Estimation of Mechanical Vibrations of the LHC Fast Magnetic Measurement System

Nathan R. Brooks, Luca Bottura, Juan G. Perez, Olaf Dunkel, and Louis Walckiers

***Abstract*—Current installation of the Large Hadron Collider (LHC) particle accelerator at CERN has required the use of a harmonic coil magnetic measurement system to quantify the magnetic field harmonic quality of the superconducting, twin aperture LHC dipoles. Current and future needs for measuring fast changing magnetic fields necessitates the use of a rotating unit (RU) and associated electronics to drive this long shaft with increased speed and measurement bandwidth. Therefore, the Fast Magnetic Measurement Equipment (FAME) project has been launched to deliver such a system. A primary obstacle to achieving the goals of the FAME project is the possibility of amplifying mechanical vibrations due to increased speeds. This paper presents the methodology and results of an experimental investigation conducted to estimate mechanical vibrations of the long shaft within a cold-bore mounted anti-cryostat at various rotational speeds using magnetic measurements.**

***Index Terms*—Harmonic coil, LHC, magnetic measurements, vibrations.**

I. INTRODUCTION

THE current rotating coil system utilized at CERN is based on a Twin Rotating Unit (TRU) [1]. This system consists of a motor unit that rotates a 16 meter long shaft composed of 13 coil-carrying hollow ceramic segments connected in series using flexible titanium bellows. For measurements of dipole magnets, each ceramic segment has 3 separate coils of wire mounted within it, 1 central coil and 2 tangential coils. The central coil is located along the central axis of the segment, while the tangential coils lie directly opposite of one another on the circumference of the segment. These coils cover the length of the segment and lie parallel to one another. During normal operation of the TRU, voltage signals produced in these 78 coils are read while the segments are rotated at a maximum speed of 1 turn/s to avoid mechanical vibrations that can cause measurement accuracy problems. The typical measurement time of this system is about 15 seconds (in the *washing-machine* mode, 3 turns in each opposite direction are performed in order to reach a constant speed of the coil before doing the acquisition). In addition, systematic errors can be reduced by taking the average of the backwards and forwards measurement. For the usual measurements on constant current dipoles and quadrupoles this time duration is considered acceptable. However, to fully analyze faster changing fields such as sextupole snap-back or future measurements of dynamic field magnets, such a system must be improved.

With this background in mind, we have started a project that aims at a the new generation of Fast Magnetic Measurement Equipment (FAME), to provide harmonic measurements at rates in the range of 1 to 10 Hz, thus allowing for the proper measurement of fast changing magnetic fields. Faster measurements require that the coils rotate continuously in one direction and at higher speeds. But, reaching higher rotation speeds also increases mechanical instability in the rotating system. Specifically, vibrations from any unbalances of the shaft segments, instability of the motor drive, along with large torques during acceleration and deceleration are of the most concern. Such movements can decrease the accuracy and repeatability of the measurement. Furthermore, if these movements are not controlled, damage to the shafts that are glued together can occur. Therefore, one key objective of the FAME project is to modify the current TRU system to investigate vibrations using magnetic measurements and apply the findings to the re-design of the new system. The modification of the original TRU resulted in a Fast Rotating Unit (FRU) capable of operating at rotational speeds near 8.0 Hz. This system was utilized to estimate vibrations of the measurement shaft within a fully-equipped dipole magnet.

II. VIBRATION MEASUREMENTS

The FRU was developed to characterize rotating coil measurement system performance at higher rotational speeds. Therefore estimating the level and impact of vibrations within the system is desired through the analysis of magnetic measurements. Using magnetic measurements instead of physical measurements is an optimal methodology. The natural operating environment of the measurement shaft is within a closed magnet. This makes physical measurements difficult, if not impossible.

A. Theory

For the sake of efficiency, the details of magnetic measurements using a rotating coil system at CERN are not discussed here. Details on the theory can be found in [2]. The discussion of the methodology used to determine vibrations from magnetic measurements will begin from the known characterization of the flux induced by an imperfectly rotating coil. This imperfection can be caused by many events. However, the end effect is a deviation in coil position. This deviation will be viewed as a vibration having a periodic occurrence. These vibrations can be the result of planar or angular deviations in position that ultimately

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produce spurious harmonics (measurement errors). We consider these vibrations to be periodic functions of the rotational angle θ. If we define the two complex quantity $\mathbf{D}$ and $\mathbf{T}$ for the transverse (planar) and torsional (angular) vibrations, respectively, their angular dependence can be decomposed in a Fourier series with complex amplitudes $\mathbf{D}_p$ and $\mathbf{T}_p$:

$$\mathbf{D}(\theta) = \sum_{p=-\infty}^{\infty} \mathbf{D}_p e^{ip\theta}. \tag{1}$$

$$\mathbf{T}(\theta) = \sum_{p=-\infty}^{\infty} \mathbf{T}_p e^{ip\theta} \tag{2}$$

According to [2], measurement of a pure $2n$-pole magnet in the presence of vibrations causes spurious harmonics of order m. Once expressed at a reference radius R_{ref} and for a certain coil sensitivity, $\mathbf{K}$, the spurious harmonics can be estimated as a function of either vibration modes $\mathbf{D}$ or $\mathbf{T}$. These harmonics are of magnitude and angle

$$\begin{aligned} &\mathbf{C}'(m)e^{-im\alpha'_m} \\ &\quad\approx (n-1)\cdot\left[\left(\frac{\mathbf{K}_{n-1}}{\mathbf{K}_m}\right)\left(\frac{\mathbf{D}_{m-(n-1)}}{R_{ref}}\right)C(n)e^{-in\alpha_n}\right. \\ &\qquad\qquad \left. +\left(\frac{\mathbf{K}^*_{n-1}}{\mathbf{K}_m}\right)\left(\frac{\mathbf{D}^*_{-m-(n-1)}}{R_{ref}}\right)C(n)e^{in\alpha_n}\right] \end{aligned} \tag{3}$$

$$\begin{aligned} &\mathbf{C}'(m)e^{-im\alpha'_m} \\ &\quad\approx in\left[\left(\frac{\mathbf{K}_n}{\mathbf{K}_m}\right)\mathbf{T}_{m-n}C(n)e^{-in\alpha_n}\right. \\ &\qquad\qquad \left. -\left(\frac{\mathbf{K}^*_n}{\mathbf{K}_m}\right)\mathbf{T}^*_{-m-n}C(n)e^{in\alpha_n}\right]. \end{aligned} \tag{4}$$

By quantifying the spurious harmonics found in a measurement, the vibrations, $\mathbf{D}$ and $\mathbf{T}$, can be inversely estimated. Using $\mathbf{D}$ and $\mathbf{T}$ the displacement of a coil's rotating axis in the horizontal direction can then be determined using (5), in the vertical by (6), and the angular offset of a coil's rotation can be determined using (7) as described in [3].

$$X(\theta) = \Re(\mathbf{D}(\theta)) \tag{5}$$

$$Y(\theta) = \Im(\mathbf{D}(\theta)) \tag{6}$$

$$\phi(\theta) = \Re(\mathbf{T}(\theta)) \tag{7}$$

B. Implementation

Evaluating the equations relating spurious harmonics to vibrations was done within a set of algorithms written in Matlab. The entire process includes calculating the measured harmonics and utilizing these harmonics to estimate vibration. The spurious harmonics found from the measurements are considered to be generated solely from angular movement or radial movement. This allowed a system of linear equations using (3) or (4) to be constructed for each spurious harmonic. This system of equations could then be solved to determine two vibrational modes for each spurious harmonic. These vibrational modes would be transverse or torsional depending on whether (3) or (4) was used. Once the vibration modes are determined, they are used to re-create the vibration signal with respect to angular position based on (1), (2), (5), (6) and (7). The results are estimations of vibrational movement during a measurement assuming that all vibrations are either radial or angular. The amplitudes of these re-created signals are then used to determine the behavior of the rotating system as a function of rotating speed.

III. MEASUREMENT RESULTS

A. Setup

Experimental measurements varied all measurement parameters including rotational speed, sampling frequency (encoder counts per turn), motor type, harmonic computation methodology, and shaft configuration. The following results represent a portion of the total number of measurements and processing done. To provide the best results for comparison, this selection consists of dipole harmonic measurements using feed-down correction, "bucking" coils, and an encoder trigger frequency of 128 points per turn.

Feed down correction is a numerical technique to reduce measurement error by finding the magnet center. "Bucking" coils are part of a compensation scheme to minimize error by wiring measurement coils in such a way to remove the main field from the signal to retrieve the higher order harmonics. Compensating the measurement signal with "bucking" coils helps to remove spurious harmonics introduced by other sources including vibrational movement and improve resolution of higher harmonics. Also, at the higher rotational speeds, only 128 points per turn could be used due to the limited sampling bandwidth of the integrator system. This restriction is one of many due to the use of the current PDI (Precision Digital Integrator) technology at high rotational speeds. Better measurements can be made with higher encoder resolution once the new integrator system, presently undergoing final commissioning tests, is available. Until then, 128 point measurements are used to provide an equal comparison of measurements at various speeds.

B. Results and Observations

Utilizing the aforementioned parameters, magnetic measurements were taken in a fully-equipped dipole magnet using the FRU and TRU. The FRU measurements were made turn by turn at speeds from 1 to 8 Hz. The TRU measurements were made without using the washing mode method (to better measure vibrational movement) at several speeds under 1 Hz. Using the "bucked" signals as harmonic references, the estimations of the angular vibration of a segment in the center of the long rotating shaft from the uncompensated signal can be seen in Fig. 1 as a function of rotating speed. The plotted data represents the maximum amplitude of the reconstructed vibration signals for each turn as described in (6).

It is obvious from Fig. 1 that increasing the operational speed increases the amount of torsional vibration. Specifically, after 3 Hz, the trend rises. Until 3 Hz, the existing vibration levels are in the same range as that of the standard TRU speeds (less than 1 Hz). Also, it is important to note that although there are some large torsional vibrations at the higher speeds, the spread of these measurements reveal that low angular deviation is possible.

One possible cause of the increase in angular deviation seen in Fig. 1 is an increase in motor instability. Fluctuations or large

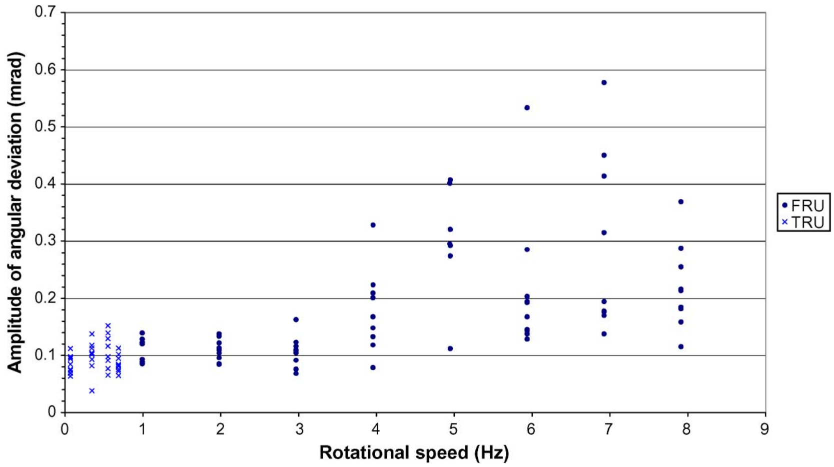

Fig. 1. Angular deviation of rotating segment (torsional vibration) as a function of rotating speed.

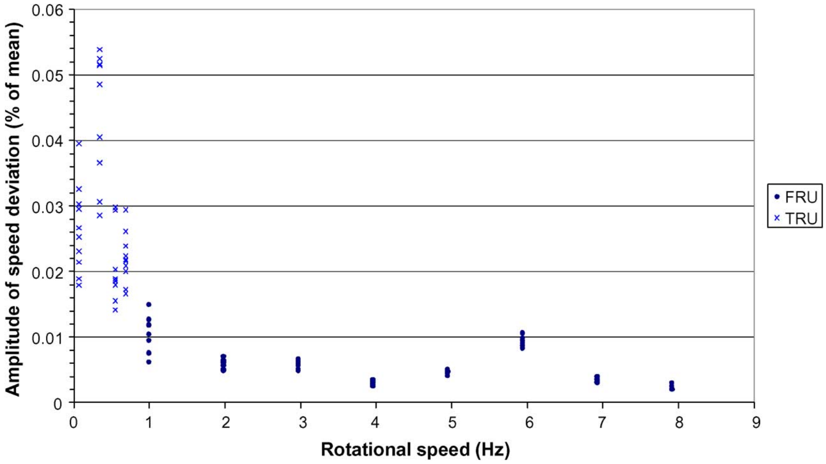

Fig. 2. Speed variation as a function of rotational speed.

variations in motor speed could cause twisting torques which together with shaft windup would cause an angular error. However, design and selection of the FRU included detailed dynamic considerations and a plot of the maximum speed deviation as a function of rotating speed seen in Fig. 2 proves that motor speed error is not the cause. In fact, the brushless DC motor used on the FRU provides more stable operations than that of the stepper motor used with the TRU. Furthermore, examination of the frequency spectrum of the speed (not shown) shows that there is no high frequency variation or "jitter" that would cause these vibrations.

Since the driving motor is not the cause, it can be assumed that the ceramic segments and their mounting accessories are the sources of this increased vibration. Given that each of the 13 ceramic segments of the rotating long shaft are interconnected using flexible bellows, there exists a natural frequency of the shafts which has been estimated to be near 6 Hz. As well, the ball bearings used in the mounting of the shaft and the flexible supports of the anti-cryostat in which the shaft rotates would also have a resonant frequency that could result in increased vibrations. See Fig. 3, reproduced from [1], to see the mechanical layout of the rotating shaft assembly.

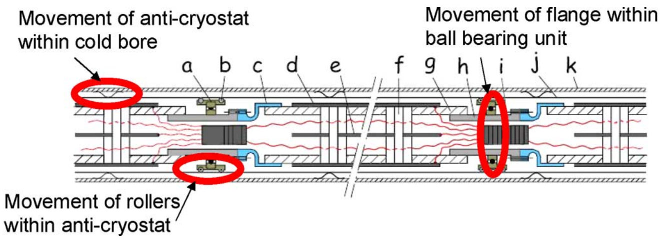

Fig. 3. Schematic assembly of a portion of the long shaft showing the main components: (a) ball bearing, (b) bronze cage with roller, (c) Ti-bellow, (d) tangential coil, (e) central coil, (f) dowel pin, (g) ceramic support, (h) SiN flange, (i) cable connector, (j) anti-cryostat, (k) cold bore. Possible sources of vibration are circled.

Another prime source of vibration could be imbalances within the ceramic shafts. To explore this possibility, a ceramic shaft imbalance measurement system is being developed along with potential imbalance correction schemes. Also, further investigation is needed to pinpoint the exact source of vibrations within the rotating shaft assembly. However, the results in this paper results demonstrate that up to 3 Hz, faster measurements can be made without significantly increasing vibrations. It must also be noted that by using "bucked" signals, even the vibrations existing at speeds higher than 3 Hz can be compensated in order to minimize measurement error. This may serve as a means of improving operations at even higher speeds in the future.

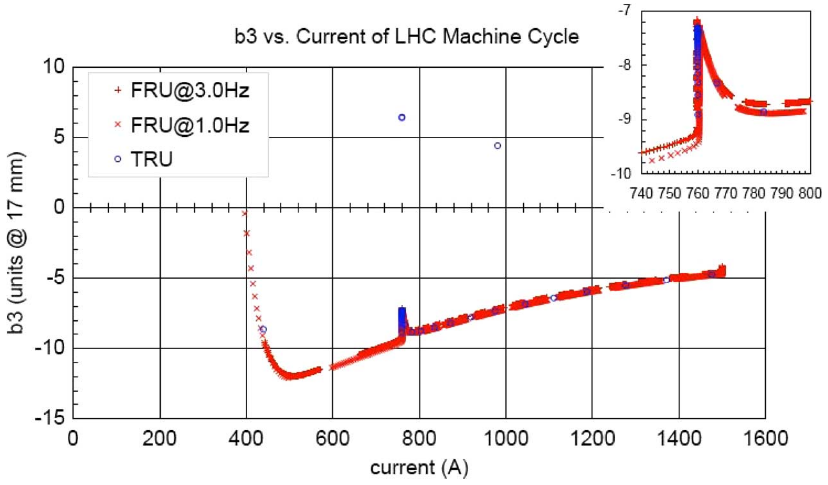

Fig. 4. Sextupole harmonic (b3) versus current of dipole magnet during LHC machine cycle.

IV. TEST IN OPERATING CONDITIONS

As a final proof of principle for fast harmonic measurements, LHC Machine Cycle measurements were taken using the FRU at operations speeds of 1 and 3 Hz. The measurements were then compared to the same type of measurements using the standard TRU rotating at ~0.8 Hz, but providing measured sextupole at 0.03 Hz (we recall that a single TRU measurement requires 6 coil rotations in addition to actuation and acquisition times). The current waveform used in the LHC Machine Cycle mimics the operation of the accelerator, and in particular is used to examine sextupole snap-back by taking measurements during magnet current ramp up following the plateau at injection (current of 760 A, 0.54 T dipole field). As seen in Fig. 4, the use of the FRU dramatically increases the resolution of the measurement. The difference between harmonics coils data taken with the TRU and FRU are at most 0.5 units @ 17 mm, and are at least partially due to lack of reproducibility among powering cycles.

V. CONCLUSIONS

The measurements presented in this paper are based on experimental testing of the FRU system on a fully-equipped LHC dipole magnet. The FRU system consists of a modified TRU system and a modified PDI based data acquisition system. Primary modifications in the TRU system included upgrading the driving motor system, installing low noise slip rings, and re-designing the wiring system between the RU and measurement shaft. The next phase of testing will utilize a completely new RU design designated the μRU (micro-Rotating Unit). This design has been optimized for portability and flexibility. In addition, modifications have been made to the design of the measurement coils of the ceramic shafts to provide optimal signal collection at the new higher operations speeds. This along with a complete upgrade of the data acquisition system from PDI to FDI (Fast Digital Integrators) using DSP (digital signal processing) and new integrator technology, will allow the new rotating coil measurement system to provide high resolution measurements through increased bandwidth.

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