PRELIMINARY DESIGN AND ANALYSIS OF THE FODO MODULE SUPPORT SYSTEM FOR THE APS-U STORAGE RING *

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Abstract

The most technically challenging module of the planned APS Upgrade (APS-U) project is the Focusing-Defocusing (FODO) module. The girder for the FODO must support a ~6m long string of three transverse gradient dipole magnets and four quadrupole magnets. The challenges which emanate from retrofitting the existing APS tunnel with new hardware along with the stringent requirements for alignment and vibrational stability [1] necessitate a unique engineering solution for the magnet support system. FEA is heavily relied upon in order to create an optimized solution and reduce the number of design iterations required to meet specifications. The prototype FODO magnet support design is presented from the ground up, along with FEA justification and the expected vibrational performance of the module.

INTRODUCTION

The APS is planning an upgrade of the storage ring, which will involve replacing all of the existing hardware in a several month time frame. To meet this difficult schedule constraint, magnets, vacuum chambers, and supports will be assembled to a plinth, and installed as a module. After removal of the existing storage ring hardware, modules will be lifted on air casters and brought to their installation location. Technicians will deflate the air casters and rest the module on three outriggers for initial rough alignment. Next, the plinth will be grouted in place, and the outriggers will be removed. Finally, the magnet support and alignment system will be used to precisely align the girder. A three-point semi-kinematic support system has been chosen in order to reduce the time and effort required for alignment.

Given the large combined mass (~9,145 kg) of the seven magnets which comprise the FODO section, design specifications will be most difficult to meet for this module. To work within the available space around the FODO in the storage ring, all installation and maintenance must be performed on the aisle-side. A prototype FODO module has been procured with a string of dummy magnets which will test fabrication methods, mechanical stability with and without water flow, installation logistics, and vacuum performance (Fig. 1).

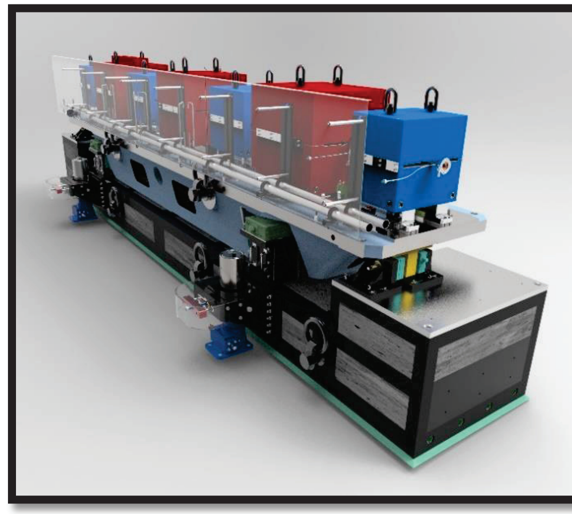

Figure 1: Assembled FODO prototype module.

PLINTH DESIGN

The FODO plinth is a hybrid steel and concrete structure developed through an R&D collaboration with a university, concrete fabricator, steel fabricator, and ANL. Through the use of a proprietary concrete mixture, steel reinforcing bar, and a steel cage which surrounds the concrete, long term shrinkage rates have proven to be acceptably small. The plinth contains all mounting features for the FODO girder support and outriggers, lifting eyes for rigging, and shelves for the two longitudinal gradient dipole magnets, which are positioned directly upstream and downstream of the FODO module. The embedded steel weldments which support the girder have been designed to maximize stiffness while staying within the geometrical boundaries defined by the storage ring walls. The weldments also bring the girder supports as close as possible to beam height in order to reduce the moment of inertia of the girder system and reduce geometric amplification of ground vibrations.

GIRDER DESIGN

The FODO girder has been designed to optimize its stiffness with respect to static deflection and modal response. This was done using a topology optimization software called GTAM [2]. The constraints, an objective function and an initial geometry seed were inputs to the software. An image of the topology optimized geometry is shown in Fig. 2 [3].

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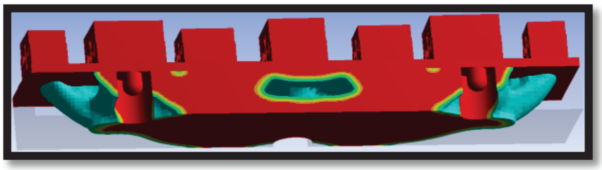

Figure 2: Optimized FODO girder geometry.

Ductile cast iron, A536, GR-60/40/18 was chosen as the girder material because of its design flexibility, low cost, and favorable vibration damping properties. Several design iterations were required with input from a cast iron foundry to transform the ideal geometry into a manufacturable part.

Following the casting process, the girder will be post-machined. Alignment of the magnets on the girder will rely on machining tolerances of the mating parts. Magnet centerlines will be precisely machined relative to fiducial surfaces on the outside of the magnet, and stop-blocks pinned and bolted to the top surface of the casting will be precisely machined after they are assembled to the casting. Pusher-blocks will position the magnets against the stop-blocks with a known force.

Since the design of the support system is semi-kinematic, it is not possible to profile the girder to account for static deflection. The static deflection due to the self-weight of the casting will be negated by grinding the top surface of the casting flat while resting on the three-point support locations. Thus, the static deflection is due to the weight of the magnets alone. The deviation from a best-fit line of in-plane deflection points along the beam path is calculated to be 14 microns.

ALIGNMENT SYSTEM

Airloc-414 KSKC tri-wedge type jacks have been chosen as the vertical alignment device for the FODO support based on the recent success of the ESRF magnet support system [4]. Preload will be achieved prior to alignment with a stack of spring washers which allow the preload to be maintained throughout the adjustment range of the jack. DU Glacier friction reducing plates will be assembled underneath the jacks to allow for lateral adjustment of the girder. A hole through the center of the casting allows for aisle-side adjustment of the wall-side wedge jack with an extension wrench.

ANSYS simulations show that the first mode frequency of the assembly can be significantly raised by using stiff lateral pushers. Therefore, all lateral pushers will use smaller Airloc 2012 wedge jacks rather than conventional pusher screws. A schematic of the pusher locations is shown in Fig. 3.

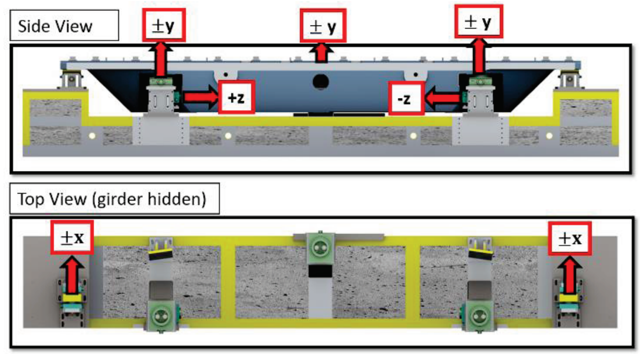

Figure 3: Later pusher locations .

Three outriggers will be procured for the FODO prototype which will be used to rough-align the plinth to within ± 1mm in all degrees of freedom prior to grouting. Since the wall-side outrigger will not be easily reached once installed in the storage ring, the design incorporates push-pull screws so that all lateral adjustments may be made on the aisle-side. The vertical motion is provided with motorized 20-ton NOOK acme screw jacks. A rendering of an outrigger is shown in Fig. 4.

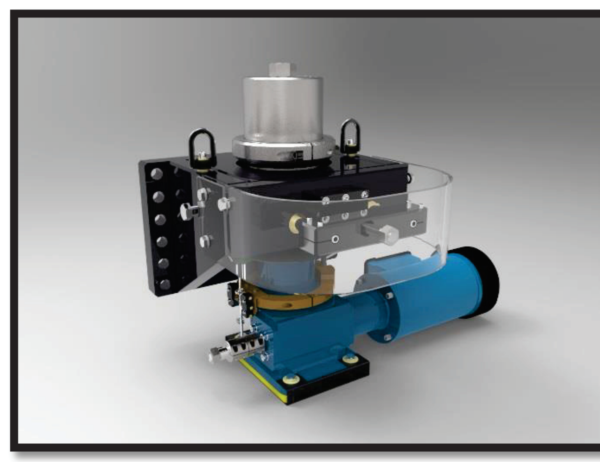

Figure 4: FODO Outrigger.

ANALYSES

Modal Analysis

In order to accurately predict the modal response of the FODO module, dynamic stiffness testing was completed on the vertical and lateral support components. A single wedge jack was placed underneath the center of mass a large granite block, and a modal analysis was conducted while the block was balanced on the jack [5].

Using the equations of motions for this simple dynamic system along with the experimentally determined rigid body modes, the 6x6 diagonal stiffness matrix and damping coefficients of the component were determined.

The experimentally determined stiffness matrix for each vertical and lateral support component was input into an ANSYS modal analysis along with the geometry of the magnets, girder, and plinth. The first mode is a rocking mode at 38.8 Hz, shown in Fig. 5.

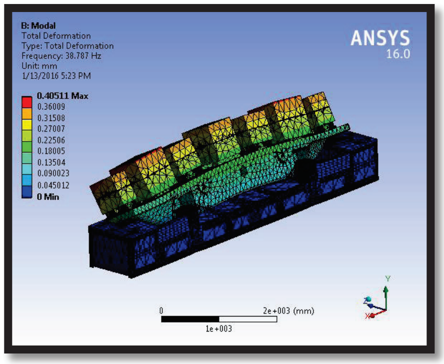

Figure 5: First mode, 38.8 Hz.

Floor Stiffness Analysis

Given the large mass of the assembly, it is possible that the compliance of the storage ring floor will play a significant role in the dynamic performance of the module. Therefore, it is important to include the effect of the floor and underlying aggregate in the modal analysis. Although the approximate stiffness of concrete may be assumed, the aggregate underneath is more difficult to characterize since the stiffness of aggregate varies widely from site to site. Therefore, the floor stiffness was measured as a function of depth for the S28 Experiment Hall floor at the APS by exploiting the frequency dependent properties of shear waves (S-waves) through elastic media, a technique commonly employed by geophysicists [6]. The measured S-wave velocity vs. depth is shown in Fig. 6, from which the Young's modulus of the floor layers may be easily extracted [7].

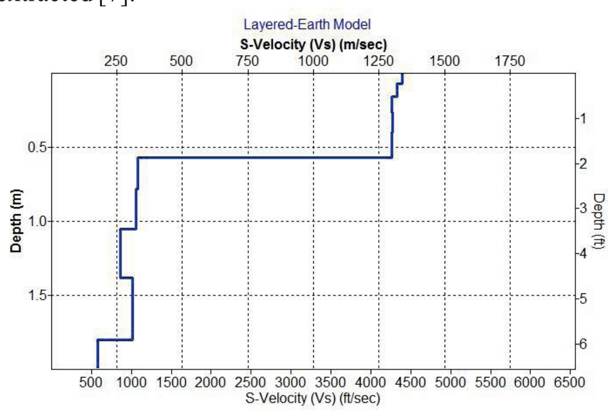

Figure 6: S-wave velocity as a function of depth at APS S28.

By including the floor compliance in the modal analysis, the first mode becomes 35.4 Hz, a reduction of ~10%. In future efforts, similar stiffness measurements for the APS storage ring floor will be obtained.

Random Vibrations Analysis

Ambient floor motion data was taken in 2014 in the APS storage ring at S28 over the frequency range of 1-100 Hz. This floor motion was used as the input to an ANSYS random vibration analysis. The response motion was probed at a point on the upstream quadrupole pole tip. Damping was set to 2% based on an average of the modal damping values found during component testing.

The results are shown in Fig. 7. The RMS vibration response is 13 nm in the X-direction, and 12 nm in the Y-direction. This analysis shows that the dynamics of the system do not play a significant role in amplifying low-frequency motion at the quadrupole pole tip.

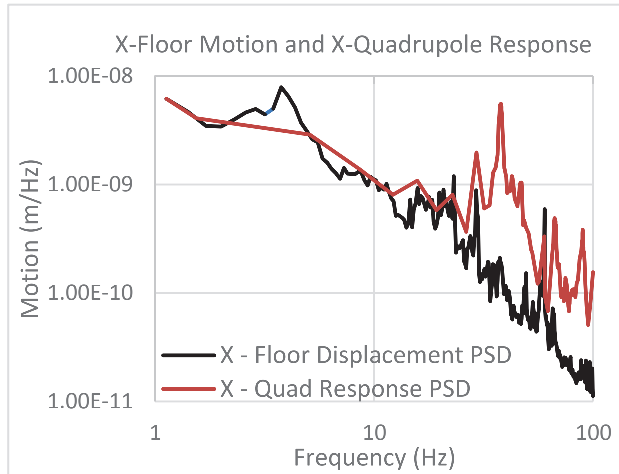

Figure 7: Results of Random Vibration Analysis.

Thermal Analysis

Temperature fluctuations in the storage ring tunnel will be held to $\pm 0.1^{\circ}$C. The resulting thermal deformations of the girder must be analysed to show that they are negligible compared to the 30-micron RMS magnet-to-magnet alignment tolerance. The z-direction pushers have been placed such that they contact the girder near its neutral axis. This prevents the girder from "bowing" and causing large thermal displacements.

Although a time varying $\pm 0.1^{\circ}$C temperature change in the tunnel air will not cause the same temperature change in the girder, this analysis assumes a steady state ΔT of 0.1°C in the entire FODO module. Experimentally determined stiffness values are used for both vertical and lateral supports. The bottom of the grout surface is assumed fixed. The thermal deformation of the girder is shown in Fig. 8.

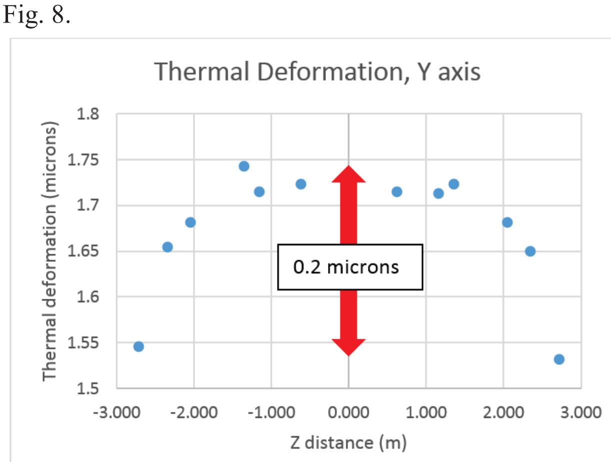

Figure 8: Thermal deformation.

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