITTER ON BOARD SATELLITES CONTRIBUTES TO THE IMAGE QUALITY ADVANCE”

is amplitude response tolerance.

As mass acting on the sensor affects natural frequency, a very basic tap test using a small impact hammer can be used to determine the frequency response and related natural frequency. Once the natural frequency estimate is known, the user can establish an upper frequency limit as a factor, based on the desired amplitude response tolerance as previously discussed.

RANGEABILITY AND RESOLUTION CONSIDERATIONS

Piezoelectric measurement chains permit adjustment of the full-scale measurement range using an amplifier. By using a lower full-scale range, the broadband noise is