Testing and Measurement of Mechanism-Induced Disturbances

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Abstract

Many space mechanisms with moving parts such as gimbals, cryocoolers, shutter mechanisms, filter wheels, fast steering mirrors, and reaction wheels produce dynamic forces and torques that have the potential to interfere with the function of other onboard instruments. Jitter sources include direct reaction forces and torques from linear and rotary actuators, inertial imbalances, misalignments and internal loads operating against asymmetric inertia and or stiffness to name a few. The drive to address disturbances from mechanisms in space hardware is prompted by the need to meet certain mission requirements, e.g., signal quality from a science-producing instrument, line of sight stability, or optical jitter. The minimization of jitter can be approached through integrated analytical procedures and experimental tests capable of identifying the source, nature and magnitude of the driving forces and torques. Even if a mechanism is designed to eliminate jitter, e.g., having reaction cancellation features, small loads are always present due to manufacturing tolerances, slight imbalances, and coupling between degrees of freedom. In this paper, we discuss advances made in the measurement verification process of jitter loads at Ball Aerospace & Technologies Corporation (BATC) over the past few years. In particular, the strategy used to deal with a wide range of loads and applications prompted the development of a capability to custom build measurement platforms with the needed performance using modular hardware. Examples of jitter mitigation and cancellations are discussed to illustrate some of the work carried over the past decade.

Introduction

Force and **m**oment **p**latforms (FMPs), also known as dynamometers, are now commonly used to measure imparted loads in the six degrees of freedom from either operating mechanical systems with moving parts placed on top of the device or non-operating systems excited using shakers and stingers. Such devices can be used in many applications, including JPL's force limiting during vibration testing of space hardware [1], static and dynamic balancing of rotating systems [2], measurement of inertial properties, and hybrid testing where a subset of the unit under test is accounted for through the application of equivalent loads obtain from real-time simulations [4]. The other use of such devices is in jitter measurement [3] and is the subject of the current contribution.

FMPs use three or more judiciously encapsulated tri-axial force sensors between two sufficiently rigid plates. They are designed to be statically determinate, so that all torques are transmitted mainly as forces through the load cells. Loads from the tri-axial force sensors are related to the forces imparted on the top interface plate through a system of equilibrium equations. The unit is then calibrated as a system to measure resultant dynamic loads on top of its surface.

Depending on the geometry of the FMP, the number and type of force sensors and the characteristics of the unit under test, there are limitations on the capability of the FMP. These limitations are on the magnitude and accuracy of the imparted forces and torques, their frequency range and the sensitivity of the system as an instrument. In addition, depending on the test location and whether a low frequency table is used, there is a noise floor that needs to be characterized prior to each test.

Because of the wide range of requirements from one program to another, BATC elected to implement a strategy that builds custom FMPs tailored for each program using modular hardware. FMPs are built from

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a toolkit of hardware and flexible software to respond to the particular needs of the application producing jitter.

The paper addresses the experience and capabilities for jitter verification at BATC. In particular, the following topics are discussed:

(a) The modal characteristics of measuring platforms and their dynamic coupling with the behavior of the instrument under test. Often, the potential for interaction between the instrument and the measurement platform prompts the identification of the frequency content of the setup in the frequency band of interest. In addition, the type, number and layout of the force sensors together with the choice of the encapsulating hardware are discussed in light of stiffness and measurement requirements.

(b) The different methods used for dynamic calibration of a six-degree of freedom FMP in light of the test setup environment, and applicable requirements. These include harmonic stinger tests, frequency response function tests, speaker tests and independent measurement verification, e.g., through a Vibration Lab data acquisition system network or portable systems.

(c) The handling of background noise to ensure adequate measurements. There are two sources of background noise: one from the measuring equipment used in the test setup and the other is of environmental origin, often induced by nearby operating machinery and/or human activities.

Finally, the paper gives examples of jitter measurement, mitigation and verification of mechanisms, including cryocoolers and momentum wheels.

Measurement Verification

Fast steering mirrors, gimbals, reaction wheels, shutter mechanisms, cryocoolers and other instruments with moving components impart dynamic loads that require proper characterization to meet mission requirements such as those involving line of sight stability, optical jitter and image quality. These dynamic loads need to be measured and often mitigated using advanced design layouts. In certain mechanisms involving optical systems such as fast steering mirrors, gimbals, reaction wheels, shutter mechanisms, cryocoolers and other instruments with moving components, inertial load couplings and reactions from actuation need to be cancelled and therefore the verification of imparted loads becomes essential during the integration of the mechanisms. In many applications, jitter elimination is addressed through either active or passive isolation systems. The performance of such systems needs to be evaluated through measurements and FMPs are essential for such verifications.

Over the past twenty five years, BATC built and internally calibrated several multi-degree of freedom precision FMPs to measure jitter and reaction loads from space instruments. Some of the tables are static and others are dynamic, capable of simulating complex multi-axis external jitter input. These tables were used for multiple space programs and in multiple environments, including vacuum, cold temperature, simulated weightlessness (as low as a fraction of 1 Hz). In addition to simultaneously measuring three forces and three moments in the time and frequency domains, the tables were used for static and dynamic balancing, JPL's force limiting during environmental testing, and bearing contact angle verification. Depending on the application, FMPs were developed to meet a variety of requirements involving particular geometric configurations, weight, stiffness, and low jitter load amplitudes and frequencies. Some FMPs were built for applications where the frequency of interest is around 0.5 Hz. Other dynamometers were built to handle high frequency measurements where stiffness requirements are dictated by high bandwidth control loops (e.g., fast steering mirrors).

Because there is no dynamometer that can address all sorts of requirements from one program to another, BATC elected to acquire the capability to rapidly put together customized **e**xported **f**orce and **t**orque (EFT) test setups depending on the mechanism under test and what is being measured. To this end, the EFT Facility at BATC acquired dozens of tri-axial sensors of varying capabilities, high quality in-line charge amplifiers, signal conditioners, and a large number of input/output multichannel, high resolution and high dynamic range analog DAQ cards. The hardware for developing FMPs is modular so that the right equipment is selected to support single or multiple setups at a time. The tool kit to allow quick FMP implementation and currently allows for measurement magnitudes ranging from 3E-5 N to 200 N, with higher/lower ranges possible. Multiple special EFT stiff tables (Figure 1) provide a low 5-Hz isolation system with a top plate providing a standard 2-inch (5.1-cm) grid mounting pattern. Clean tents with 15°C to 25°C temperature control provide enclosures when stringent cleanliness or environmental levels are required for flight hardware.

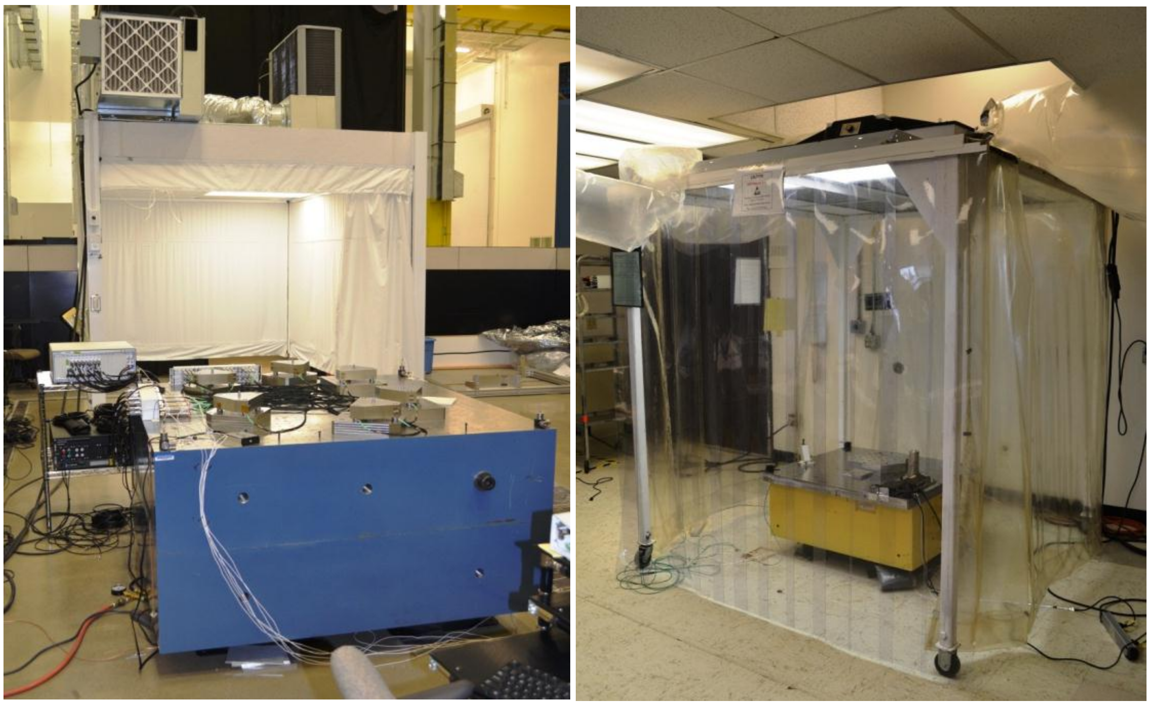

Figure 1. EFT tables with clean tents: 30,000 lb (60” x 60”) (left) and 4,400 lb (36” x 34”) (right) 133 kN (1.5 m x 1.5 m) (left) & 19.6 kN (.91 m x .86 m) (right)

The extent of stiffness verification of FMPs is performed first through analysis using a finite element model representing the load cells and encapsulating plates with and without the mechanism under test and later, once assembled, using frequency response function testing. To ensure that the setup configuration does not contribute to the measured data at particular frequency ranges, frequency response functions are expected to have clean frequency responses. That is no gains (or tolerable gains) in the frequency range of interest must be shown, as illustrated in Figure 2, when the setup is excited in the three axes and at different locations of the top plate of the FMP.

For example, the first generation 1-kHz FMP is shown in Figure 3. The system uses three Kistler type 9067 tri-axial load cells, nine Kistler 5010B0 charge amplifiers, National Instruments type PCI-6033E data acquisition card, and utilizes LabVIEW’s interface software to acquire data at 5000 samples/sec. The system resolves the three orthogonal forces from each of the three tri-axial load cells to the three resultant forces in the X, Y and Z axes and three moments M_X, M_Y, and M_Z. Jitter forces and moments are measured from 1 Hz to 1 kHz with a resolution of 0.5 Hz. Upon acquisition, fast Fourier transforms are performed on the data to provide frequency domain equivalent data through a software interface.

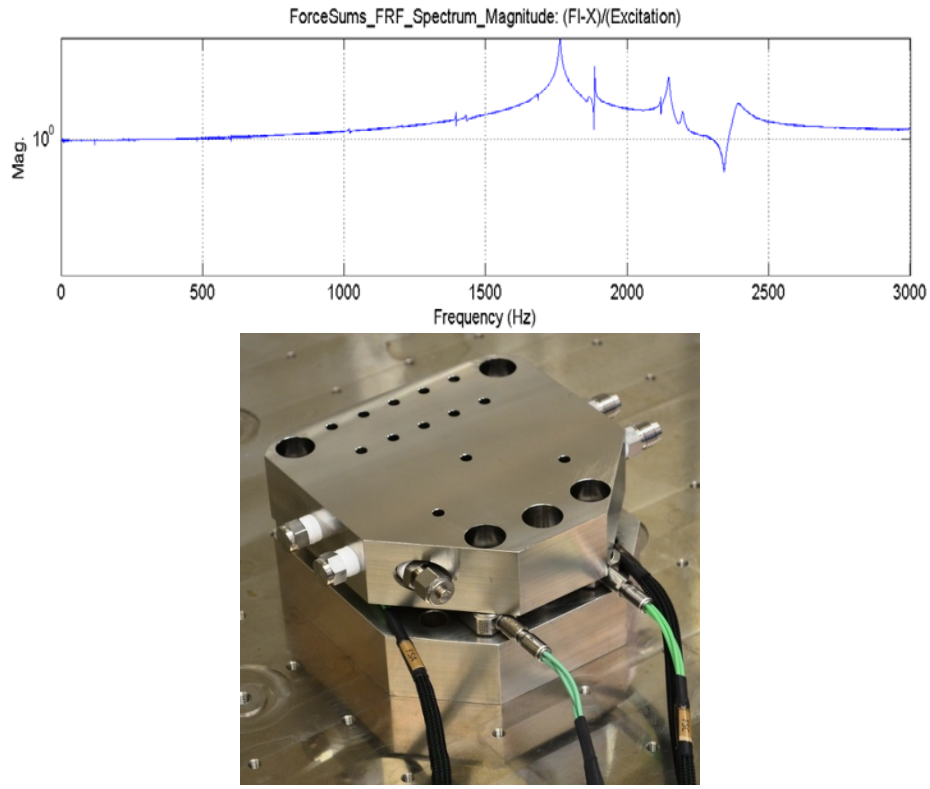

Figure 2. Tap test showing clean response to high frequency with little gain (top) and partial FMP hardware during assembly (bottom)

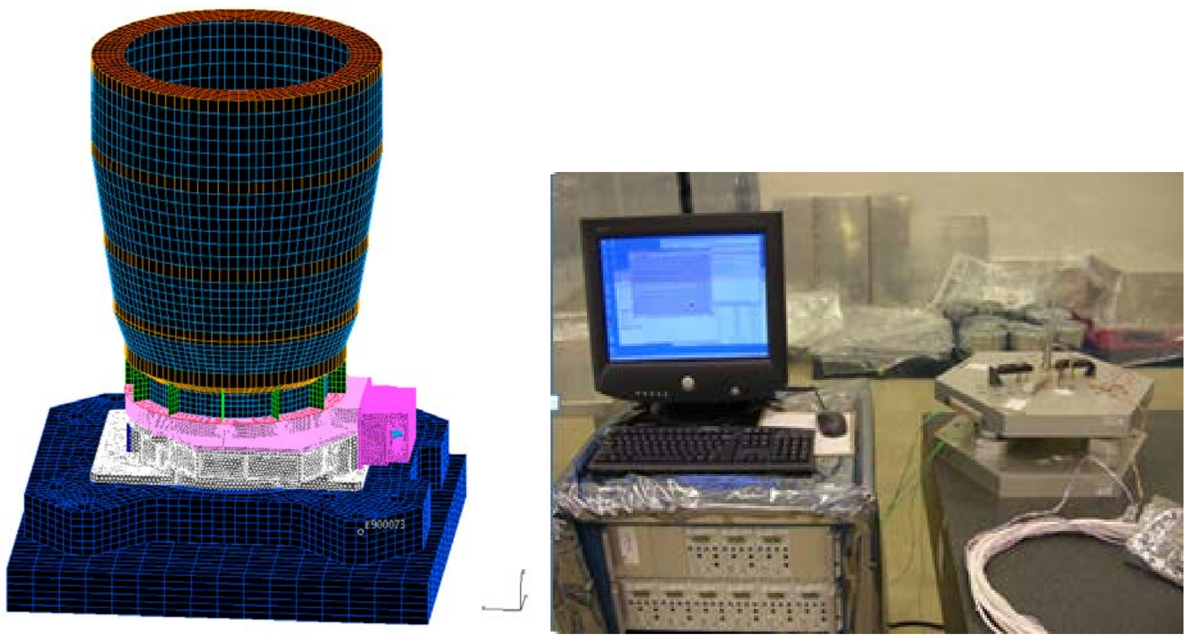

Figure 3. An Integrated example of a model of a mechanism with a later generation of BATC FMP (left) and 1 KHz FMP, charge amplifiers and computer system for data acquisition (right)

EFT testing generates large amount of data over short time spans. In addition to data acquisition and management, the Ball-developed Dynamic Measurement and Analysis software platform provides real-time fast Fourier transforms and power spectral densities, and sliding window analysis. Multiple dynamometers can be used within a single setup with real-time viewing of time-domain and limited frequency domain. A configuration file allows for quick addition of new dynamometers and sensors such as encoders and accelerometers. Finally, both real time and frequency data can be easily imported into Excel or MATLAB for processing with a suite of scripts, allowing analysis and automatic data plotting.

Background Noise Measurement

When characterizing EFT from mechanisms, identification of the magnitude and spectral properties of the noise floor at different times of day (and sometimes at different physical locations) is performed. The noise floor is lower during the late evening/early morning time, and when testing is performed in the massive reinforced concrete test pit facility which is part of a large testing facility at BATC. The noise floor magnitude depends on the type of electronics used in the FMP design, its size, and whether an EFT table is used for support. Typical background noise is less than 1E-4 N as illustrated in Figure 4. The bulk of the noise is of environmental nature. At times, shutting down equipment in the vicinity of the test may be required, and facilities in upper floors or nearby urban roads are usually noisier.

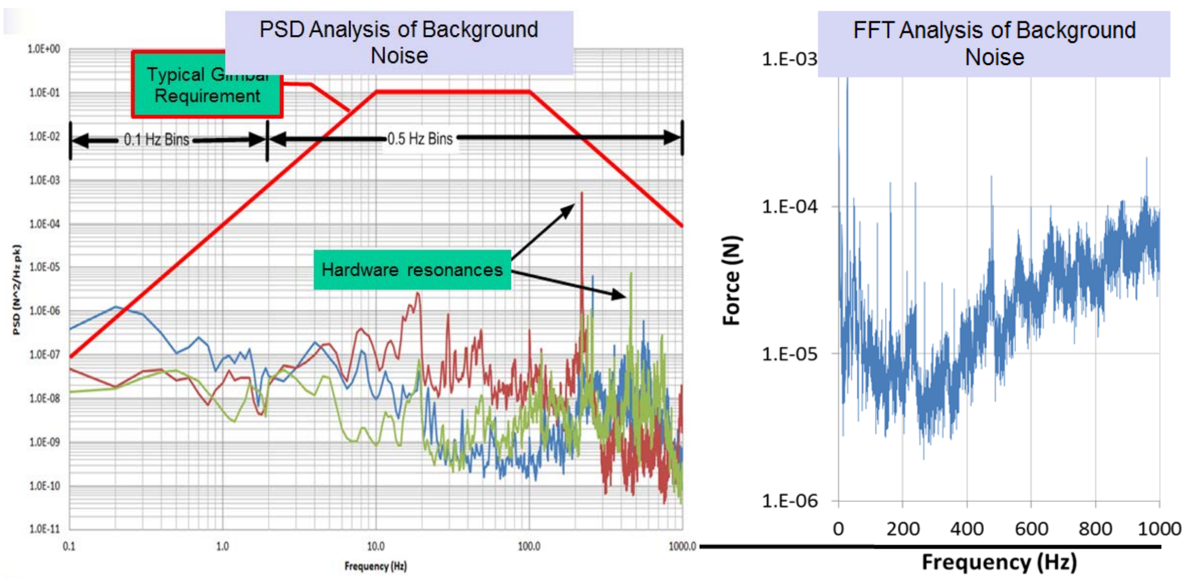

Figure 4. Typical background noise characterization processed by a dynamometer

When noise gets in the way of measurements at a particular frequency range, special filtering is used to extract the necessary signal of interest. Signal-to-noise ratio measurements significantly improved through a development program in which a new set of quality electronics are integrated. Reference [2] presents an example where filtering using a 10-Hz low bandpass was required to achieve balancing of a rotating mechanism. An example of dynamometer noise floor measurement for the Y-axis is shown in Figure 5. In this case, the maximum noise of 0.00175 lbf (7.8 mN) was measured and was less than the derived 0.004-lbf (17.8-mN) limit needed for accurate measurements of the static and dynamic imbalances of the GMI instrument.

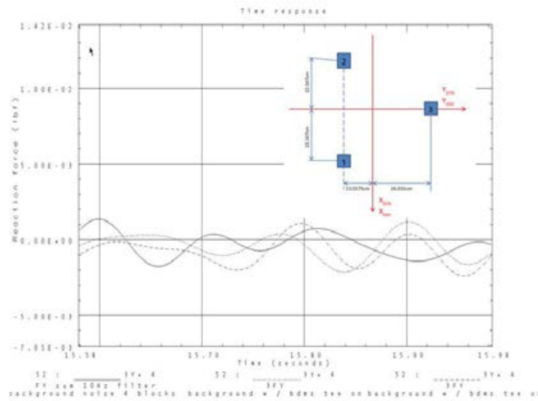

Figure 5. Noise floor showing measurements filtered using low bandpass of 10 Hz

Calibration of EFT Setups

BATC developed several procedures to calibrate its EFT setups as a system. These include harmonic stinger tests, frequency response function tests, and speaker tests. EFT setups are first analyzed to identify their modal characteristics with and without the mechanism intended for measurement. To ensure a good correlation between analysis and tests, the spring rates of the load cells themselves are characterized and are accurately modeled. Once the model of the setup is properly correlated with test data, and its predicted response is validated through combinations of sine sweeps and tap testing, an integrated model of the correlated setup and the unit under test is evaluated to ensure adequate stiffness of the setup. Again, there should be no gains that would affect measurements in the expected jitter frequency range. At this stage, the FMP is ready to proceed for calibration as a unit.

The calibration of the FMP entails three parts. First, the setup is shown to have the necessary sensitivity to accurately make the necessary measurements. The noise floor is identified and compared to the program requirements which are either specified or derived from higher level requirements. At a minimum, the noise floor is required to be one order of magnitude below the minimum measured force/torque in the six degrees of freedom.

Second, the forces measured by the FMP are validated using two separate and independently calibrated data acquisition systems and three loading methods. This is performed to isolate and quantify the source and magnitude of potential random measurement errors and identify the load cells/channels that may be erroneous. Harmonic stinger tests are used to excite the setup at certain frequencies. A calibrated load cell is placed at the interface between the stinger and the EFT setup to measure the input force. The input force is also measured using the setup as the sum of the contributions of all load cells through its transformation matrix relating the individual loads to the resultant forces and moments of the FMP. The input load is applied separately along the different axes of the setup and is required to match the measured output load. The Spectral Dynamics data acquisition system at BATC's Vibration Lab is often used as the first independent mean for measurement. A second portable data acquisition system is used to ensure concordance with the reference input load. The fixity of the FMP setup is evaluated to ensure that the most adequate and practical configuration among clamped, simply supported and free-free that delivers the most separation between the modes of the setup and the jitter forces frequencies is used. Finally, Speaker tests are used as a source for input loads that can be placed at different locations of the setup and different heights above the interface plate of the FMP. The calibration consists in applying known forces using a speaker precisely located and oriented on the setup and measuring the reaction forces and moments imparted on the surface of the plate. The speaker is attached to a fixture through an encapsulated load cell. The speaker is actuated using a form generator to deliver loads of varying magnitudes at particular input frequencies. Tests are required to show that the input load from the speaker force transducer and the measurement from the setup are the same in different orientations. In particular, this test is important in the calibration of the measured three moments.

Third, the calibration program evaluates data collected from auxiliary tests with rotating payloads with known, off-axis masses which are precisely located on a rotating disk mounted to the FMP.

These tests assess the performance of the setup in measuring certain loads that result from simultaneous measurements from all load cells, over a good range of amplitudes. Such tests can also be used for trouble shooting and mitigation prior to handling critical hardware.

When the unit under test has large moving surface areas, jitter measurements may require testing in near vacuum environment to ensure that air drag is not affecting the inherent jitter measurements. BATC has developed the necessary tooling to ensure that tests are conducted under such condition in vacuum chambers. Of course, such environments require a good portion of the setup to be vacuum compatible.

Examples of Jitter Mitigation and Isolation

Mechanical Cryogenic Refrigeration

Traditionally, high-precision space infrared instruments have been cooled using expendable cryostats which are inconvenient in the sense that they are not only large and heavy; they are also short-lived, and only capable of cooling small detectors. Cryostats are however highly reliable, because they are passive and have no exported jitter to impact sensitive optics and detectors.

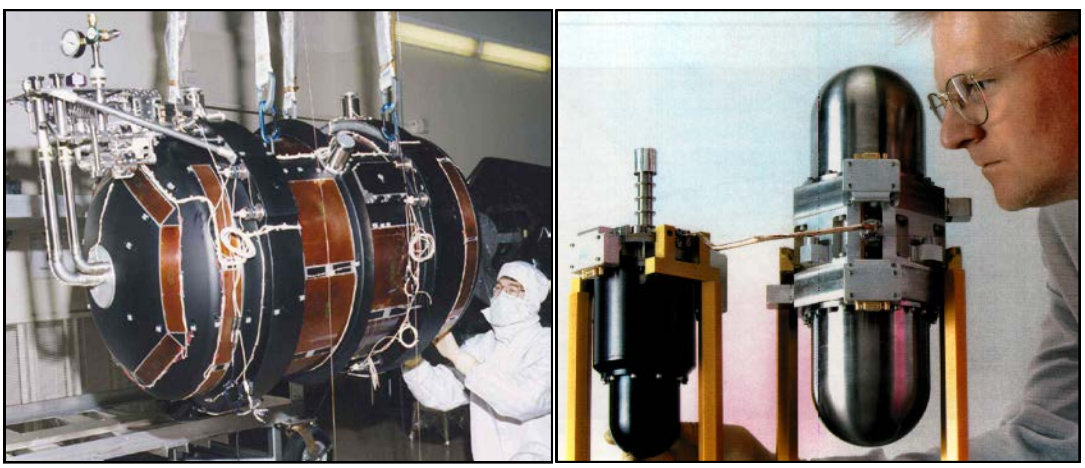

Figure 6. Early expendable cryostats (left) and cryocoolers (right)

In the past two decades, mechanical cryogenic refrigerators (cryocoolers), shown in Figures 6-7, saw their reliability improved dramatically. They can support much larger (10-100X) detectors and sustain missions of much longer durations (2-5X). But, cryocoolers have moving mechanisms that can produce significant jitter. Until recently, these levels of jitter have been unacceptable for the highest precision space instruments.

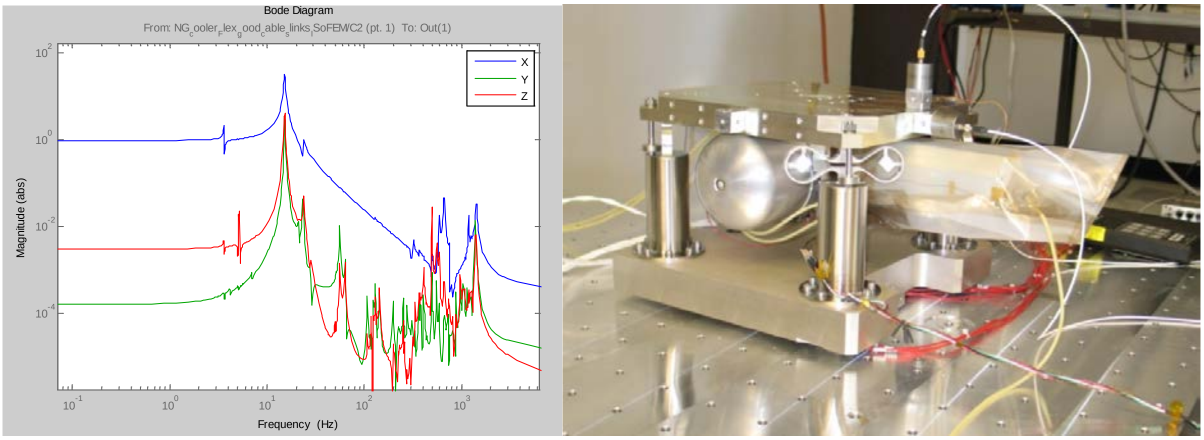

Figure 7. Bode plots of the BATC cryocooler (left) and cryocooler with soft mount (right)

BATC addressed exported force and torque (EFT) mitigation of cryocoolers on the basis of simple passive concepts using mature, flight-proven elements with performance verification using a high-fidelity EFT test bed. Effectively, low resonant soft mounts of about 10 Hz are introduced to (a) maximize attenuation at cooler operating frequencies greater than 67 Hz, and (b) minimize cross talk and moments (see Figure 2). As a result, the cooler EFT is attenuated by more than a factor of 40, from 400 mN to about 10 mN. The soft mount isolators use flight-proven heritage. The cooler itself has good flight heritage with internal vibration control already <400 mN. The EFT mitigation program improved the performance of BATC's line of cryocoolers dramatically as illustrated in Figure 8.

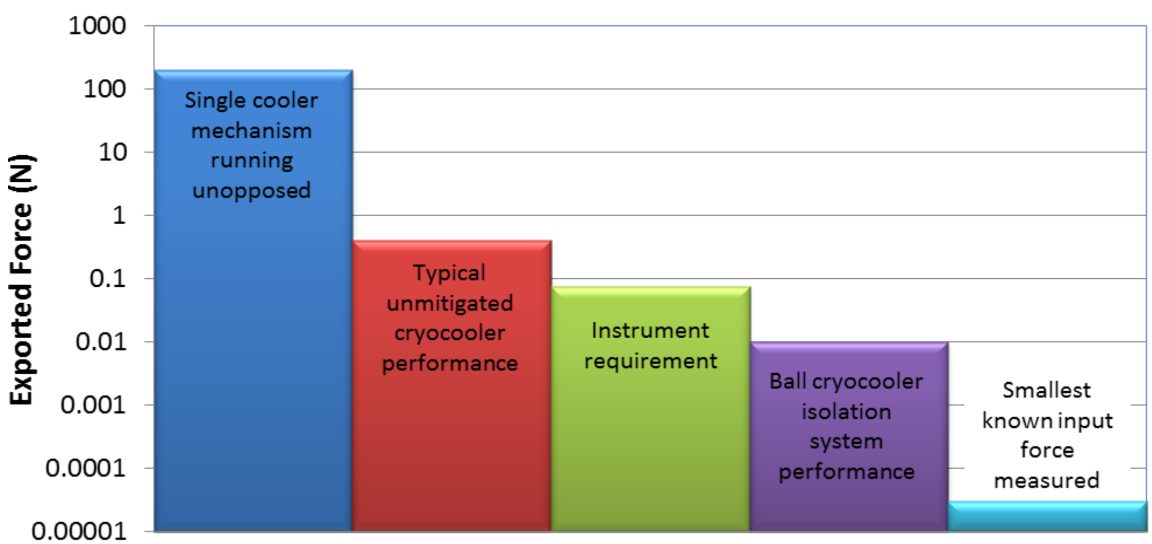

Figure 8. Isolation performance of BATC's cryocoolers

EFT control is achieved at several levels. First, at the system level BATC transitioned from a single cooler mechanism to a mechanism pair. This has brought down the imparted loads by allowing for the design of effective actuation control architecture with reaction cancellation over the frequency range of interest. In addition, the design of a soft mount system has provided additional reduction of the exported loads.

<u>Isolation in Reaction wheels</u>

Jitter due to reaction wheel vibration is isolated through constrained-layer flexures. The flexures were developed during a BATC R&D program in which three competing designs were proposed. The final design retained for testing was produced in collaboration with CSA Engineering and was built to flight hardware standards using materials with proven flight heritage.

The jitter isolation mounts are an assembly of soft flexures that attach between a reaction wheel and the spacecraft interface, providing low frequency isolation in the six degrees of freedom, yet they deliver relatively high second order spring surge modes. Thus, by design, jitter isolation mounts have their first six modes below 10 Hz and all subsequent modes above 100 Hz.

The final jitter isolation mount design, shown in Figure 9, is a hexapod of six struts configured in a Stewart platform. Each strut is made of two centrally connected rings of 10-mil (.025-mm) thick 3M ISD142R viscoelastic layer constrained between two 9-mil (.23-mm) thick and 0.5-in (1.3-cm) wide 300-series stainless steel sheets.

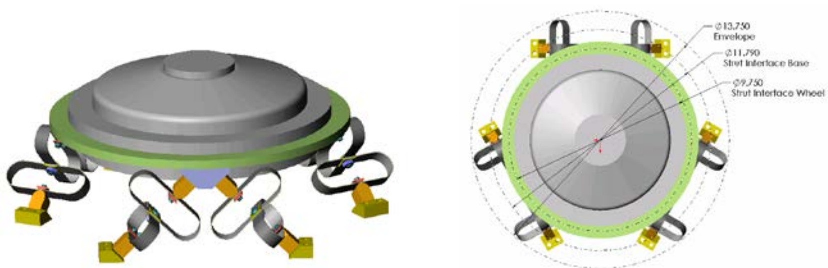

Figure 9. BATC Robi Wheel on jitter isolation mount

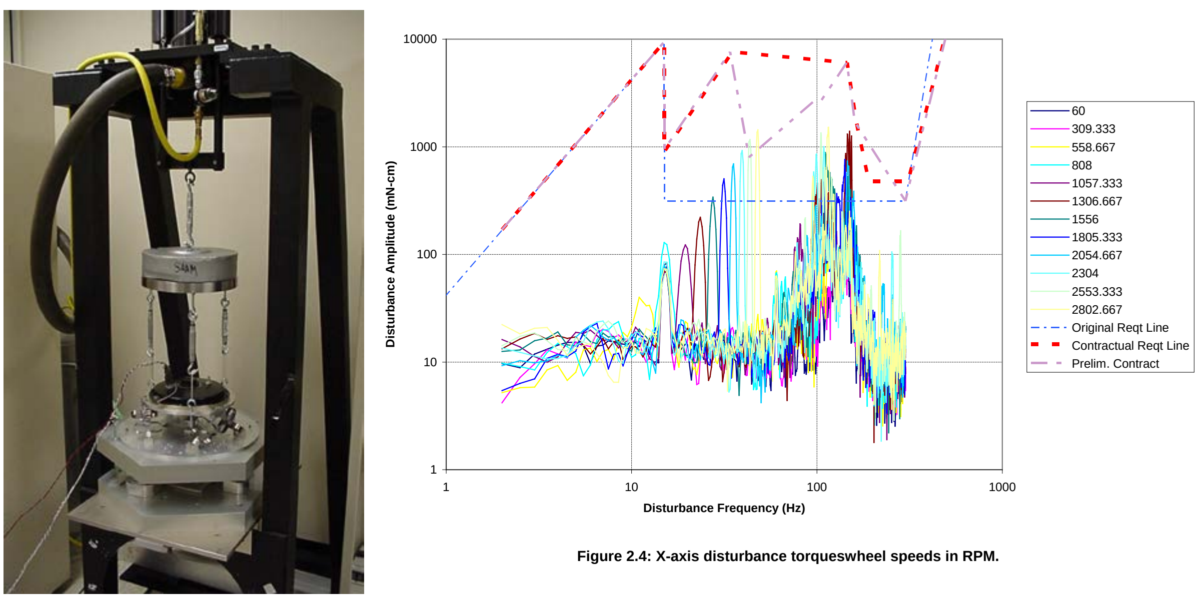

Figure 10. BATC Robi Wheel on jitter isolation mount and zero-*g* air lift (left) and typical requirement program verification (right).

Conclusion

Ball Aerospace & Technologies Corporation made substantial capital investment to develop good control of exported forces and torques from space mechanisms. And over the past decade, there has been a continuous improvement of the hardware and analysis tools used to develop advanced verification capabilities.

In order to meet a wide range of jitter requirements from multiple programs, BATC elected to have the capability to rapidly design custom FMPs for each application by combining modular hardware. This choice prompted the development of a facility with tool kits of multiple input channels, sensors of different capacity and sensitivity, high-performance filters, shakers of different sizes, and data acquisition systems. The EFT facility at BATC includes soft tables for the elimination of environmental disturbances. In the pursuit of quietness, testing has been carried in several environments, such as a massive reinforced concrete pit and vacuum chambers. Recently, the EFT facility has successfully characterized BATC's line of cryocoolers, shutter mechanisms and performed static and dynamic balancing of rotating instruments, to name a few.

FMPs have the advantage of providing resultant jitter forces and moments imparted by a mechanism either directly at its mounting interface or at a higher assembly interface, depending on what is tested. Other methods of jitter verification, such as those based on the recovery accelerations or motions, from accelerometers or transducers would have the disadvantage of being indirect methods and are therefore less reliable. The main disadvantage of FMPs is in the introduction of additional spectral content from the measuring device itself. However, such addition is monitored and separation from the frequency band of interest is one of the elements of the design process. FMPs may be considered complex to develop. However the return on investment is quite important, especially when high performance is required from precision mechanisms and instruments.

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