# A SURVEY OF REACTION WHEEL DISTURBANCE MODELING APPROACHES FOR SPACECRAFT LINE-OF-SIGHT JITTER PERFORMANCE ANALYSIS

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## 1.0 ABSTRACT

The National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) are planning spaceflight missions that will operate high-performance optical payloads with highly vibration-sensitive scientific instruments for Space Science and Earth Science observations. Accurately predicting spacecraft jitter (i.e., micro-vibrations) due to on-board internal disturbance sources is a formidable multi-disciplinary engineering challenge. This is especially true for observatories hosting sensitive optical instrument payloads with stringent requirements on allowable line-of-sight (LoS) jitter. Mechanisms mounted on the observatory's spacecraft bus are typically the source of jitter-producing disturbances. Historically, reaction wheels (RWs) have been the principal sources of spacecraft on-board disturbances on NASA and ESA missions. It is well-known that RWs can export undesirable torque and force disturbances into the spacecraft's flexible structure, perturbing an instrument's LoS pointing stability. Consequently, there is a critical need for high-fidelity RW disturbance models to support jitter analyses. This paper will first explicate the importance of RW disturbance modeling, then survey methodologies and approaches developed over the past two decades for modeling RW disturbances. Both empirical and analytical models of RW disturbances will be discussed. Some observations on RW disturbance modeling will be provided for the community's consideration.

## 2.0 INTRODUCTION

There is a continual trend by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) to push toward higher-performing payloads and instruments on the next generation of space and Earth science missions. The result is increasingly demanding requirements for science/observational image quality, image registration, and image navigation. We can think of "image quality" as having to do with short-term instrument LoS displacements that occur during the image integration time, whereas "image registration" primarily concerns longer-term displacements of the instrument between successive image acquisition times. Platform attitude knowledge and instrument pointing knowledge are the drivers for "image navigation."

This paper is concerned with the reaction wheel (RW) disturbances that directly impact image quality. This is because trends are moving toward more capable imaging systems with increased focal plane detector resolution and sensitivity. In addition, these more capable systems are being used to observe fainter objects. This could result in longer image integration times, usually leading to space observatories with more demanding performance requirements for tighter instrument pointing stability and allowable line-of-sight (LoS) jitter. Future missions, such as those illustrated in Fig. 1, will demand higher-performance Guidance, Navigation, and Control (GN&C) systems for their space-based observatories. For example, the Habitable Exoplanet Observatory (HabEx) is a NASA decadal survey concept under study at the NASA Jet Propulsion Laboratory (JPL) to directly image Earth-sized exoplanetary systems around Sun-like stars. HabEx must be designed to manage LoS jitter to within 0.1 to 0.5 milli-arcseconds to achieve the desired exoplanet image quality.

The GN&C design process for these type of ultra-fine pointing missions will require highly accurate modeling of micro-vibration disturbance environments on each observatory to fully understand and mitigate impacts to image quality. It is generally true that each observatory has a unique micro-vibration disturbance environment to be examined and characterized. Micro-vibration-inducing disturbances can arise from bus-mounted rotating mechanical devices, such as RWs and/or momentum wheels (MWs), and also such devices as cryocoolers and cryopumps. Other micro-vibration sources could include internal payload mechanisms and appendage drive mechanisms.

## 3.0 MOTIVATION

Predicting, managing, controlling, and testing spacecraft micro-vibrations caused by on-board internal disturbance sources is a formidable multi-disciplinary system engineering challenge, especially for observatories hosting sensitive optical sensor payloads with stringent requirements for allowable LoS jitter. Although individual projects may have their own mission-unique definitions of "LoS jitter," one can generally consider this to be undesired motion of a payload's sensor optical boresight axis over the duration of the sensor's focal plane integration time. The performance impact of micro-vibrations is clearly depicted in Fig. 2, where time-varying LoS pointing

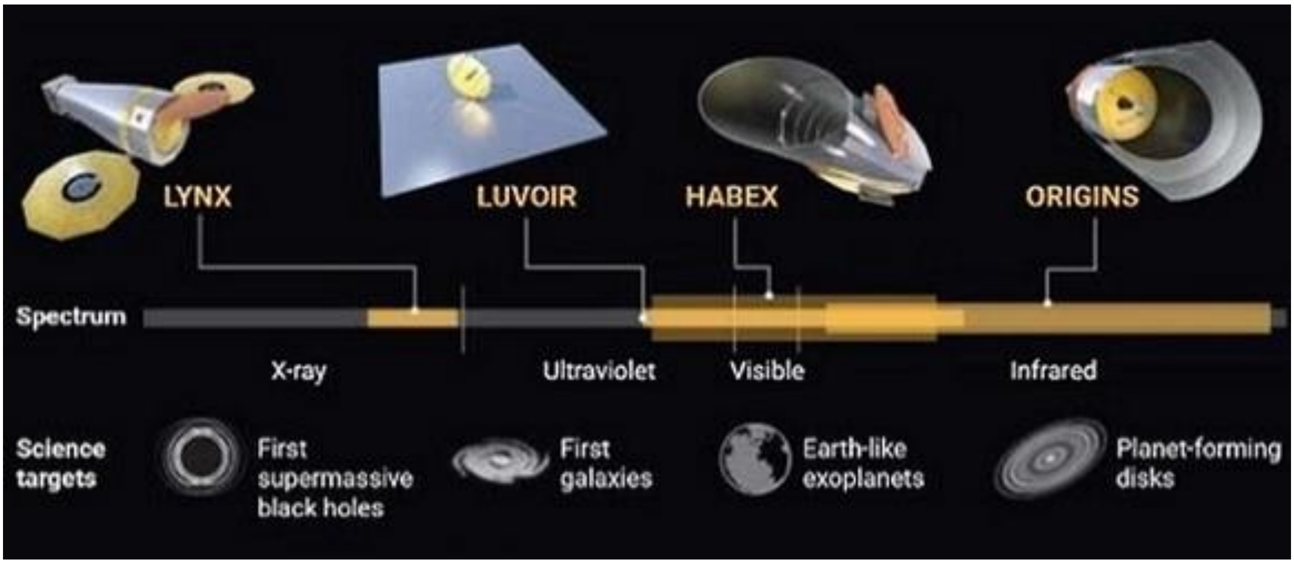


*Figure 1. NASA Decadal Survey Large Mission Concept Studies with Challenging Pointing Stability Requirements*

(i.e., centroid jitter on the focal plane) is illustrated on the figure's left [1]. The right side of the figure compares the relative quality of three images (from left to right): with significant micro-vibration perturbations, when measures had been applied to mitigate the perturbations, and lastly when the imager LoS was undisturbed during the image-taking period.

The primary motivation for this paper stems from the fact that, with the partial exception of [1], the GN&C community of practice lacks practical knowledge references to aid engineers in understanding, analyzing, and managing spacecraft jitter. The reality appears to be that only a handful of government and industry subject matter experts are called upon time and again to solve complex spacecraft jitter problems. Solving the spacecraft LoS jitter problem, a major part of which typically is modeling RW exported disturbances, entails the application of flight-proven methodologies and techniques from previous missions. However, many of these methodologies and techniques are not readily accessible, thus creating the need to capture and transfer this knowledge to the next generation of spacecraft jitter analysts. Frankly, much of this detailed knowledge is treated as proprietary information across industry and is often closely held by the various spacecraft engineering organizations.

It should be noted, however, that some outstanding work has been done by ESA engineers to document good micro-vibration practices and lessons learned from a mechanisms perspective [2]. In some relevant related work, a multi-disciplinary team of ESA mechanisms, attitude control, and systems engineers recently studied

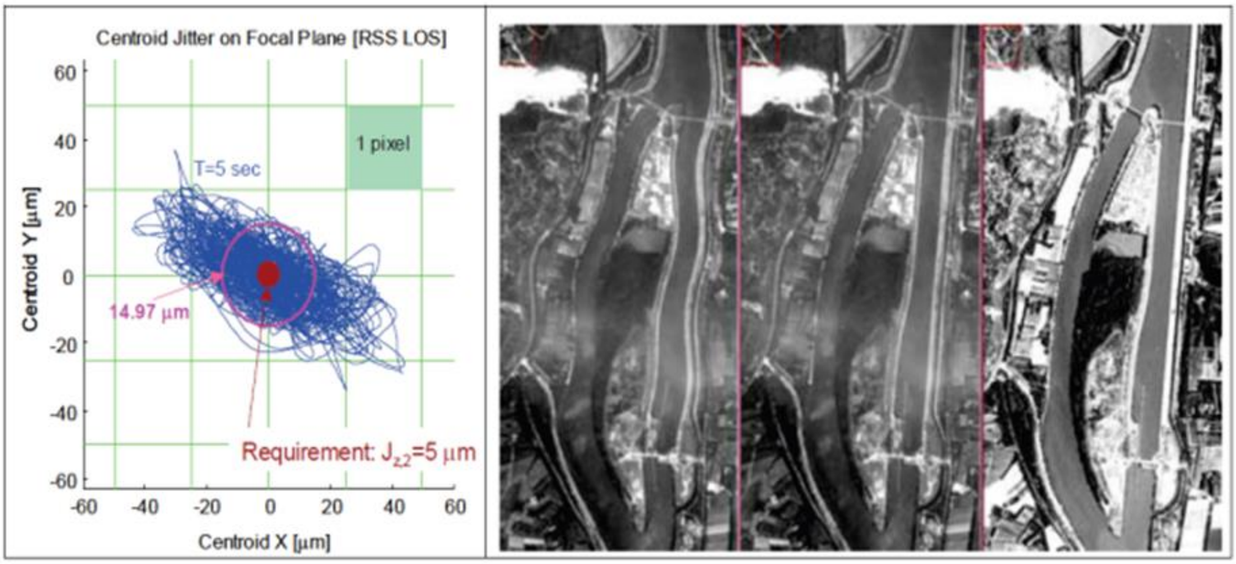


*Figure 2. Example of LoS Pointing Errors and Resulting Effects on Image Quality [1]*

the ways in which requirements on allowable exported micro-vibration from a mechanism disturbance source are at least partially influenced by a spacecraft's attitude determination and control system (ADCS), revealing the difficulties a mechanisms engineer may encounter when trying to verify these requirements [3]. The work provides fresh insights into deriving an exported micro-vibration requirement in a way that satisfies pointing performance without needlessly complicating the task of the mechanisms engineer.

Recognizing the challenge of capturing the knowledge behind understanding and managing spacecraft LoS jitter, the author and his JPL colleague, Dr. Oscar S. Alvarez-Salazar, in 2018 surveyed spacecraft micro-vibration problems, experiences, potential solutions, and lessons learned in the hope of leveraging this information on new system development projects [4]. In addition, the NESC GN&C Technical Discipline Team (TDT) recently sponsored the development of a "Jitter 101" process overview by the Aerospace Corporation [5]. This is a step in the right direction, but more work is needed to capture and disseminate jitter engineering knowledge.

Another strong motivation for this paper arises from discipline-advancing research work sponsored and performed by the NESC over the past two years to identify, investigate, and develop new "low-jitter" NASA science observatory GN&C system architectures. In 2017, the GN&C TDT conducted a preliminary feasibility study on the benefits of cold-gas micro-thrusters for spacecraft fine-pointing control in comparison to RWs [6]. In the study, low-fidelity, rigid-body models of the Wide Field Infrared Survey Telescope (WFIRST) and Microscope spacecraft were built in a simulation, and fine-pointing control was simulated using cold-gas micro-thrusters and RWs (operating separately). Encouragingly, the simulation results clearly showed the advantages of cold-gas micro-thrusters over RWs, but the limited fidelity of the simulation left important questions unanswered.

To address some of those questions, the NESC GN&C TDT is now engaged in a higher-fidelity follow-on assessment, titled *"Micro-Thrusters for Low-Jitter Space Observatory Precision Attitude Control."* This study further investigates the potential micro-vibration disturbance environment reduction benefits of micro-thrusters versus RWs. The team is studying competing science observatory GN&C system architectures, comparing the traditional use of RWs for precision attitude control during science imaging periods with electric propulsion (EP) colloidal technology micro-thrusters for precision attitude control. ***As part of this ongoing NESC study, the subject of RW disturbance modeling has risen to the forefront.***

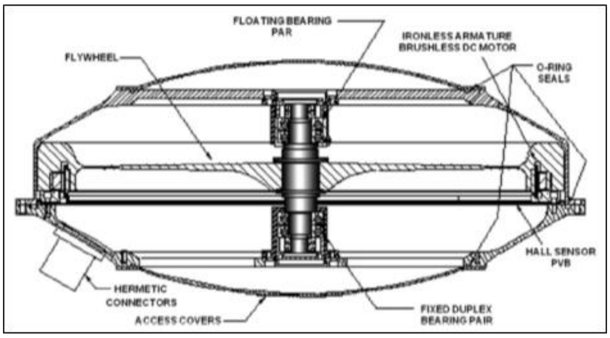


*Figure 3. Cutaway Drawing of a Typical RW Showing Shaft-Mounted Flywheel [16]*

RW disturbances will be modeled with higher fidelity than in 2017, with the NESC team adding several effects not previously included [7]. The objective is a direct comparison of the on-board micro-vibration disturbance environment from RWs with the disturbance produced by EP colloidal micro-thrusters.

## 4.0 BACKGROUND

RWs are rotating mechanisms commonly used by spacecraft GN&C engineers as attitude control actuators for performing large-angle spacecraft attitude slews and precision attitude control/pointing stability functions. In its most basic form, a RW consists of a direct current (DC) brushless motor-driven, high-inertia flywheel (also referred to as the "rotor") mounted inside a housing. The flywheel is shaft-mounted and typically suspended on a grease- or oil-lubricated set of rolling element ball bearings, allowing it to freely spin about one axis. RWs are momentum exchange devices that produce control torques, about a single axis, on the spacecraft (by virtue of Newton's third law of motion) and absorb angular momentum due to externally applied disturbance torques (e.g., torques caused by solar radiation pressure) acting on the spacecraft. RWs are the virtually ubiquitous spacecraft attitude control torque actuators because, unlike thrusters, they require no propellant—always a limited resource on spacecraft. Multiple RWs, usually arranged in a four-wheel pyramidal configuration[1], are typically mounted on a spacecraft bus for the purpose of three-axis platform stabilization. Fig. 3 is a cutaway illustration of a typical RW, showing the shaft-mounted flywheel; Fig. 4 shows one type of RW mounting on a spacecraft bus.

It has been well known for decades that RWs can export undesirable torque and force disturbances that can perturb an instrument's LoS stability. RWs have been the principal sources of spacecraft on-board disturbances on many NASA and ESA missions. This is a general observation, and each observatory will have unique sources of LoS pointing disturbances. However,

[1] NASA's James Webb Space Telescope has six Rockwell Collins Deutschland GBMH (formerly Teldix) RWs.

one can state with certainty that characterizing the nature of RW disturbances is a critical step in observatory jitter analysis. High-fidelity modeling of RW disturbances has grown more important, as NASA and ESA missions now being formulated will have more stringent pointing stability requirements than previously flown.

Analysts need to know how best to model RW disturbances for their particular mission application as a function of the program/project lifecycle. Analysis efforts occurring early in the lifecycle, for example during a mission's formulation phase, may have only simple low-fidelity RW disturbance models to use in simulations of spacecraft LoS jitter. Obviously, jitter analysts will strive to leverage similar RW disturbance modeling work from previous missions. However, some early observatory design decisions might rely on analysis conducted with RW disturbance models with lower-than-desired fidelity. The limitations of these lower-fidelity models should be clearly highlighted for and communicated to program/project decision-makers. Typically, higher-fidelity RW disturbance models are developed and employed in the preliminary design phase of the mission lifecycle to provide refined predictions of spacecraft LoS jitter and aid program/project decision-makers by technically informing the wheel selection process for a given mission application.

Jitter analysts may not always have to develop the higher-fidelity RW disturbance models themselves. The delivery of high-fidelity proprietary RW disturbance models, typically provided by a vendor under the constraints of a non-disclosure agreement, can often be negotiated. It is imperative that project jitter analysts know specifically what is included in a proprietary RW disturbance model. This can be problematic if the model supplied is a "black box" input-output representation with underlying wheel disturbance physics masked. In the author's view, the GN&C community of practice would benefit from a common scalable open-source RW disturbance model, clearly defined and documented, to support initial assessment of pointing/pointing stability performance in early mission concept studies. Obviously, this open-source model would need to be tailored by jitter analysts to match particular applications, but such a model could provide a common starting point for many missions.

## 5.0 RW DISTURBANCE MODELING

The RW disturbances are of variable frequency, unlike the disturbance frequencies generated by control moment gyroscopes and cryocoolers, which tend to operate for long periods of time at the same fixed speed of motion. Managing and mitigating the disturbances of the constantly running variable-speed RWs tends to be difficult. As will be discussed in the next section, a RW will, over its range of rotating speeds, produce a fundamental disturbance harmonic at the wheel rotation rate along with several sub/super harmonic tones. These harmonic disturbance tones may excite (i.e., couple with and amplify) spacecraft flexible structural modes, causing micro-vibrations at critical payload instrument optical path locations. Uncertainty in predicting RW harmonics and sub-harmonics can lead to higher levels of GN&C system design conservatism. Verification that a system meets the required jitter specification involves propagating all jitter sources through the structure, from their source (e.g., RWs and mechanisms) to the instrument, and comparing results to requirements. Conventional analysis assumes a rigid point-mass RW with the exported force and torque from flywheel mass imbalances propagating from the RW location through the flexible spacecraft structure to the particular node of interest where amplitude of jitter is to be predicted.

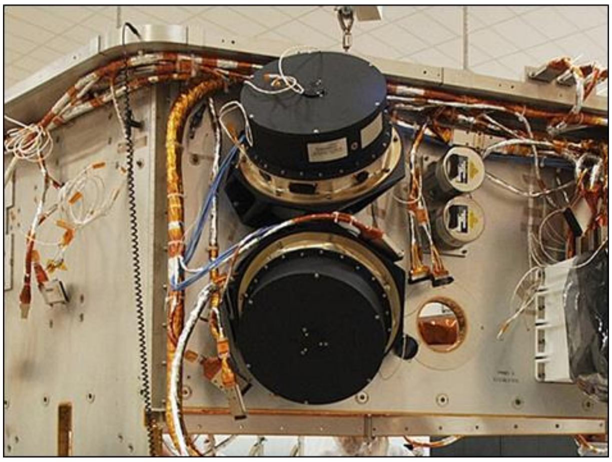

*Figure 4. RW Pair on the Kepler Spacecraft Core Structural Panel (Photo Credit: Ball)*

### 5.1 Origins of RW Disturbance Modeling

This section will discuss how RW disturbances can originate from various wheel-internal sources, such as inertia wheel imbalance, bearing torque noise due to imperfections, bearing friction effects, motor torque ripple, and motor cogging. An accurate RW disturbance model will account for most, if not all, of these sources. Given the predominance and significance of RW-induced disturbances on observatories, the literature is populated with detailed technical information on the nature of RW disturbance characterization, analysis, and modeling [10-32]. As generally described in the cited references, it is fortunate for jitter analysts that the root sources of disturbances in rotating mechanisms, such as RWs, tend to adhere to established and well-understood rules of physics.

A comprehensive literature search was performed in the preparation of this paper. One objective was to ascertain when technical literature on the topic of RW disturbance modeling first entered the public domain. A 1975 report identified in the course of the search [8] documented one of the first known activities to measure RW-emitted forces and torques about three orthogonal axes during constant wheel speed operation, as well as during acceleration and deceleration. This work was performed by Sperry Flight Systems for NASA's Marshall Space Flight Center to provide measured RW disturbance data to prime contractors for the Large Space Telescope (LST) Phase B studies. Of course, LST would become better known as the Hubble Space Telescope.

Not long after that, in 1982, we find Bosgra and Prins documenting their research into the testing and investigation of force and torque "irregularities" in running RWs [9]. This work was performed at the Space Department of the National Aerospace Laboratory in The Netherlands. The authors discuss the measurements and statistical analysis of RW exported force and torque data taken on six contemporary (early 1980s) European wheels, both with ball bearing suspensions and, interestingly enough, magnetic bearings. The RWs tested also had a combination of DC and alternating current (AC) drive motors.

While not specifically addressing the mathematical modeling of RW disturbances, these early historical examples demonstrate intellectual curiosity and interest in better understanding the nature of RW force and torque disturbances dating back at least four decades within the GN&C community of practice.

The mathematical basis for analytically modeling RW disturbances can trace its origins in the literature to the excellent work documented in the United States by Bialke in the mid- to late 1990s [10-13]. In [12], for example, Bialke provides one of the earliest detailed descriptions in the open literature of the constituent elements in a RW disturbance model. Reference [12] documents the fundamental relationships for a simple "design" type model of a RW system. Fig. 5 is a detailed time-domain block diagram that effectively defines Bialke's detailed mathematical model of a typical RW. The details of the individual elements of this block diagram are discussed in detail, and the data constants are also provided in [12] for two representative industry standard RWs that were available in 1998. Similarly, Heimel and other Europeans wrote at around the same time about the micro-vibration characteristics and microdynamic behavior of MWs and RWs [14-15].

These early sources provide fundamental information. As described in [10-15], the primary root-sources of disturbances in rotating mechanisms such as RWs are:

1) Flywheel mass imbalances, both static and dynamic. These are often the most significant source of disturbances emitted by a wheel. Essentially, as depicted in Fig. 6, static imbalance concerns the offset of the flywheel's center of gravity from its rotation axis. The result is a once-per-flywheel-rotation radial force

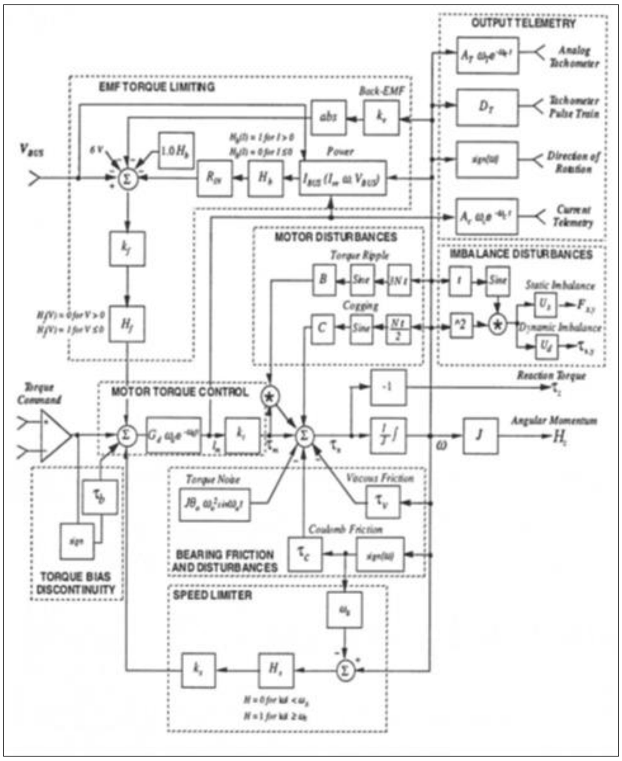


*Figure 5. Time-Domain Bock Diagram Defining Bialke's Detailed Model of Typical RW [12]*

disturbance. The dynamic imbalance concerns the wheel product of inertia about its rotation axis, also shown in Fig. 6. The dynamic imbalance results in a once-per-flywheel-rotation torque disturbance. During the manufacturing process, RWs are balanced by the vendor to meet customer-imposed imbalance specifications. However, vibration forces and torques emitted by even a well-balanced RW can degrade the performance of precision instruments on observatories. Thus, for vibration-sensitive mission applications, fine-tuning of static imbalance to improve the levels by a factor of 2 to 5 can be performed after the bearings are installed [12]. Of course, such fine-tuning will likely incur additional cost and extend the wheel delivery schedule.

2) Ball-bearing imperfections in the inner and outer races, as well as the balls themselves and even the bearing cage. These imperfections include ball defects, surface roughness, out-of-roundness, and mechanical run-out. Such irregularities can produce disturbances at the sub-harmonic and higher-order harmonics of the RW rotation rate. Typically, disturbances produced by bearings are of secondary importance, but as RW manufacturers improve their ability to mass-balance their wheels, bearings could eventually become the dominant disturbance torque [21].

3) Bearing viscous and coulomb friction effects. In a RW motor, the effects of friction can be broken down into viscous friction, which varies with speed and temperature, and coulomb friction, which is constant

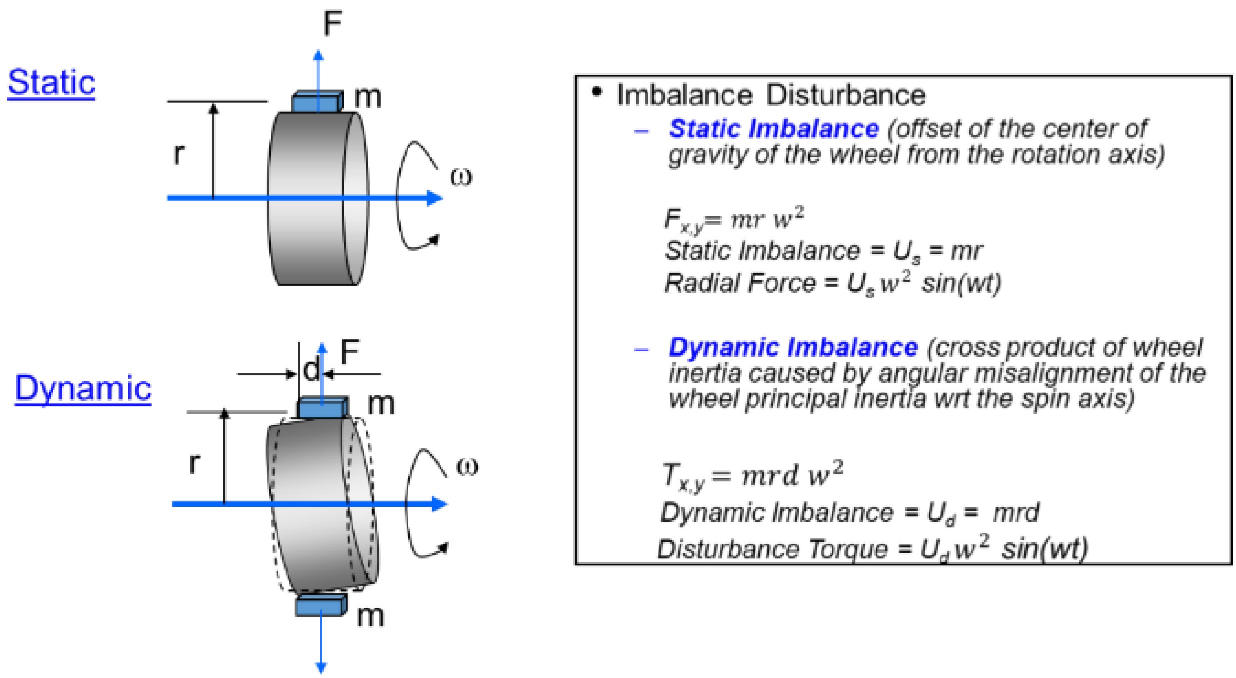


*Figure 6. Force and Torque Disturbances Due to Static and Dynamic Imbalances [7]*

with polarity dependence on the wheel's direction of rotation. Stiction and Stribeck friction effects are rarely seen. Any detailed modeling of friction (e.g., developing a LuGre friction model) is generally unnecessary.

4) Torque ripple. This is caused by high-frequency phase switching in a brushless DC motor between stator phases upon passage of the rotor's magnetic poles. Torque ripple represents the amount of variation in motor torque due to the particular commutation method used and the shape (e.g., sinusoidal) of the back electromotive force. The magnitude of the torque ripple is inversely proportional to wheel speed, which can be significant when operating near zero. Since resonances are at a minimum near zero wheel speed, analysts have a solid rationale to exclude this disturbance source from jitter predictions [21].

5) Cogging torque: Also called "detent," this disturbance is present in a conventional brushless DC motor. It is due to the change in reluctance of the iron stator as the magnets are rotated at a frequency corresponding to the number of poles in the rotor and teeth in the stator [12]. It is thus independent of wheel speed, and ironless motor designs have no cogging torque.

Regarding zero RW speed, it should be noted that this paper will not address the nature of the RW disturbance at low or zero wheel speed, assuming that good practice would ensure that RWs operating on the observatory during precision pointing science observational periods would be maintained well above zero speed and simultaneously well away from speeds that could excite observatory structural vibrations that could contribute to LoS jitter. This operational approach would avoid bearing-induced disturbance while crossing through zero wheel speed when changing the wheel rotational direction. A simple bearing disturbance model during RW spin direction reversal, however, is provided in [10].

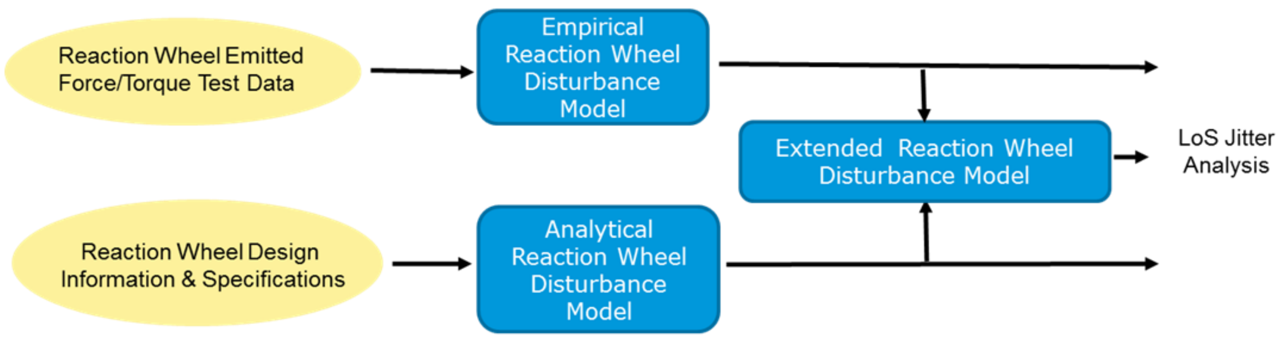


*Figure 7. Types of RW Disturbance Models Used in Jitter Analysis [16]*

In closing this section, the author wishes to mention the excellent 2011 paper from Heimel, which documents “spacewheel” micro-vibration sources and counter-measures, not from the GN&C engineering or jitter analysis perspective, but rather from the pragmatic and practical point of view of a RW manufacturer. It makes sense to highlight here Heimel’s “Golden Rule of Wheel Noise Mitigation at the Source”—simply put, to keep a wheel quiet, treat it gently.

## 5.2 Empirical RW Disturbance Model

It is clear from the abundant literature that the community has developed multiple RW disturbance modeling approaches. Two major types of RW disturbance models exist: analytical and empirical models. These are depicted in Fig. 7 along with a third type, the extended model, which is a hybrid combination of the first two. The empirical model represents steady-state wheel harmonic disturbances, and it is developed from RW disturbance characterization test data. The analytical model is a physical model derived from solving a set of coupled rotor dynamics system equations of motion, and captures not only the fundamental harmonic but also the wheel structural modes. The extended model combines the empirical and analytical models, representing all harmonics and wheel structural modes.

From RW emitted force/torque characterization testing, it is well known that RW disturbances are tonal in nature. The empirical model captures this aspect of wheel behavior. So-called “waterfall plots” are often used to display the overall tonal signature of a given RW disturbance. Fig. 8 shows a waterfall plot developed from frequency domain RW disturbance test data that displays the distinct ridges of disturbances occurring at frequencies that are a linear function of wheel speed [16]. The empirical model is built by extracting model parameters/coefficients from steady-state RW disturbance test data. A fundamental empirical model assumption is that the disturbances can be represented by discrete harmonics of the RW speed with amplitudes proportional to the square of the wheel speed.

The empirical model thus represents the harmonic quality of RW disturbances, i.e., it accurately identifies multiple disturbance frequencies and provides an estimate for the amplitudes at those frequencies [16]. Empirical models are typically steady-state representations for a given set of discrete wheel speeds, and do not reflect transient behavior during periods of wheel speed changes.

Empirical models are useful to analysts in the way they represent RW disturbance in discrete harmonic forms. However, and most importantly, the empirical model does not account for the internal flexibility of the RW itself. This can result in large disturbance implications at some wheel speeds. In her ground-breaking research into RW disturbance modeling in the late 1990s and early 2000s at the Massachusetts Institute of Technology (MIT), Masterson found that the typical empirical model severely underpredicts the data for wheel speeds at which resonance interactions occur between bearing harmonics and flywheel structural modes [16].

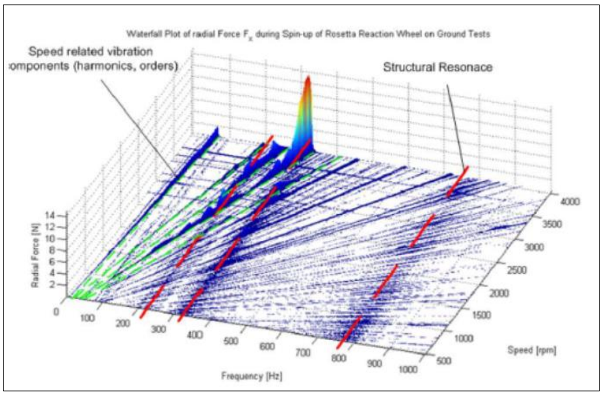


*Figure 8. Waterfall Plot Revealing the Tonal Signature of a Typical RW Disturbance [19]*

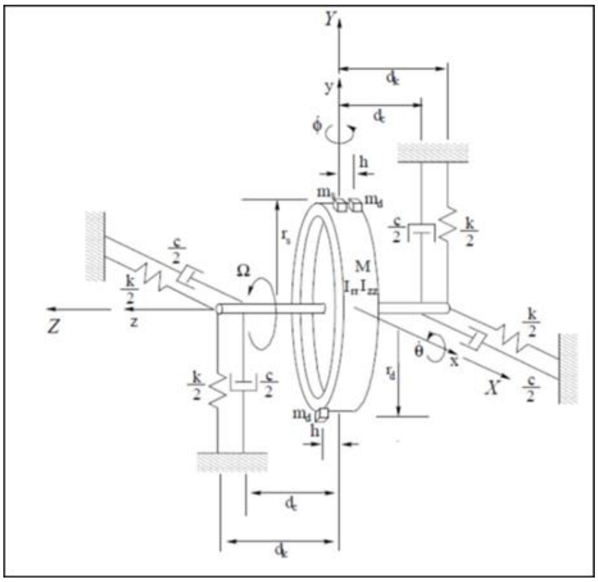

*Figure 9. Analytic Model of a Balanced Flywheel on Flexible Supports [16]*

## 5.3 Analytical RW Disturbance Model

The analytical model uses principles from rotor dynamics to model structural wheel modes. The model is developed with energy methods, and captures the internal flexibilities and fundamental harmonics of an imbalanced wheel. A parameter fitting methodology extracts the analytical model parameters from steady-state RW vibration data.

Analytical models of RW disturbances use physical representations of rotating machinery dynamics. As depicted in Fig. 9, the RW can be modeled as a symmetrically balanced flywheel rotating on a rigid shaft, with linear springs and dampers included to represent shaft and bearing flexibility. The most significant disturbance source, flywheel mass imbalance, is modeled with lumped masses positioned strategically on the wheel. The equations of motion of the full system are solved using energy methods (i.e., Lagrange's equation) or the Newton-Euler method [31]. One significant challenge of the analytical modeling approach is that numerous parameters must be determined accurately.

Subsequent to Masterson's research, other researchers have investigated RW gyroscopic effects and their impact on dynamic interactions between the RW itself and the supporting spacecraft structure [21-25, 29-32]. After all, a RW is a rotary machine device, and rotor dynamics should be accounted for to completely capture the coupled dynamics.

All RWs have inherent structural vibration modes. Some conventional RW jitter analysis methodologies consider the static and dynamic imbalance of the flywheel but ignore the flexible modes of the flywheel and housing assembly as well as the gyroscopic effects of the rotating flywheel. Fig. 10 illustrates the three dominant RW structural modes to be captured in an analytical model. These are the radial (lateral) and axial flywheel translation modes, as well as the radial rocking mode due to gyroscopic torque from the rotating flywheel precession. In the context of jitter analysis, the radial rocking mode is of the greatest impact, hence our interest. The underlying mathematical and rotor dynamics details are well beyond the scope of this short survey, but the essential ramifications of RW flexibility can be concisely summarized as follows, based upon the excellent analysis and modeling of the rocking whirl phenomena by Lee and Warner [21].

When the flywheel is rotating, internal RW flexibility in the shaft and/or flywheel naturally leads to precession. The result is the generation of a gyroscopic torque exerted on the spacecraft body through the RW mounting mechanical interface to the bus. The frequency of this gyroscopic torque is the natural frequency of the radial rocking mode, which itself is a function of the RW's rotation rate. Thus the properties of the systems dynamics will vary over time as a function of wheel speed.

If the wheel speed coincides with the frequency of this rocking mode, resonance will occur. The jitter amplitude at this resonance depends on modal damping. The fundamental problem, however, is that jitter amplitude can grow excessively if the RW operation dwells on this resonance-inducing speed. Similarly, if the bearing excitation harmonic frequency matches the rocking modal frequency, resonance again results.

The situation becomes even more intriguing when we observe that the mathematical formula describing the natural frequency of the rocking mode, Eq. 3 in [21], has two possible solutions: one representing the forward whirl of the rocking mode and the other representing the backward whirl. The solution is a combined function of wheel speed, the flywheel rocking (transverse) moment of inertia, the flywheel polar moment of inertia, and bearing support rotational stiffness. These two solutions display the bifurcation shown in Fig. 11 as the wheel speed increases. Note that the forward whirl natural frequency increases with wheel speed, while the backward whirl frequency decreases. According to Lee and Werner, the bifurcation is a consequence of the natural frequency depending not only on rotational stiffness, but also on the gyroscopic effect due to precession of the flywheel [21]. The terminology associated with these bifurcated rocking mode frequency solutions can differ. For example, Heimel refers to the "lower branch" (or negative whirl mode) and "higher branch" (or positive whirl mode) [22].

Resonance occurs whenever the wheel speed produces disturbances with frequencies coincident with any flywheel rocking mode natural frequency. This will likely not manifest itself as a jitter amplitude issue if the wheel speeds are being commanded by the spacecraft's ADCS to rapidly pass through a resonant frequency. Significant jitter could well occur, however, if and when

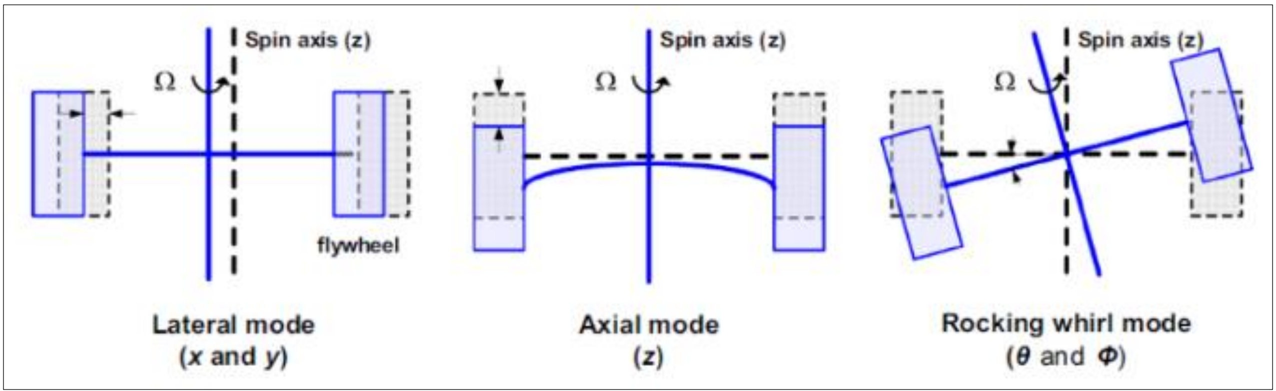


*Figure 10. The Three Dominant Structural Modes of a Typical RW [31]*

the ADCS commands a near-constant wheel speed over longer time periods at or near the resonance forward or backward whirl frequency. The wheel speeds where disturbance harmonics cross a flywheel rocking mode resonant frequency can be computed in a straightforward manner, as seen in Eq. 4 in [21].

The results can be plotted as illustrated in Fig. 12, showing, for a typical RW, where the intersections occur between the bearing harmonic lines and flywheel rocking whirl lines. The intersection between any harmonic line and the rocking natural frequency curve determines a resonant wheel speed. The rocking modes are illustrated by the forward and backward whirl natural frequency as a function of wheel speed. The bearing harmonic excitation frequency varies with wheel speed according to their harmonic number.

The higher bearing harmonics intersect the rocking modes at lower wheel speeds. It is important to note that the higher the bearing harmonic, the lower the resonant wheel speed. Lee and Werner rightfully point out that this observation goes counter to intuitive expectations that higher harmonic disturbances have higher frequency and therefore resonance can occur only if the speed is high enough to resonate [21]. Further, experience might lead one to believe that since the spacecraft structure has a larger attenuation due to roll-off, any excitation of that higher frequency should be benign. But intuition does not apply in this case.

From Fig. 12, one can make two fundamental observations. The first is that backward whirl contributes more to jitter because the resonances occur at relatively lower frequencies. The second observation is that backward whirl causes resonance with all bearing disturbance harmonics. Readers interested in obtaining additional insights into and analysis of the details of rocking whirl phenomena are directed to [21] and [22].

If rocking modes and bearing harmonic disturbances are not included to capture the rocking whirl phenomena effects in jitter analysis, then all the potential resonances depicted in Fig. 12 are therefore unconsidered. This leaves the door open for an analyst to underpredict in-flight jitter amplitudes. For high performance vibration-sensitive observatories, analysts should completely model the dynamic coupling between the RW and the spacecraft itself. At NASA's Goddard Space Flight Center (GSFC), the standard approach to fully represent RW disturbances involves coupling the Finite Element Model (FEM) of the RW itself to the observatory's FEM to form an integrated dynamic model of the RW-spacecraft system [33]. Along these lines, [21] outlines an excellent approach for combining a RW flexible body dynamic model with spacecraft flexible body dynamics.

### 5.4 Extended Model

In an extended (or hybrid) RW disturbance model, the key features of the empirical and analytical models are

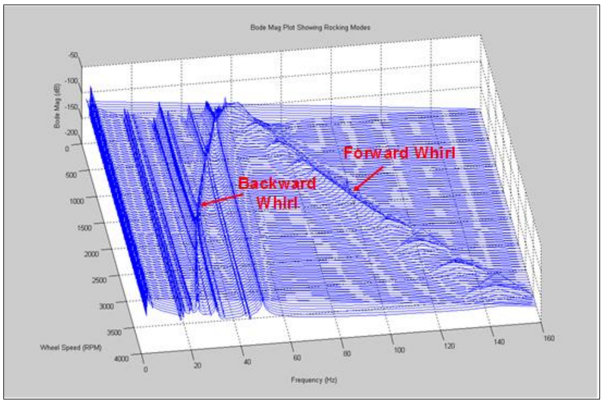


*Figure 11. Rocking Mode Frequency Bifurcation in a Typical Flexible RW [21]*

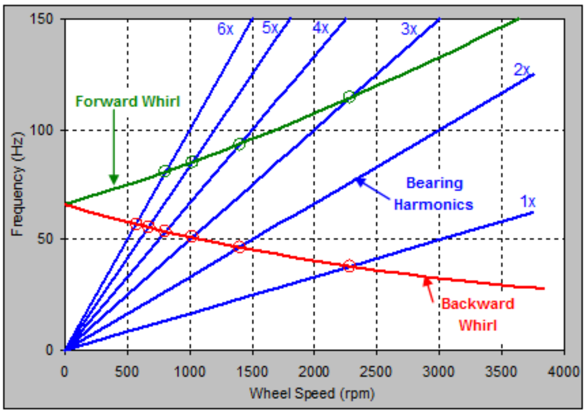


*Figure 12. The Resonant Intersection of Bearing Harmonic Lines with Rocking Modes in a Typical Flexible RW [21]*

combined. In this hybrid fashion, the extended model serves to capture all wheel harmonics as well as disturbance amplifications caused by harmonic excitation of the structural wheel modes. A good example of an extended RW disturbance model was developed at Bradford Space in The Netherlands by combining empirical and theoretical models [32]. This combined model was validated by tests on different types of Bradford RWs. The validated combined RW disturbance model is now being used to predict micro-disturbance performance for future RW designs.

## 6.0 OBSERVATIONS

For a given observatory, the jitter team should assess their mission-unique set of micro-vibration disturbance sources, then design a comprehensive, customized plan for their disturbance modeling campaign. This plan should include the associated component-level testing to inform and validate empirical disturbance models.

A technically sound RW disturbance modeling effort consists of analytical work and focused pre-launch ground testing. Since it is good engineering practice to anchor models with physical test data, it is fortunate that a number of ground-based micro-vibration test facilities can be used to characterize RW disturbances [34-39].

RW disturbances are difficult to model accurately since their frequency and magnitude change with wheel speeds. Disturbances can interact with wheel structural modes, greatly amplifying their disturbance level, and RW structural resonances can likewise contribute to the micro-vibration disturbance environment.

An cautionary observation regarding the characterization testing of RW-generated disturbances: Performance will be affected not only by the specific boundary conditions employed in the characterization test, but also potentially by selected test conditions for vacuum, temperature, and gravity effects [2]. Also, the disturbance generated by a given individual RW may vary over the course of the observatory's integration and test campaign due to the mechanical wear of internal components such as bearings and/or the bearing retainer. It is possible for the disturbance generated by a single RW to worsen after its initial run-in and subsequent use during multiple routine spacecraft bus ADCS tests. Also not to be overlooked is the potential for the disturbance produced by an individual RW to increase following exposure to the various system-level shock and vibration test environments (e.g., sine vibration, random vibration, pyro-shock) an observatory experiences in a typical spacecraft integration and test activity flow. RW disturbance characterization tests are recommended, where practical, between major shock and vibration mechanical tests [2]. This approach has the benefit of providing traceability to a specific test environment if post-test RW disturbance is significantly worse compared with its initial baseline.

Another cautionary observation is that seemingly identical RWs, such as those from a common manufacturing lot, may not be truly identical from a disturbance generation perspective. For example, [2] provides a plot of test data illustrating how eight seemingly identical RWs generate varied mechanical noise, differing by up to one order of magnitude in power spectral density. As shown, an unavoidable inherent variability will always exist between individual seemingly identical wheels, or, for that matter, between any other set of "identical" disturbance-generating mechanisms. It may be advisable, especially in a high-performance mission application, to perform disturbance characterization testing on more than one RW from a given large family of potential flight wheels to measure the range of wheel-to-wheel disturbance variability. Results from the testing of multiple wheels would directly support the process of "cherry picking" individual flight RW units based on their individually measured disturbance data.

On high-performance vibration-sensitive observatories, GN&C engineers may elect to employ some form of isolation system to mitigate the impact of RW disturbances. A RW disturbance model of reasonable fidelity is needed early in the formulation phase of a mission to determine whether an isolation system will be required to meet LoS pointing stability requirements. This is especially true for observatories hosting high-performance, vibration-sensitive instruments. For example, a two-stage passive vibration isolation system will be used on the James Webb Space Telescope to attenuate higher frequency (>2.0 Hz) micro-vibration disturbances associated with RW static and dynamic imbalances, as well as bearing run-out [40].

Care must be taken to fully model and test integrated dynamic behavior of the assembled RW-isolator system. Under certain dynamic conditions it is possible to worsen the disturbance environment. RW disturbances can potentially be amplified by the isolator structural modes coupled to the RW's wheel-speed-dependent gyroscopic effects. The dynamic coupling of the RW with an isolation system may introduce unexpected phenomena. A byproduct of passive isolation is that it can introduce new secondary modes in the system. For example, the Chandra X-ray Space Observatory encountered an unpredicted resonance condition during acceptance spin testing of its RW/isolator assembly [41]. As described in [41], subsequent forensic investigation revealed that the coalescence of the isolator rocking mode, wheel bending mode, and wheel spin inertia created an undesirable nutation condition.

It is highly desirable to establish quantitative uncertainty bounds for a given RW disturbance model before it is used in observatory jitter analysis. This is a challenging exercise, but it is important for a model user to know and understand the limits of the model being used to verify adequate in-flight jitter performance. A common practice is simply to determine if a model's disturbance predictions are qualitatively "in family" with previous model results. Accomplishing this objective of establishing quantitative uncertainty bounds is easier if a statistically significant set of RW characterization test data is available to process and evaluate. Planning and executing a sufficiently comprehensive disturbance characterization test campaign, perhaps employing statistically based design of experiments practices for bearing level and wheel level tests, would provide the solid data basis for uncertainty quantification.

A last observation is that the GN&C community of practice would benefit from having a scalable open-source RW disturbance model to support assessment of pointing and pointing stability performance in early mission concept studies.

## 7.0 SUMMARY

Some final key points for the reader's consideration:

**1)** There is a need for empirical and analytical RW disturbance models. The need for one or the other—or both—will depend on mission jitter requirements.

**2)** RW flywheel mass imbalances, both static and dynamic (caused by non-uniform flywheel mass distribution), generate micro-vibrations at a frequency synchronous to the RW rotation speed. These are often the most significant source of disturbances emitted by a wheel.

**3)** The cogging and torque ripple disturbances induced by RW motor and motor driver are typically insignificant contributors to jitter.

**4)** Conventional RWA jitter analysis usually considers the flywheel's static and dynamic imbalance, but ignores bearing harmonic disturbances and flexible modes of the flywheel and housing assembly.

**5)** One may not be able to ignore flexibility of the RW itself (i.e., the flywheel and housing structure flexibility) when modeling RW disturbance for jitter analysis in high-performance, vibration-sensitive observatories.

In closing, the author wishes to point out that RWs have been and will continue to be the workhorses for most spacecraft attitude control applications. However, as described by Heimel [22], science observatory missions with ambitiously stringent pointing stability requirements may decide to replace RWs with micro-thrusters. The ESA Gaia mission is a good example of migration to micro-thrusters for low-noise precision attitude control purposes [42]. The possibility of this trend continuing should be a sobering thought for RW designers and manufacturers. It should also motivate them to more vigorously explore ways to further reduce RW-generated disturbances. For example, the use of magnetic bearings might mitigate undesired RW exported disturbances.

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