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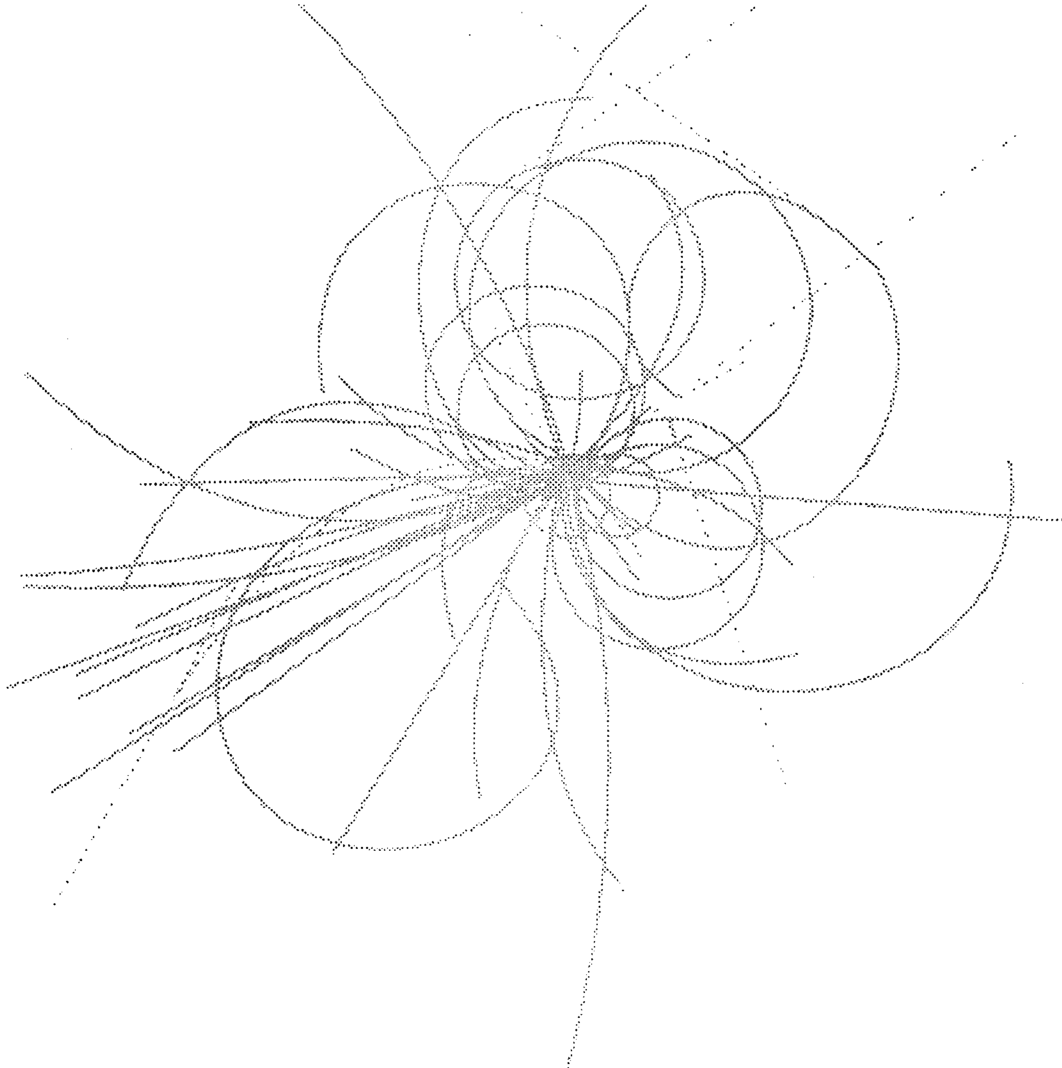

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THE MECHANICAL RESPONSE OF THE SSC DIPOLE MAGNET TO GROUND MOTION

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Abstract: One of the requirements for successful performance of the Superconducting Super Collider (SSC) particle beam accelerator is minimization of the effects of ground motion on the beam path. It is therefore important to be able to quantify this effect. To achieve this objective, a finite element dynamic model of the 40 mm dipole magnet was developed and validated with experimental data. The natural frequencies and mode shapes predicted by the model were in good agreement with experimental data. The model was used to predict beam path displacement resulting from ground motion. The magnitude and frequency of the ground motion had been previously measured at the SSC site in Ellis County, Texas.

INTRODUCTION

The dipole magnet is one of the major components of the Superconducting Super Collider (SSC) particle beam accelerator. Its main functions is to bend the path of the beam as it circulates in the collider ring.[1] This path must be maintained in precise orbits for optimum accelerator performance. One important factor that affects beam path stability is ground motion.[2] As such, it is important to quantify its effects in terms of the displacement of the beam path.

Several studies on ground motion effects on accelerator design in general, and the SSC accelerator in particular, have been carried out. A good overview of the effects of ground motion in designing accelerators was developed by Fischer.[2] Ng and Peterson[3] studied the effects of ground motion on the SSC using an ideal and uniform model of the SSC site. Tolerable ground motions for the SSC were investigated by Fischer and Morton.[4] Goss[5] characterized ground vibrations at the SSC site.

A dynamic model of the dipole magnet was developed to study seismic and transportation loads.[6] For that model the cold mass and vacuum vessel were modeled with beam elements.

There are several sources of ground motion to be considered in the design of the SSC magnets. The principal sources are ambient ground motion, trains and highway traffic crossing the main ring, and quarry blasting in nearby Midlothian, Texas.[1,7]

In this paper, a finite element dynamic model of the 40 mm dipole magnet was developed and was validated with experimental data. This was achieved by tuning the model until a good agreement was achieved between experimental and analytical natural frequencies and mode shapes. Ground motion test data taken from the SSC site in Ellis County, Texas,[7] was used as input data for the model to determine the displacement of the beam tube. The model development and analysis were carried out using ANSYS, a general-purpose, commercial finite element program.

TESTING EQUIPMENT AND PROCEDURE

In order to verify the finite element representation of the magnet, its vibrational characteristics were determined experimentally. The parameters of interest were the magnet's natural frequencies, mode shapes, and associated damping. This experimental program was carried out on a full-length 40 mm dipole magnet designated "DSHIP." DSHIP was assembled at Fermilab and was specially instrumented there for vibration studies. It has no heat shields or super insulation, but is otherwise identical to other SSC 40 mm dipole magnets.

The experimental procedure involved taking a series of frequency response functions (FRF) along the length of the vacuum vessel and the cold mass. A frequency response function is a complex function defined as the Fourier transform of a system's response (acceleration in this case) divided by the Fourier transform of the input (Figure 1). Vibrational input to the magnet was supplied by an electromechanical shaker driven by a random noise signal and was measured by a quartz force transducer. Output was measured by an array of piezoelectric accelerometers. These measurements were converted into FRFs by a Hewlett Packard 3567A dynamic signal analyzer. Finally, the FRFs were converted to the desired modal parameter using a PC-based structural analysis system.

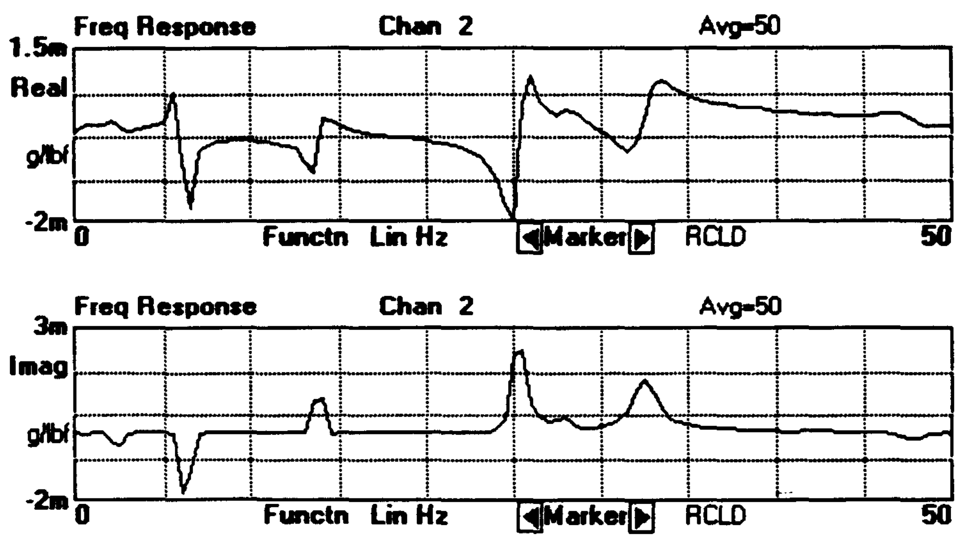

Figure 1. A Typical Frequency Response Spectrum for the Cold Mass.

The specific technique used to determine the modal parameters was to fit a polynomial function, in rational fraction form, to the FRFs. Because the magnet's modes of vibration are in general lightly damped (less than 2% critical) and widely spaced, there was very little coupling between modes. However, a multi-degree-of-freedom version of the polynomial method was used in an effort to obtain the most accurate results possible.

The magnet's test configuration was developed to make the correlation with numerical results as straightforward as possible. Great care was taken in mounting the magnet to the floor in order to approximate a truly "constrained" (zero displacement/zero rotation) boundary condition. This involved pouring 5-ft- thick, steel-reinforced concrete footings to which the magnet was bolted using 1.25-in. all-thread rod. Measurements were made at 3-ft intervals down the entire length of the magnet in order to give the experimentally determined mode shapes the best resolution possible.

Results of the experimental program were consistent with earlier modal tests carried out on similar superconducting magnets.[8] Measurements showed a high degree of coherence and repeatability with very little noise. The quality of the mode shape resolution was generally excellent. This leads to confidence regarding the accuracy of the modal parameters determined.

MODEL DEVELOPMENT AND ANALYSIS

The major components of the 40 mm dipole magnet are the vacuum vessel, five support posts, two external support feet, a cold mass, and its support structure. These components were included in the dynamic model. Other components, namely the heat shields, cryogenic fluid pipes, and thermal insulation materials, were not considered significant contributors to the dynamic characteristics of the magnet and as such were not included in the model.

A thin shell ANSYS element, STIF-63, was used to model the vacuum vessel, support post tubes, and the cold mass skin. A thick plate element, STIF-43, was used to model the support post discs, external support feet, and cold mass support structure. The laminations contained within the cold mass skin were also modeled with STIF-43 elements. These laminations include the beam tube, inner and outer coils, and the iron yoke. While they do not contribute much to the structural strength of the cold mass, their contribution to the dynamic characteristics of the magnet has to be accounted for because of their enormous weight. It should be pointed out that the objective here is not to account for every detail of the cold mass but to include enough detail to give a good characterization of its dynamic behavior. The total weight of these laminations was distributed among 13 laminations. The locations of these laminations were selected to give an even distribution of the weight. One lamination was located at each end of the cold mass, and one was located above the center of each support post, for a total of seven. Six more laminations were added, one between every two that have already been defined. The model input values for these laminations were a pseudo-thickness and pseudo-density. These were determined such that they would result in the total weight of the actual laminations being represented.

Two separate models were developed and analyzed for this study. A model of the cold mass was developed and analyzed to ensure that its dynamic behavior was understood. This was then incorporated into a larger model of the entire magnet. Advantage was taken of symmetry to model only half of the magnet.

Model development was carried out in two phases. In the first phase the model was tuned to get a good match between natural frequencies and mode shapes predicted by the model and those obtained experimentally. Tuning was done by modifying the modulus of elasticity of the cold mass laminations until the natural frequencies predicted by the model matched those obtained from testing as closely as possible. In the second phase, the model was enhanced for seismic analysis so it could be used to predict beam tube displacements due to ground motions. The response spectrum method of seismic analysis was used. The modes were combined with the SRSS method. Also, Guyan reduction was used for both types of analyses to minimize problem size and to reduce computation time and space requirements.

A vertical displacement spectrum of 0.5 mμ magnitude and 2.7 Hz frequency was input into the model to represent ground motion. These values were extracted from ground vibration test data taken at the SSC site.[7] A 2% structural damping, which was determined experimentally, was used in the analysis. The maximum vertical displacement of the cold mass—and hence of the beam tube—resulting from this ground motion was determined. Model development and analysis were performed using ANSYS (4.4A) on a Sun SPARCstation 1+.

RESULTS AND DISCUSSIONS

The natural frequencies and mode shapes for the cold mass determined both experimentally and by the finite element analysis (FEA) model are in good agreement as shown in Table 1 and Figures 2 to 5. This indicates that all the dynamic characteristics are included in the cold mass model. The best resolution was obtained for the higher mode shapes. As such, the seventh and eight modes, which had excellent resolution, are presented here and are compared with the corresponding modes determined analytically. It should be noted that the boundary conditions used during the characterization of the cold mass were not meant to approximate the suspension system of the cryostat. Rather, they were chosen to facilitate a simple comparison of the experimental results with those of the FEA.

Table 1. Experimental vs. FEA Frequencies/Cold Mass Only.

Mode #	Freq (Expt.) (Hz)	Freq (FEA) (Hz)
1	2.50	2.50
2	3.50	2.72
3	5.95	6.37
4	13.71	15.75
5	25.25	26.12
6	27.98	28.11
7	32.43	35.27
8	47.44	47.75

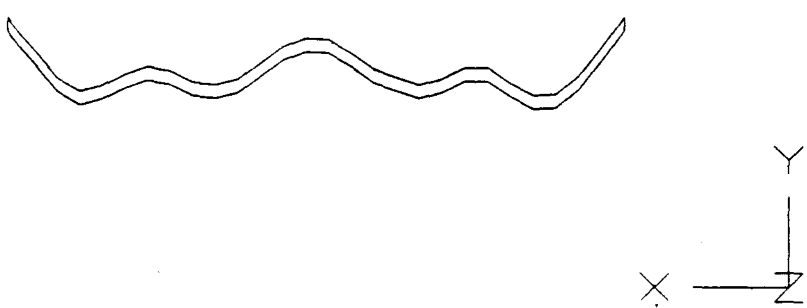

Figure 2. Seventh Mode Shape/Cold Mass/40 mm Dipole Magnet/Experimental.

Figure 3. Seventh Mode Shape/Cold Mass/40 mm Dipole Magnet/FEA Analysis.

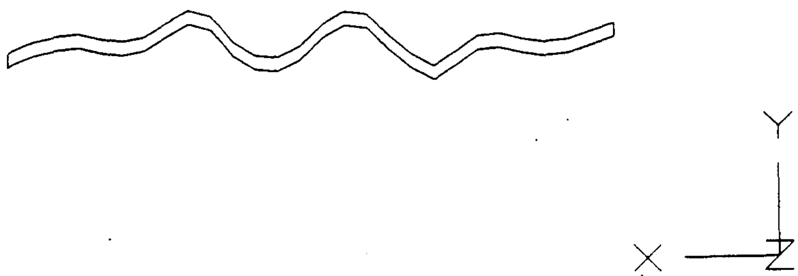

Figure 4. Eighth Mode Shape/Cold Mass/40 mm Dipole Magnet/Experimental.

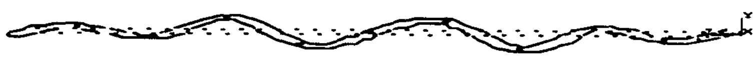

Figure 5. Eighth Mode Shape/Cold Mass/40 mm Dipole Magnet/FEA Analysis.

Table 2. Experimental vs. FEA Frequencies/Complete Magnet.

Mode #	Freq (Expt) (Hz)	Freq (FEA) (Hz)
1	6.5	5.7
2	7.5	6.6
3	15.5	15.6
4	16.5	16.4
5	-	17.8
6	20.5	25.8
7	-	29.6
8	37.5	39.4
9	39.0	41.6
10	44.0	45.1

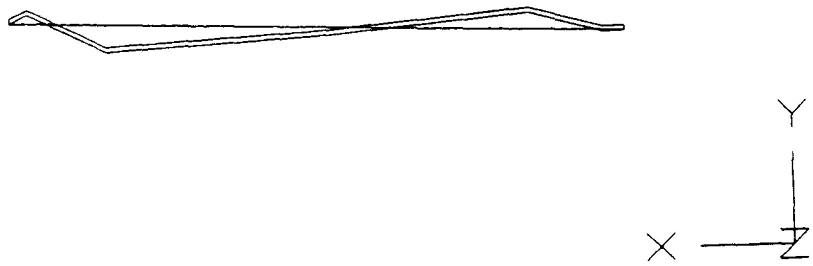

Figure 6. Second Mode Shape/40 mm Dipole Magnet/Experimental.

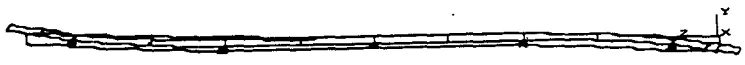

Figure 7. Second Mode Shape/40 mm Dipole Magnet/FEA Analysis.

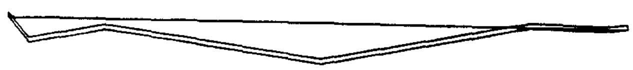

Figure 8. Third Mode Shape/40 mm Dipole Magnet/Experimental.

Figure 9. Third Mode Shape/40 mm Dipole Magnet/FEA Analysis.

While the agreement between experimental and FEA model results for the complete magnet (Table 2) is not as good as that for the cold mass, there is still good agreement. The second and third mode shapes for the complete magnet model obtained both experimentally and with the FEA model are shown in Figures 6 to 9. It would have been desirable to have experimental data to validate all of the individual component models before putting together the complete magnet model. However, the present model is a good representation of the magnet's dynamics characteristics.

Having validated the finite element model of the 40 mm dipole magnet, there are many applications which can draw upon this model for answers to important questions about the magnet's behavior in various dynamic environments. Of particular interest are the magnet's stresses and displacements due to ground motion and shipping loads. For this study, the maximum beam tube displacement for a vertical ground motion displacement of 0.5 mμ with a frequency of 2.7 Hz was determined by the model as 0.765 mμ. This displacement spectrum was derived from the ground motion test data taken at the SSC site in Ellis County, Texas. It should be cautioned that this represents the magnet's response to only one particular forcing function and does not represent the worst case

CONCLUSIONS

The following conclusions were made about the study presented here:

1. A dynamic model of the 40 mm dipole magnet was developed and was validated with experimental data.
2. Using seismic data taken at the SSC site in Ellis County, Texas, the dynamic model was used to predict displacements of the beam tube caused by ground motion using seismic data taken at the SSC site in Ellis County, Texas.

FUTURE WORK

1. The present model accounts only for vertical motions of the magnet. It should be enhanced to account for horizontal and twisting motions as well.
2. This work will be extended to include the 50 mm dipole and the quadrupole magnets.
3. These magnets will undoubtedly be transported by tractor-trailer to the construction site in Ellis County, Texas. They will experience nonlinear transient shock loads as well as continuous vibratory loadings. These shipping loads may adversely affect the mechanical integrity of the magnets. The model developed will be used to predict the stresses resulting from these shipping conditions.
4. The magnet will not sit directly on the floor when it is installed in the tunnel. A pair of magnets will be mounted, one above the other, on support stands fastened to the floor. The upper magnet's dynamic behavior will be better investigated with a model of this configuration.

ACKNOWLEDGEMENTS

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