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E. REIS, R.D. BLEVINS, T.H. JENSEN,
J.L. LUXON, P.I. PETERSEN, and E.J. STRAIT

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E. Reis, R.D. Blevins, T.H. Jensen, J.L. Luxon, P.I. Petersen, and E.J. Strait

General Atomics

P.O. Box 85608

San Diego, California 92186-9784

Abstract: The motions of the DIII-D vacuum vessel during vertical instabilities of elongated plasmas have been measured and studied over the past five years. The currents flowing in the vessel wall and the plasma scrapeoff layer were also measured and correlated to a physics model. These results provide a time history load distribution on the vessel which were input to a dynamic analysis for correlation to the measured motions. The structural model of the vessel using the loads developed from the measured vessel currents showed that the calculated displacement history correlated well with the measured values. The dynamic analysis provides a good estimate of the stresses and the maximum allowable deflection of the vessel. In addition, the vessel motions produce acoustic emissions at 21 Hertz that are sufficiently loud to be felt as well as heard by the DIII-D operators. Time history measurements of the sounds were correlated to the vessel displacements. An analytical model of an oscillating sphere provided a reasonable correlation to the amplitude of the measured sounds.

The correlation of the theoretical and measured vessel currents, the dynamic measurements and analysis, and the acoustic measurements and analysis show that: (1) The physics model can predict vessel forces for selected values of plasma resistivity. The model also predicts poloidal and toroidal wall currents which agree with measured values; (2) The force-time history from the above model, used in conjunction with an axisymmetric structural model of the vessel, predicts vessel motions which agree well with measured values; (3) The above results, input to a simple acoustic model predicts the magnitude of sounds emitted from the vessel during disruptions which agree with acoustic measurements; (4) Correlation of measured vessel motions with structural analysis shows that a maximum vertical motion of the vessel up to 0.24 in will not overstress the vessel or its supports.

Introduction

The purpose of this paper is to provide a correlation of the efforts made during five years of studies and measurements of the DIII-D vessel motions caused by plasma vertical instabilities. The large vertical displacements of the JET vacuum

vessel following instabilities of elongated plasmas resulted in the incorporation of a vessel motion diagnostic into the DIII-D vacuum vessel [1]. The vessel motion diagnostic has been used to preclude damage to the vessel by providing limits on plasma operation. Plots of the amplitude of vessel vertical motions versus plasma current measured over several years showed that maximum displacements at full toroidal current scaled linearly with plasma current [2]. The motions of the vessel were due to an impulse imparted to the vessel floor causing it to move in a damped oscillatory motion at 21 Hertz. The measured vessel motions were found to correlate reasonably well to a finite element dynamic response analysis of the vessel. The analysis assumed a uniform vertical impulse for 3 msec acting on the vessel floor. This analytical model did indeed calculate vessel displacements similar in amplitude and frequency to those measured by the vertical motion diagnostic. In addition, acoustic emissions produced by the vessel during vertical disruptions were correlated to the displacements measured by the vessel motion diagnostic. An analytical model of an oscillating sphere provided a reasonable correlation to the amplitude of the measured sounds.

In order to understand the pertinent phenomena occurring during the vertical motion of the plasma during a vertical disruption (vertical displacement event), a physics model was developed. The essentials of the model [3] are assumptions of axisymmetry and the inclusion of the effects of currents flowing from the plasma to the vessel wall and vice versa. The validity of the assumptions of the model was demonstrated from comparisons between results from calculations based on the model and numerous measurements of characteristics of the magnetic field [4,5], measurements of vessel displacements [1,2], and direct measurements of currents flowing from the plasma to the vessel wall [6]. In addition, a simulation code was written [7] which was able to account for the measured time development of the vertical displacement event by using a reasonable plasma resistivity as the only plasma input except for the initial conditions at the beginning of the vertical motion of the plasma.

The detailed understanding of the phenomena occurring during a vertical displacement event allowed the calculation

Fig. 1. Equilibrium flux plots at three times during a vertical instability.

of the actual impulse load applied to the DIII-D vessel. The analysis of Ref. [1] was then updated to provide a more accurate value of the displacement limits as measured by the vessel motion diagnostic for safe operation of DIII-D. Also, the physics model provides a tool for the understanding of vertical disruptions in the design of ITER.

Physics Model: Comparison to Experimental Results

Figure 1 shows a series of flux plots from DIII-D discharge 63458 which ended in a vertical displacement event. During the downward motion of the plasma, current flows from the plasma to the inner floor of the vessel and from the outer floor to the plasma as shown in Fig. 1c. The poloidal current is induced in the collapsing plasma according to Lenz's law. Vertical forces on the floor of the vessel are the result from the cross product of the vessel current with the magnetic field. Toroidal currents also flow in the vessel, but the resulting forces are smaller because of interaction with the weaker poloidal field.

References [3] and [4] provide a physics model and expressions for calculation of the vessel impulse load. The basic assumption made in development of the model is that axisymmetry persists throughout. Also, since the vertical motion of the plasma occurs on a time scale which is long compared to the Alfvén time of the plasma, the assumption of MHD equilibrium calculations is valid. A key element of this physics model is that the time development of the vertical instability is governed by the electrical resistivity of the plasma and of the vessel wall for toroidal and poloidal currents. The physics model, which consists of both static and dynamic parts, has been incorporated into a simulation code described in Ref. [7]. The code calculates

Fig. 2. Comparison of measured wall currents and those obtained from fitted equilibria.

Fig. 3. Vertical forces on vessel versus time from simulation of discharge 63458.

the time development of the MHD equilibrium of the plasma during a vertical displacement event.

Results from the simulation code are compared to experimental observations of DIII-D vertical displacement events. The experimental data from various DIII-D magnetic diagnostics are input to the MHD equilibrium code EFIT [8]. The EFIT code provides an efficient method for reconstructing plasma boundary shapes and global current profile parameters with the MHD equilibrium constraints from external magnetic diagnostic measurements. The EFIT equilibrium reconstruction code was modified to allow currents in plasma scrapeoff layer and vacuum vessel wall [5]. During a vertical displacement event, the best fit to the magnetic diagnostic data is obtained with a poloidal current flowing in the scrapeoff layer and returning through the vessel floor. Results from the modified EFIT code provide an experimental measurement of the presence of this current.

The validity of both the static and dynamic parts of the basic model [3] have been confirmed by comparison of model results to experimental results. The first test of the static part of the model was performed by comparing results from the modified EFIT code to measured properties of the magnetic fields. These comparisons provide, at selected times, a complete description of the plasma equilibrium. An example is illustrated in Fig. 1, where the flux surfaces of the plasma are shown at three time steps during the vertical disruption. For each of these time steps, the EFIT code provides toroidal and poloidal currents in the vessel wall and thus the forces which act on it.

The current flowing from the plasma to the vessel wall was measured directly by Rogowski loops surrounding the base of several of the vessel wall tiles [6]. A comparison of measured wall currents and those obtained from fitted equilibria at several time steps for discharge 63458 ($I_p = 1.0$ MA) is shown in Fig. 2. It is seen that both the magnitude and the time evolution of the Rogowski loop measurements agree closely with the EFIT results. The total poloidal current is about 40 percent of the initial 1.0 MA plasma current prior to vertical movement. The maximum downward force acting on the vessel floor during discharge 63458 is 33,225 lb (147.8 kN). Recent measurements of the current flow from the plasma to the armor tiles

using shunt resistors confirm the measurements made with the Rogowski loops [9].

For each of the EFIT equilibria found, the magnetic forces acting on the vessel wall can be obtained. As discussed in the following section, a good agreement was found between calculated and measured displacements resulting from the calculated forces versus time. The validity of the static part of the model is therefore supported well. The validity of the dynamic part of the model was supported from results obtained from the simulation code based on the physics model and measurements.

According to the model, the time developments of the equilibrium is determined by the electrical resistivity of the vessel wall to toroidal and to poloidal currents and of the plasma. Since the plasma resistivity (unlike the wall resistivities) is not known, a reasonable, time dependent plasma resistivity is used as input to the simulation code. Also, since the simulation code did not include a simulation of the power supplies and its control system, measured coil currents were also used as an input. Otherwise, only the initial conditions were needed to follow the time development of the equilibrium. The equilibria found this way agree well with those found from the EFIT code at several time steps. The calculated total vertical forces versus time using the simulation code and values obtained from the EFIT code for discharge 63458 are shown in Fig. 3. Because of this agreement, it is believed that the dynamical part of the physics model is basically adequate. As mentioned above, predictions can not be made by the code before some determination of the plasma resistivity is specified.

Structural Model; Comparison to Experimental Results

The dynamic response analysis of the vacuum vessel presented in Ref. [1] was updated to apply the impulse load calculated by the physics model and EFIT code for discharge 63458. The calculated maximum load distribution applied to the vessel floor for this shot is shown in Fig. 4. The impulse shape is triangular as shown in Fig. 2 with a pulse time of 16 milliseconds.

The finite element structural model for the analysis was developed using two-dimensional axisymmetric shell elements as shown in Fig. 5. The vacuum vessel is supported on the outer midplane by four equally spaced trunnions which are free to

Fig. 4. Calculated maximum load distribution on DIII-D vessel for discharge 63458.

Fig. 5. Structural model of DIII-D vacuum vessel.

move radially. The model includes the approximate effects of the ports which are modeled with zero hoop stiffness. Lumped masses attached to the ports simulate the port flanges and the various diagnostic attachments. The mass of the armor tiles are included as an effective mass density of the vessel wall. The total weight of the vessel accounted for in the analysis is 52,960 lb.

The fundamental frequency of the vessel was measured to be 21 Hertz. The analytical model was "tuned" to calculate the same fundamental frequency by varying the length of the trunnion. This approach provides the correct dynamic response of the vessel and the most accurate trunnion load history. The first mode shape of the vessel, shown in Fig. 6, corresponds to the maximum deformed shape of the vessel due to the impulsively applied loads.

The vertical load limit of the vessel based on detailed stress analysis of the trunnions is 90,250 lb per trunnion. The calculated load per trunnion for discharge 63458 ($I_p = 1.0 \text{ MA}$, $B = 1.1 \text{ T}$) is 7,800 lb. Discounting the trunnion stress due to dead weight plus vacuum loading, the loads due to a vertical displacement event of a 1.0 MA plasma can be increased by a factor of 12 before over-stressing the trunnion. This updated analysis, using the EFIT calculated vertical impulse loads, provides an additional 88 percent load limit on the vessel trunnions.

Measurement of the motions of the vacuum vessel floor were made using a motion detector at the end of an extension rod as shown schematically in Fig. 7. The vessel floor is effectively extended through a vertical port by a pipe mounted to the inside of the floor. The pipe is capped with a lid and bellows to the port and is restrained in the radial and circumferential directions. An eddy current transducer is mounted to a platform bolted to the machine pit floor. The eddy current transducer provides the transient displacement response measurement and is insensitive to time varying magnetic fields.

A comparison of the measured and calculated vertical displacement versus time of the extension rod for discharge 63458 is presented in Fig. 8. The maximum downward amplitude of the displacement is 0.025 in. This compares to the maximum value of 0.020 in calculated by the dynamic response analysis for the structural model. Agreement within 25 percent between the calculated and measured displacement is considered quite adequate.

The calculated maximum dynamic displacement of 0.020 in produced a maximum load in the vessel trunnion that is a factor

of 12.3 less than the trunnion load limit. Therefore, a maximum allowable deflection of 0.246 in can theoretically be permitted without overstressing the vessel or the support trunnions.

The vertical force on the vacuum vessel is expected to be proportional to the minor radius of the plasma, the plasma current, and the toroidal field. Measurements of the DIII-D vessel displacement agree well with this scaling [10]. Plots of the amplitude of the vertical displacements of the vessel versus plasma current are shown in Fig. 9. Since most of the hard disruptions occurred at near maximum toroidal field of 2.2 Tesla, a linear fit through the maximum displacement at each value of plasma current provides the best representation of peak vessel motion. Linear scaling of this line to the revised displacement limit of 0.246 in shows that a vertical instability event of a 6.0 MA plasma in DIII-D would be required to equal the load limit of the vessel trunnions. The design limit of the DIII-D vessel and coils is for operation of 4.0 MA elongated plasmas. Therefore, the response of the vacuum vessel to vertical displacement events should not restrict operation of the DIII-D device for typical discharge configurations.

$f_1 = 21$ Hertz
Fig. 6. Fundamental mode shape of vacuum vessel.

Acoustics Model; Comparison to Experimental Results

During plasma operation in which vertical displacement events occurred, operators of DIII-D were disturbed by sounds emitted from the tokamak. The sounds were sufficiently loud to be felt as well as heard, and were described as a low boom and a higher frequency bang. A primary concern was that the sounds may be the result of the vacuum vessel or the E and F-coil solenoid motions which could limit operations to reduced plasma currents. A detailed study was performed to (1) determine if the sounds were associated with vessel motion, (2) quantify the sound-vessel motion relationship, (3) determine if the sounds could be damaging to human hearing, and (4) investigate other phenomena related to the sound.

To analytically determine if the magnitude of sound could be the result of vessel motion alone, an acoustics model of a

Fig. 7. Schematic of vessel motion diagnostic.

rigid sphere oscillating in air at 21 Hertz was adopted. The DIII-D vacuum vessel is approximately spherical in shape with a radius of 8 feet. A theory for the sound radiated by a rigid oscillating sphere in an infinite fluid reservoir has been developed in Ref. [11]. Because the vessel deforms elastically rather than as a rigid body, its motion cannot be characterized by a single displacement. Therefore, a range of the displacements measured by the vessel motion diagnostic for a series of shots in which disruptions were intentionally induced was used as input to the analysis.

Time history measurements during disruptions for discharges 55249 through 55671 were made for near field sound, vessel displacements, and vessel accelerations. Measurement of the emitted sounds were made using four microphones located at positions show schematically in Fig. 10. The sounds were recorded and post processed using a structural dynamic signal analyzer. The time histories of all three measurements showed a sharp rise to a peak value near the start of the vertical instability and then a ringdown, oscillating at about 21 Hertz. Typical maximum vessel displacement at the inner wall of the vessel is 0.050 in and typical maximum sound levels adjacent to the vessel are 112 db, 8 pascals.

Spectral analysis of the recording of the near field sounds from DIII-D showed that the time histories were dominated by 21 Hertz sound. Correlation with the frequency of the measured vessel motions confirms that the sounds emitted during vertical

Fig. 8. Comparison of the measured (solid line) and calculated (dashed line) vertical motion of the vacuum vessel.

Fig. 9. Amplitude of vessel motion versus plasma current.

instabilities are due to vessel motions. There was also substantial sound in the 110 to 150 Hertz range. This sound is apparently associated with local plate and bending modes of the vessel.

Comparison between predicted and measured magnitude of sound emitted from the vessel is presented in Table I. The resultant sound pressure, about 0.19 pascal per 0.001 in displacement at 21 Hertz, correlates very well with the sound measured during vertical instabilities. The good agreement between theory and measurement of sound amplitude further demonstrates that the low frequency sound in the vicinity of the vessel is due to the fundamental vibration mode of the vessel.

The sound emitted by the vessel will increase in proportion to the vessel displacements. The present near field sound levels pose no threat to the hearing of humans. A factor of ten increase in vessel displacement would produce sound levels that would be marginally threatening to humans, and certainly would be very alarming to anyone in the vicinity of the tokamak.

Conclusions

The physics model presented in Ref. [3] and developed into a simulation code [7] calculates vessel currents and forces which agree well with experimental measurements. The direct measurement of currents in DIII-D tiles confirms the flow of large attached currents flowing between the plasma and vacuum vessel floor. The MHD equilibrium fits to magnetic diagnostic data using the EFIT code yield poloidal and toroidal currents that are in good agreement with the directly measured values and the values calculated by the simulation code. Good agreement

Fig. 10. Schematic of sensor locations for acoustic measurements.

was found between the forces calculated from the physics model and the forces used to correlate vessel displacements. During a vertical instability, the plasma equilibria calculated by the simulation code using a reasonable input value of plasma resistivity agree with experimental measurements. The simulation code can be used to calculate the vertical instability impulse forces imparted to the vessels of ITER.

An update of the structural dynamic response model using the force-time history predicted by the EFIT code calculates a maximum displacement within 25 percent of the value measured using vessel motion diagnostics. Therefore, the forces calculated from the physics model as confirmed by the vessel current measurements are consistent with the predicted and observed displacements of the vessel. Plots of the amplitude of the vertical displacements of the vessel versus plasma current confirm the physics model that a near linear scaling of the vessel force with plasma current and toroidal field is adequate. Based on stress analysis of the vessel supports, a revised deflection limit on the vessel of 0.246 in will not restrict operation of the DIII-D device.

Table I
Comparison Between Predicted and Measured Sound at 20 Hz

Shot		Measured Peak Displacement (in)	Measured Peak Sound (Pa)	Predicted Peak Sound (Pa)
55645	High	0.051	8.0	9.76
	Low	0.010	4.4	1.91
	Average	0.025	5.9	4.78
55649	High	0.045	6.7	8.61
	Low	0.075	3.5	1.44
	Average	0.023	4.8	4.30
55655	High	0.047	8.2	9.00
	Low	0.06	3.0	1.16
	Average	0.024	5.3	4.50
55663	High	0.050	8.6	9.57
	Low	0.09	4.5	1.72
	Average	0.025	6.3	4.78

The 21 Hertz sound emitted from the DIII-D device following a vertical instability is due to the vessel oscillating in its first natural mode. The amplitude of the measured sounds agrees very well with those predicted by the acoustics model in which the measured vessel motions are input. The 120 Hertz sound appears to be caused by the shell bending modes of the vessel. The sound at present levels is not damaging to human hearing.

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