Dynamic Analysis of the TFTR Bumper Limiter

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ABSTRACT

Of the many components and systems comprising a fusion reactor like the Tokamak Fusion Test Reactor (TFTR), few, if any, are subjected to more extreme and severe conditions than the protective armor for the interior vacuum vessel wall. The primary TFTR limiter, referred to as the Phase II bumper limiter, provides protection of the inner vacuum vessel wall from neutral beam shine-through, normal plasma loads, and major disruptive instabilities. The highly transient nature of forces and temperatures induced by these conditions produces significant dynamic responses in various parts of the bumper limiter structural system. This paper addresses the incorporation of a finite element dynamic analysis in the study of bumper limiter behavior when subjected to several electromagnetic load scenarios. These loads, due to a variety of realistic plasma conditions, were used in the interactive design and optimization of limiter components and support locations and flexibilities which enable the structure to perform within established criteria.

1. Background

In a tokamak, such as TFTR, there is an inevitable diffusion of energy and high temperature plasma particles to the vacuum vessel walls despite the presence of intense magnetic fields. A variety of mechanisms are incorporated into TFTR to protect the vessel from these particles and their high temperature effects. A bumper limiter is installed along the inner vacuum vessel wall to intercept the heat and flux of the plasma and prevent impurities absorbed by the wall from contaminating the plasma. It provides complete toroidal coverage of the inner vessel wall with poloidal coverage of ±60° from the torus midplane, an area of about 22 m^2 (Figure 1).

Each bumper limiter segment is comprised of an actively cooled 9.5 mm thick Inconel 718 backing plate, covered with titanium carbide coated graphite tiles. Titanium carbide reduces chemical sputtering thereby impeding plasma deterioration. Approximately 2700 tiles are required to form the limiter surface. Small area limiters are not considered adequate for the absorbtion of potential high power plasma and particle depositions[1].

There are twenty toroidal limiter sectors each divided into three poloidal sections (+60° to +34°, +34° to -34°, and -34° to -60°). Figure 2 shows a set of limiter plates being test fitted in the TFTR vacuum vessel. Each plate is made of two 9° segments that are connected by electrically insulated joints which reduce eddy currents and are able to carry structural loads. Eddy currents are further reduced by a slitted backing plate design, which increases the electrical resistance by increasing the electrical path length and reducing the eddy current loop size. This decreases the magnitude of the electromechanical forces on the plates.

The bumper limiter design is driven by the effects of highly transient thermal and electromechanical (EM) loads. Thermal analysis has previously shown that limiter cool-down is achieved with an appropriate safety margin[1]. The EM loads can be quite severe and have been minimized via material selection, geometric optimization, electrical isolation, and support flexibility. The largest EM loads are the Lorentz forces due to the interaction of the eddy currents induced by plasma disruptions and the toroidal magnetic field. In particular, four disruption scenarios were examined: an inwardly moving and a stationary large plasma, and an inwardly moving and a stationary small precompression plasma. Time dependent electromagnetic forces due to these plasmas can now be accurately calculated and applied to the limiter plates using SPARK [2].

2. Analytical Approach

In order to ascertain the dynamic behavior of the bumper limiter structure, the finite element method was applied via version 63 of the MSC/NASTRAN program [3]. Due to the general symmetry of the limiter system, the analysis of one large center limiter section (+34° to -34°) and one smaller outer section (+34° to +60°) was deemed representative. The doubly curved limiter plate segments occupy slightly less than an 18° toroidal sector. Each Inconel limiter plate is attached to the vacuum vessel by four supports located approximately six degrees toroidally apart for the center plate and 7-8 degrees toroidally apart for the outer plate.

Several assumptions were made during the course of this analysis which allowed for the simplification of the actual limiter into a model that could be examined with greater ease without violating the integrity of the structure. The analysis assumed that materials were homogeneous and isotropic and that the structure would respond elastically to induced dynamic loads. In addition, it was assumed that the connection of the limiter support to the vacuum vessel is rigid and that any dynamic effects that may be induced via the vessel are ignored. The limiter end of the supports all have the ability to transmit axial forces to the vessel but the lateral support conditions of the limiters indicating shear flexibility, vary from total fixity to total freedom. The purpose of this support mechanism is to allow free thermal expansion of the structure thereby minimizing thermally induced forces. Free rotation is permitted at the limiter end of all supports.

There are two effects contributing to the overall damping of the structure. The first is conventional structural damping which was assumed to be 0.5%. The second is known as effective mechanical damping which represents a recently developed technique for preserving the conservation of energy in the system by coupling the electrical and mechanical components of behavior in the presence of a magnetic field. This effect has been shown to be a real, frequency dependent phenomenon [4]. Functions which defined the damping were developed for each limiter plate and incorporated into the finite element model.

The principal goal of the dynamic finite element analysis is to optimize the complex limiter design by minimizing the backing plate deformations while not over-stiffening the structure to the point of exceeding plate support and material allowables. The sensitivity of these responses as a function of mass, stiffness and geometry of the structure due to the aforementioned highly transient loads must all be accounted for in order to achieve a successful design with appropriate safety margins.

The finite element model, composed primarily of plate elements, includes an accurate depiction of stiffeners and slits in the backing plates, mount assemblies and non-structural mass (i.e. tiles). Based on the completed models (Figures 3 and 4), decay time constants were determined for the limiters, and appropriate dynamic loads were developed for the four disruption scenarios using an assumed plasma disruption time constant of one mega-amp per milli-second.

3. Analytical Results

A comprehensive set of finite element analyses used to define structural behavior and transient response were performed on the bumper limiter design. First, modal analyses were performed which examined the natural frequencies of the limiter plates and their corresponding mode shapes. Then, a series of detailed transient analyses was performed for the actual dynamic load cases of both limiter plates. Results from these transient analyses are output for individual structural elements and nodal points as a function of time. Transient plots, along with data on participation factors and the mode shape plots, give an excellent overview of the true dynamic response of structure.

The nature of the EM loads is such that a large net resultant moment is induced in the plates with virtually no net force. This is due to large opposing forces caused by the eddy currents. Typically, a limiter plate wants to twist each section around its poloidal centerline, and this is confirmed when full amplitude dynamic loads are applied statically to the plates. Interestingly enough, the dominant modes indicated in a majority of transient analyses were those with this twisting shape. For the center and outer plates the dominant modal frequencies are 55 HZ and 103 HZ, respectively (Figures 5 and 6). The total response, of course, contains the variable effects of many modes as a function of time, reflecting the transient nature of the loads and the frequency dependent effective mechanical damping. Of the four different disruption plasmas analyzed, the large inwardly moving plasma consistently indicated the severest responses in both limiter plates. In addition the outer limiter plate generally produces greater stresses and reaction forces than the more flexible center plate. This is attributed to the fact that the eddy current produced net moments increase away from the poloidal midplane. Since the center plate is situated at this location, currents are reversing and the gross forces produced are relatively low over a substantial area of the plate.

The final configuration of the TFTR bumper limiters represents the culmination of extensive design optimization made possible by the iterative modification of the finite element model. Parameters as diverse as plate thickness, slit locations and lengths, support locations and flexibilities, and structural insulator tie locations were all studied in various combinations with respect to the established performance criteria.

A specialized post-processing program was developed that could read through the large output files associated with a dynamic analysis and provide concise summary information. For example, peak amplitudes and times of occurrence for specified node displacement and element forces can be provided indicating maximum response and a corresponding frequency between peaks. In addition, cumulative displacements can be tallied which are extremely useful in determining fatigue life estimates of structural components. It should be noted that because of the damping present, only a few response cycles occur for each disruption with the peak amplitudes decreasing significantly with each cycle.

Specifically, the two most critical results were plate tip displacements and limiter support forces. For the center and outer plates, the maximum plate tip displacements are 3.4 mm and 2.5 mm, respectively. These are primarily rigid body motions magnifying the rotation of the plates about their centroidal axes and mounts. The results are within the design allowables for the tile mounting system. The bumper limiter supports carry axial force and shear from the freely rotating limiter end to the rigid vacuum vessel end where the shear is manifested into a shear and moment. The support allowables are based on a beam-column-type curve which define acceptable combinations of axial force and bending moment. The most severely loaded mount is on the outer plate and experiences a peak axial force of 6200 newtons (1400 pounds) and a peak moment of 250 N-m (2200 inch-pounds) within a few milliseconds of each other. To put a conservative margin on the results, they are assumed to occur simultaneously but there is still a significant margin of safety for the mount.

An examination of the transient insulator joint forces is important because they act as the only structural ties between segments of each limiter plate assembly. All were found to be within prescribed allowables. Forces are also generated in the plates due to the accelerations in motion caused by the plasmas. Instantaneous accelerations could exceed 100 g's, but drop off rapidly and do not create appreciable forces.

A parametric study of support fixity at the limiter end was revealing. For both limiter plates, it was found that as long as free rotation is permitted, (i.e. translations are fixed) the forces in the mounts will not exceed allowables for any plasma condition, or for 150 °C bakeout conditions. Obviously, total shear fixity will produce higher forces in the mount, but they will be acceptable. This is extremely important because it is conceivable that a support could temporarily lock up due to a thermal, friction or tolerance condition and it is reassuring to know that its performance will still be within defined limits. However, if rotations are not permitted, support forces will exceed allowables for the large inwardly moving plasma and bakeout.

4. Conclusions

The finite element method has been utilized in the design of the TFTR Phase II bumper limiters. By studying a variety of parameters and working within specified guidelines, an optimized configuration was developed which met all criteria for withstanding several plasma disruption scenarios.

ACKNOWLEDGEMENTS

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References

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[4] Bialek, J., et al, "Modeling the Coupling of Magnetodynamics and Elastomechanics in Structural Analysis", Proceedings of Tenth Symposium on Engineering Problems of Fusion Research, Philadelphia, PA., December 5-9, 1983.

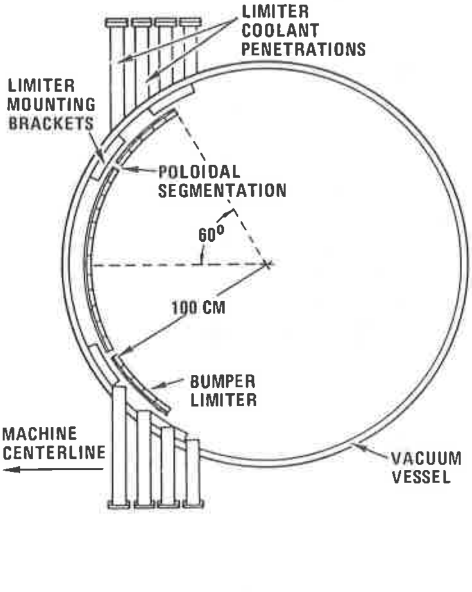

Figure 1 - Schematic of Bumper Limiter Location in TFTR

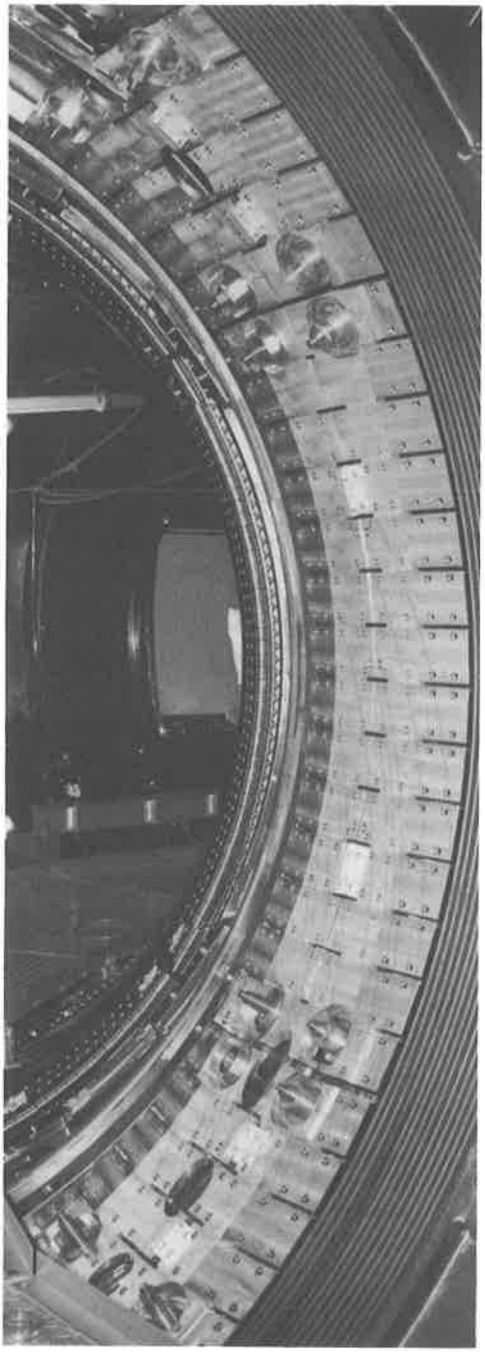

Figure 2 - Prototype Bumper Limiter Segments Test Fitted in TFTR

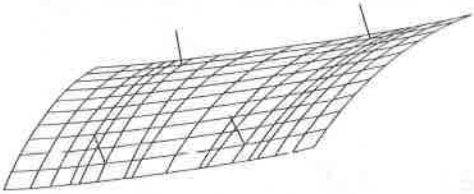

Figure 3 - Finite Element Model of Outer Limiter Plate (Isometric)

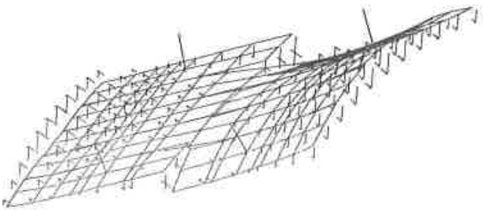

Figure 5 - Dominant Mode of Outer Limiter Plate (103 Hz) With Deformation Vectors

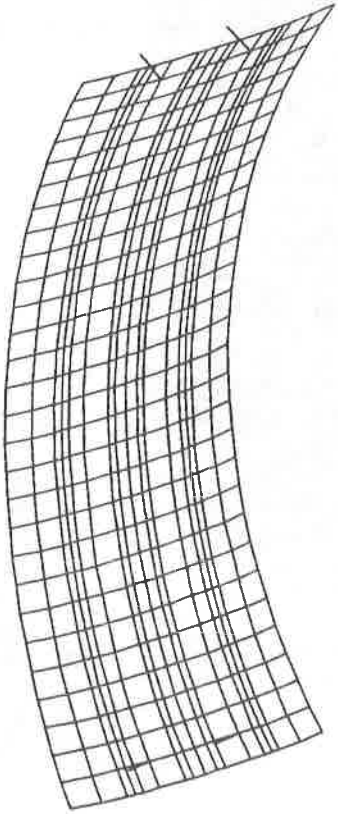

Figure 4 - Finite Element Model of Center Limiter Plate (Isometric)

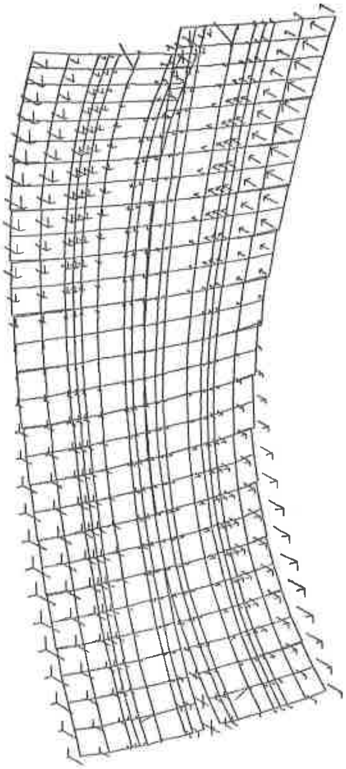

Figure 6 - Dominant Mode of Center Limiter Plate (55 Hz) With Deformation Vectors