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UCRL--53307

DE83 000026

Dynamic Testing of MFTF Containment-Vessel Structural System

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Manuscript Date: April 1, 1982

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Abstract

Dynamic (modal) testing was performed on the Magnetic Fusion Test Facility (MFTF) containment vessel. The seismic design of this vessel was heavily dependent upon the value of structural damping used in the analysis. Typically for welded steel vessels, a value of 2-3 percent of critical is used. However, due to the large mass of the vessel and magnet supported inside, we felt that the interaction between the structure and its foundation would be enhanced. This would result in a larger value of damping because vibrational energy in the structure would be transferred through the foundation into the surrounding soil. The dynamic test performed on this structure (with the magnet in place) confirmed this later theory and resulted in damping values of approximately 4-5 percent for the whole body modes.

This report presents a brief description of dynamic testing emphasizing the specific test procedure used on the MFTF-A system. It also presents an interpretation of the damping mechanisms observed (material and geometric) based upon the spatial characteristics of the modal parameters (mode shapes).

Introduction

Since the early 1950's the Lawrence Livermore National Laboratory (LLNL) has been investigating the use of strong magnetic fields for confining fusion fuel. The TMX and TMX-upgrade experiments performed at LLNL in the late 70's utilized an "open" tandem mirror system of magnetic confinement within a vacuum vessel. The Magnetic Fusion Test Facility (MFTF), currently nearing completion at LLNL, will provide a large-scale magnetic mirror device and supporting facility for performing physics experiments and technology development needed to bridge the gap between the smaller TMX experiments and a mirror fusion energy device. The successes of the TMX experiments have led to a rescoping of the MFTF project to the MFTF-B project. MFTF-B will be a large-scale tandem mirror experiment which is expected to achieve conditions nearly equivalent to scientific breakeven. The MFTF and MFTF-B projects should provide advances in technology which are required for an operating fusion power plant.

One of the objectives of the MFTF and MFTF-B projects is to learn to design and construct large vessel systems comparable in size to those needed in fusion power reactors. The design of the MFTF and MFTF-B vessels was performed by LLNL engineers. The vessel system was designed to carry static and dynamic loads. The dynamic analysis of the vessel required an estimation of structural damping. Since there were no other structures of similar construction available, these values were essentially unknown and estimates had to be made based upon those values normally used for welded steel structures. Typically these values would be within 1-2 percent. However, because of the large mass of system when the magnet was in place, we felt that higher damping values (4-5 percent) could safely be used. This was due to the fact that the overall structure would interact with its foundation and radiate energy away through the soil. To resolve this difference we decided to dynamically test the MFTF-A vessel and actually measure the damping values. The test method, the methodology used to evaluate modal damping from the test data, and the results of the test and analysis are included in this report.

When completed the MFTF-B vessel system will consist of three distinct sections (see Fig. 1):

- ◇ East end vessel,
- ◇ West end vessel,
- ◇ Central cell vessel.

The vessel system will provide the vacuum environment for the plasma

Figure 1. MFTF-B vessel system

and will support and insulate the magnet system and neutral beam sources and diagnostics. The overall length will be 65.6 m. Each end vessel will be 20.1 m long by 10.6 m in diameter. The central cell will be 23.0 m long by 8.0 m in diameter. The total vessel system will weigh approximately 7 million lbs and will be constructed entirely of stainless steel.

The structural design of the MFTF-B vessel is outlined in a report by Vepa and Sterbentz[1]^{*}. A finite element analysis with the SAP4 code was used to perform static and dynamic analyses of the vessel system. The design of the vessel system was performed by repeated

[*] Numbers in brackets [] refer to references listed at the end of this report.

analyses (i.e., choose a configuration, analyze, make changes and reanalyze). A response spectrum analysis was used to determine the stresses due to seismic loading on the structure. The stress levels predicted by the response spectrum analysis are dependent on the damping of the structure. The modal damping ratios used in the design were 5 percent (i.e., 5 percent of the critical damping). These values were estimates and a reduction of their value from 5 to 2 percent would require rather expensive structural modifications. Consequently, it was very desirable to determine their true value by dynamic testing.

At the time of testing only the east-end portion had been constructed (Fig. 2). This "plug vessel" is 20.1 m long by 10.6 m in diameter. The vessel is a thin cylindrical shell constructed of stainless steel stiffened by "I"-shaped circumferential stiffening rings. The vessel skin resists the vacuum and magnetic loads, and the stiffening rings mainly resist the gravitational loads. The massive Yin-Yang magnet was hung in the vessel at the time of the dynamic test (see Fig. 2). The east-end dome cover was in place. The west-end was open due to ongoing construction.

Figure 2. MFTF vessel configuration at time of dynamic test.

Mathematical Description of Dynamic Testing Method

To accomplish the dynamic testing of any structural system, we must first construct a mathematical transfer function model of the structure. That is to say, we divide the structure into a series of nodes. Physically, these nodes are defined as any location where the structure is either excited or where the resulting response motion is measured. These transfer function nodes are analogous to the nodes of a finite element model, constructed for a structural analysis code (such as SAP IV).

The input excitation at any node will cause resulting response motions at all of the other nodes. Mathematically, the response at node i ($x_i(t)$) due to an excitation force applied at node j ($f_j(t)$) is described by the following expression

$$(1) \quad x_i(t) = \mathcal{S}_{ij}[f_j(t)].$$

This expression tells us that the structure acts as a system which maps, or converts, the input function $f_j(t)$ at node j to a resulting output motion $x_i(t)$ at node i . When the input function $f_j(t)$ is an impulse (or delta) function $\delta(t)$, then we call the output motion at node i the impulse response motion and denote it as $h_{ij}(t)$. In terms of Eq. 1 we have

$$h_{ij}(t) = \mathcal{S}_{ij}[\delta_j(t)].$$

Using the convolution, or Duhamel, integral. [2,7], we can use this impulse response function to describe the motion at node i due to a general input function $f_j(t)$ at node j , i.e.,

$$(2) \quad x_i(t) = \int_{-\infty}^{\infty} h_{ij}(t-\xi) f_j(\xi) d\xi.$$

Equation 2 is usually written in the notationally simpler form

$$(3) \quad x_i(t) = h_{ij}(t) * f_j(t).$$

In the time domain the evaluation of this convolution equation is rather tedious. On the other hand, in the frequency domain it can be written in a very straightforward and convenient manner. This fact can be appreciated if we make use of the convolution theorem which briefly paraphrased states, "If $H(w)$ and $F(w)$ are the Fourier transforms of the functions $h(t)$ and $f(t)$, respectively, then the Fourier transform of the convolution product $x(t)=h(t)*f(t)$ is simply the product of the individual transforms, i.e., $X(w)=H(w)F(w)$." Using this theorem we can rewrite Eq. 2 or 3 as

$$(4) \quad X_i(w) = H_{ij}(w)F_j(w),$$

where $X_i(w)$ and $F_j(w)$ are the Fourier transforms of $x_i(t)$ and $f_j(t)$, respectively. $H_{ij}(w)$ is called the transfer function between nodes i and j and is also the Fourier transform of the impulse response function $h_{ij}(t)$.

If we assume that the structure in question behaves (reasonably) linearly, then the impulse response motions $h_{ij}(t)$ and, consequently, the transfer functions $H_{ij}(w)$, can be described by the following simple equations

$$(5) \quad h_{ij}(t) = \sum_{k=1}^N {}_{ij}A_k e^{-\alpha_k t} \cos(2\pi w_k t + \varphi_k), \quad \text{and}$$

$$(6) \quad H_{ij}(w) = \sum_{k=1}^N \frac{{}_{ij}A_k e^{i\varphi_k}}{\sigma + 2\pi i(w - w_k)}$$

$$w > 0$$

$$i, j = 1, \dots, N.$$

In Eqs. 5 and 6, N is 3 times the number of nodes* used to describe,

[*] The number of mode shapes that can be obtained is limited by the number of nodes used to model the structure. However, the number of modal damping and frequencies that can be obtained is not limited by the number of nodes but instead only by the accuracy of the acquired measurement data.

or model, the structure in the x, y and z directions. Note that, as we have already mentioned, Eqs. 5 and 6 are Fourier transform pairs. That is to say, $H_{ij}(\omega)$ is the Fourier transform of $h_{ij}(t)$ or, equivalently, $h_{ij}(t)$ is the inverse Fourier transform of $H_{ij}(\omega)$. For the sake of illustration, we show a single term of the summation of Eq. 5 and its transform Eq. 6 in Fig. 3.

(A) TIME DOMAIN - EQUATION 5

(B) FREQ DOMAIN - EQUATION 6

Figure 3. Damped sinusoid and its corresponding transform.

In our work we will deal mainly with the transfer function, Eq. 6. In this equation there are 3 main sets of constants or parameters. Two of them are real valued (σ_k and w_k), and the other is complex ($_{ij}A_k \exp[i\varphi_k]$) with a real and imaginary portion. For mechanical systems these parameters have physical significance. Namely, w_k is the k th modal frequency; σ_k is the k th modal damping; and $_{ij}S_k = _{ij}A_k \exp[i\varphi_k]$ is a measure of the relative strength of the k th mode between nodes i and j . When combined for all values of $i, j = 1, \dots, N$, these $_{ij}S_k$ parameters provide a spatial description of the k th mode (mode shape).

When we test a structure, the first task is to obtain the transfer functions between the nodes. To accomplish this we excite the structure at node j with a forcing function $f_j(t)$ that is typically a short pulse or hammer blow. We then place accelerometers at node i to measure the resulting response $x_i(t)$. Both $f_j(t)$ and $x_i(t)$ are recorded, fed into a digital computer, and Fourier transformed to obtain $F_j(w)$ and $X_i(w)$. The transfer function $_{ij}(w)$ is then (digitally) obtained by dividing $F_j(w)$ into $X_i(w)$ (see Eq. 4), i.e.,

$$(7) \quad H_{ij}(w) = \frac{X_i(w)}{F_j(w)}$$

Since we are assuming that the structure behaves linearly, we expect this transfer function to be described by some form of Eq. 6. That is, there exist parameters $_{ij}S_k$, w_k and σ_k that when used in Eq. 6 will match the measured transfer function $H_{ij}(w)$. To find these parameters we use a computer code called *TRANSF* which is available on the Livermore Time Sharing System (LTSS) [5]. This code uses a least-squares-fit technique to find the set of parameters that best matches the measured data.

At first glance it would appear that we require N^2 measurements to obtain all the transfer functions $H_{ij}(w)$ ($i, j = 1, \dots, N$). However, due to certain symmetries [3], this is not the case and, in fact, we only require N measurements. There are several ways in which these N measurements can be made. Typically, for large structures, we apply the excitation at a single node (call it M) and then measure the response at the other nodes (including node M). This technique gives us the N transfer functions $H_{1M}(w)$, $H_{2M}(w)$, ..., $H_{NM}(w)$. The remaining $N^2 - N$ transfer functions can then be generated from this limited set as per the rules described in Ref. 3.

In summary, to dynamically test a structure we proceed as follows:

- (1) Determine nodal locations of the structure (see next section for a description of MFTF-A nodal locations).
- (2) Excite the structure at a convenient node and measure the response motions at all the other nodes (including the excitation, or driving point, node).
- (3) Using Fourier transform techniques, determine the transfer functions between the nodes.
- (4) From these transfer functions, extract the modal parameters of the structure using the *TRANSF* computer code.

Test Plan for MFTF-A Containment Vessel Structure

The dynamic testing of the MFTF-A containment vessel structure was accomplished through a joint effort between engineers from the Structural Mechanics Group of the Nuclear Test Engineering Division and engineers from Agbabian Associates (AA) of El Segundo, California who were subcontracted to provide the input excitation and to measure and record the resulting response motions. The obtained data was placed on 9-track magnetic computer tape by AA and then transferred to the LTSS for subsequent processing by LLNL engineers.

A transfer function model of the MFTF-A containment vessel (see Fig. 4) was constructed by locating nodes on all of the four major support rings at equal circumferential intervals. These intervals were chosen at angles of 22.5° . In addition to this, we also took advantage of the vessel's symmetry and only took measurements of and modeled half of the structure. Two nodes were also placed on each leg of the structure. Originally, it was our intent to locate nodes on the magnet hangers. Unfortunately, at the time the testing was performed, these hangers were sealed and, consequently, unreachable.

The input excitation was accomplished via a 12-lb instrumented hammer located on the side of the vessel at node 15. As shown in Figs. 5 and 6, the hammer was mounted on a pivot which permitted reproducible 180° full-swing drops. A soft head was used on the hammer which enhanced the lower frequency content of the input pulse. In Fig. 7 we show a typical input pulse in both the time (a) and frequency (b) domains. As seen in this figure, force levels of 1145 lbs were achieved with an essentially flat frequency spectrum out to 80 Hz. This level of excitation resulted in response motion accelerations in the range of 10 to 20 milli-gees, (i.e., 0.010 to 0.020 g).

Kistler servo accelerometers were used to record the response motions. The test equipment permitted us to measure the response at four nodes (both x and y directions) simultaneously. Consequently, the transducers had to be relocated several times during the test in order to obtain all of the required data. To facilitate this relocation, the accelerometers were equipped with magnetic bases. Because the containment vessel was constructed from nonmagnetic stainless steel, we had to glue mounting blocks (32 mm cubes) onto the

Figure 4. Measurement/excitation locations (nodes) on vessel.

vessel and then mount the accelerometers on these blocks (see Fig. 8). These blocks were mounted on the vessel rings a distance of 305 mm out from the skin (see Fig. 9). In addition to helping relocate the accelerometers in a timely manner, these mounting blocks also served another important function. They were mounted with the top face level; consequently, this enabled us to obtain a consistent orthogonal coordinate system in the x and y directions.

Data signals from the accelerometers were fed into a minicomputer system located nearby. As the signals were received they were graphically displayed so that their quality could be judged. In addition, this computer system was able to perform some simple pre-analysis on the data such as filtering, transforming and averaging. Once we were satisfied with the data quality, it was

Figure 5. Instrumented hammer used to excite vessel.

Figure 6. Another view of instrumented hammer showing full swing.

Figure 7. Typical input force in time and frequency domain.

transferred from the computer memory to magnetic cassette tapes. The data on these tapes was later re-formatted by Agbabian, written onto 9-track computer tapes, and then read into the LTSS as disk files.

To improve the signal-to-noise ratio, the response motion (at each node) was obtained by repeating the test excitation six times and then averaging the results in the frequency domain. This is a rather common technique, and in our case it proved to be extremely successful. As a matter of fact, the random or ambient noise was essentially eliminated. This enabled us to perform the test with minimum impact on the vessel's construction schedule in as much as we did not require a particularly quiet environment during our testing.

Figure 8. Typical accelerometer and mounting block.

Figure 9. Location of mounting block on support rib.

MFTF Vessel Test Results

In Fig. 10 we show typical transfer functions between the excitation node 15 and several other nodes where response motions were recorded. As shown in this figure, the modes with the largest magnitude are all located well above 33 Hz. Consequently, they are not subject to seismic amplification since real earthquake motions typically have only small amounts of frequency components above 33 Hz. In the range of seismic concern (0 - 33 Hz) there are four main modes which we have labeled from A to D as illustrated in Fig. 11. As shown in both Figs. 10 and 11, the magnitudes of these modes are approximately two orders of magnitude less than the higher ones. These modes were located and their parameters extracted using the *MODAL* family of codes (which includes *TRANSF*). The dampings associated with modes A - C (0-11 Hz) are all close to 4 percent. As the frequency of the modes (above 11 Hz) increases, the damping decreases. For example, mode D (approximately 19 Hz) has a damping value of about 2 percent and the higher modes (above 33 Hz) exhibit damping values close to 1 percent. Table 1 summarizes the modal parameters of modes A-D.

Table 1. MFTF Vessel modes within the region of seismic concern.

Mode	Frequency	Damping	Characterization
A	3.75 Hz	3.9%	Rocking
B	7.57 Hz	4.4%	Twisting
C	10.30 Hz	4.6%	Twisting
D	19.10 Hz	2.2%	1-D Breathing

To fully appreciate the importance of these modes we must examine their spatial characteristics. In other words, we must consider their mode shapes. This can best be accomplished by viewing the 16 mm computer movies that were generated (by *MODAL*) and show the structure vibrating in each of its determined modes. Figures 12 through 15 show

Figure 10. Typical transfer functions of containment vessel.

selected frames from this movie. In all of these figures the structure is viewed along each of its coordinate axes. In addition, the linear perspective view appears at the top left. The thin line in these figures represents the static or undisplaced state of the vessel. The thick lines show the displaced state of the structure for that particular mode.

Figure 11. Location of vessel modes A - D.

Mode A

Shown in Fig. 12 are the spatial characteristics or mode shape for Mode A. This mode of vibration occurs at 3.75 Hz and has an associated damping of 3.9 percent of critical. This is a rocking mode with the predominant motion in the horizontal radial (north/south) direction. Although this mode is susceptible to any earthquake with motion in the N-S direction, it has a reasonably high damping factor that will help to attenuate the force levels developed.

Figure 12. Mode A of the MFTF containment Vessel.

Mode B

Shown in Fig. 13 are the spatial characteristics for the mode located at 7.57 Hz. The damping associated with this mode is 4.4 percent of critical. This is a twisting mode with the predominant motion occurring in the horizontal (N-S) radial direction. The structure twists or pivots about approximately the third ring. Just as with Mode A, this mode will be susceptible to an earthquake with strong N-S motion.

Figure 13. Mode B of the MFTF containment vessel.

Mode C

This mode is another twisting mode (see Fig. 14) which is located at 10.3 Hz and has an associated damping value of 4.6 percent of critical. Like modes A and B this one has predominant motion in the horizontal (N-S) radial direction and will also be sensitive to earthquakes with strong motion in that direction. This mode differs from mode B in that the structure twists or pivots about

Figure 14. Mode C of the MFTF containment vessel.

(approximately) its axial center point rather than the third support ring.

Mode D

Figure 15 shows the spatial characteristics of the mode that is located at 19.1 Hz. The critical damping associated with this mode is 2.2 percent. The predominant motion of this mode is in the vertical

Figure 15. Mode D of the MFTF containment vessel.

radial direction. This mode is somewhat more difficult to visualize (from just viewing the displacement figures) than the previous three. However, once the computer movies were studied it became obvious that the best way to describe this mode is as a one-dimensional (vertical) breathing mode.

Higher Order Modes

Returning to Fig. 10 we can see that there are several large (magnitude) modes. Since these modes lie in a frequency region greater than 33 Hz, they will not be amplified by any earthquake motion and, consequently, are of lesser concern. However, for the sake of completeness and academic curiosity, two of the larger modes were studied using our system's identification code *MODAL*. These modes were (arbitrarily) labeled HA and HR and were located at 49.5 Hz and 70.4 Hz, respectively. Both had damping values of 1 percent of critical. The spatial characteristics of these modes are shown in Figs. 16 and 17. In contrast to modes A - D which were associated with whole body motion, modes HA and HB are more closely related to local motions such as "flapping" of the ends of the vessel.

Figure 16. Mode HA of the MFTF containment vessel.

Figure 17. Mode HB of the MFTF containment vessel.

Summary and Conclusions

The cooperative effort between Agbabian Associates and LLNL engineers to dynamically test the MFTF-A containment vessel system proved very successful. In this effort Agbabian Engineers provided the requested excitation loads and measured the response motions. LLNL (Nuclear Test Engineering Division) engineers performed the analysis of the response motion data. Partially due to an averaging technique that was used at the time of the testing, the quality of the measured data was quite good. This enabled us to locate and extract the parameters of several interesting modes of vibration of the structure. The test results and analysis yielded several interesting and useful conclusions:

Damping Values

- ◇ Typically, low amplitude, forced-vibration tests conducted on steel vessels normally yield damping values considerably smaller than those determined in this series of tests. However, because of the very large weight associated with this structure, it is reasonable to assume that the relatively high values of damping measured, represent a combination of material damping and radiation, or geometric, damping (in which the vibrational energy is radiated into the foundation and soil).
- ◇ All modes do not have the same damping value associated with them. The higher modes above 33 Hz have significantly less damping (approximately 1 percent of critical). Furthermore, an examination of the mode shapes associated with these higher modes indicates they tend to be local in nature as opposed to the gross modes (A, B and C). As such, the damping associated with these higher modes is primarily material damping with little or no geometric effects (hence, the lower measured values).
- ◇ The 12-lb instrumented hammer technique used to load the structure was able to excite whole body as well as local modes of vibration.

Recommendations

Based upon the results of the dynamic tests that were performed on the MFTF-A containment vessel system the following recommendations are offered:

- ◇ For seismic analysis the damping values that should be used are dependent upon the type of analysis performed. When fixed base models (which do not account for soil-structure-interaction effects) are used, a value between 5 and 7 percent is recommended. On the other hand, when soil-structure-interaction models which account for the radiation, or geometric, damping effects are used, a value of 3-4 percent is recommended.
- ◇ In this particular test only vibrational modes in the transverse and vertical directions were studied. In future tests it is recommended that some measurements in the longitudinal (axial) direction also be made.
- ◇ The dynamic behavior of the MFTF-A vessel without the magnet in place should be studied. This will help to clarify the effect the mass of the magnet has on the overall response of the structure. It is therefore recommended that the vessel be dynamically tested after the magnet has been removed.
- ◇ During the construction of the MFTF-B system, simple dynamic testing should be periodically performed as a confirmation of the construction and design.

Acknowledgments

The authors would like to thank the following people for their assistance and contributions: Bruce Barclay of Agbabian Associates for his thorough job of providing high quality test result data; John Reed, the MFTF-A Containment Vessel Engineer, for his most valuable assistance in planning and executing the test, Chuck Gilliam and Don Podesta, vessel and magnet technician supervisors, for their help during the testing; and Bob Murray, Dave Coats and Tom Nelson of the Engineering Mechanics Section (NTED) for their assistance in the structural analysis of the test results. We are especially grateful to Jerry Gerich and Vic Karpenko for supporting the testing effort.

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