AXISYMMETRIC AND NON-AXISYMMETRIC STRUCTURAL EFFECTS OF DISRUPTION-INDUCED ELECTROMECHANICAL FORCES ON THE JET TOKAMAK

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The large-scale mechanical response of the JET Vacuum Vessel and other structural components to disruption-induced loads has been analysed. The observed toroidal variations of the VDE-induced rocking motion can be explained by non-axisymmetric plasma forces. New evidence has been found in support of a plasma kink mode model which could account for the generation of the observed sideways forces.

1. INTRODUCTION

Plasma instabilities and, particularly, VDEs (*Vertical Displacement Events*) induce large eddy and halo currents on JET [1] first wall which give rise to deflections of several millimetres and transmit high loads throughout the structure [2]. Research activity is ongoing in order to analyse the structural dynamics of these phenomena from both experimental and computational viewpoints, with the purpose to enable safe machine operation. We shall focus first on the Vacuum Vessel, which is one of the most heavily loaded components, by describing the two main kinds of disruption effects i.e. rocking oscillations and sideways motion.

2. ROCKING MOTION OF THE VACUUM VESSEL

2.1. Axisymmetric rocking motion

Disruption-induced loads are characterised by radial and vertical components of several MN, with typical time scales ranging from 20 to 50 ms. Since the installation of additional Restraining Rings (1989) the Vessel has become quite rigid with respect to radial axisymmetric forces and, in the present configuration, the most conspicuous mechanical effects are due essentially to the vertical loads. Because of the particular arrangement of the supports, which block the vertical movement of all the ports, vertical forces exert a torque around a rotation centre positioned as in Fig. 1 and set the Vessel in a sort of axisymmetric "rocking" motion at ~14 Hz. This oscillation gets excited practically during all dynamic events and can be easily detected from the difference of the radial displacements δ_{MVP} measured at the top and bottom of the Main Vertical Ports (MVP). The qualitative stress pattern in such an event is also depicted in Fig. 1. The stress level throughout the structure is usually low, except for a concentration at vacuum-critical welds located at the corner at the root of the MVPs. Dynamic simulations using a detailed FE model of half an octant and simplified lumped parameter Simulink models with 2 and 3 d.o.f. have been carried out in order to assess the peak stress in various situations, and their results are in good agreement. The vessel response history for a "typical" case of upwards VDE, the most common and dangerous kind of event, is plotted in Fig. 2. The force history includes: 1) an initial steady-state phase, corresponding to the flat-top of the pulse, due to the attraction between plasma and divertor coils; 2) an upwards force pulse due to eddy and the halo currents induced by the plasma instability; 3) a large downwards force swing ΔF due to the plasma current quench and to the currents induced in the divertor coils; and finally 4) a slow decay of the attractive force between the divertor coils and the iron circuit. The most important feature is the force swing ΔF, which determines the dynamic part of the response and is responsible for the swing of the stress that has to be considered to assess fatigue life. The results of these computations, thoroughly validated against experimental data, show that the ratio between the MVP radial

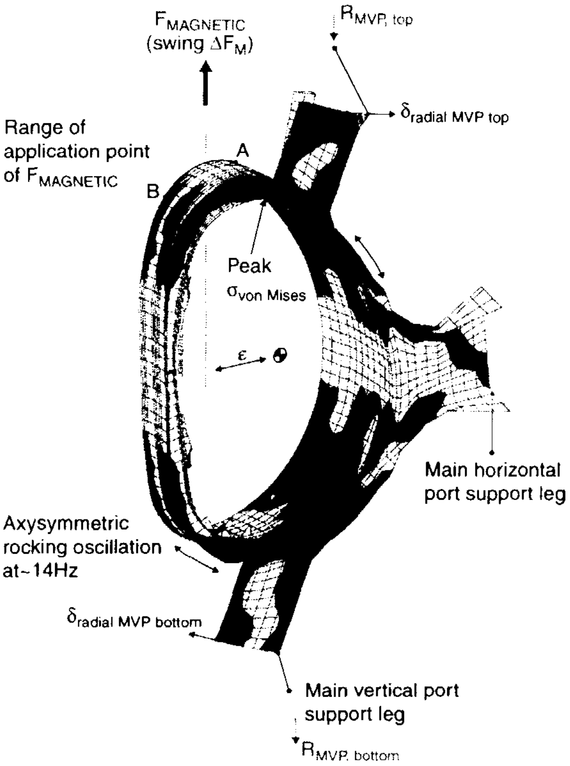

Fig. 1 - FE model showing the rocking motion mode

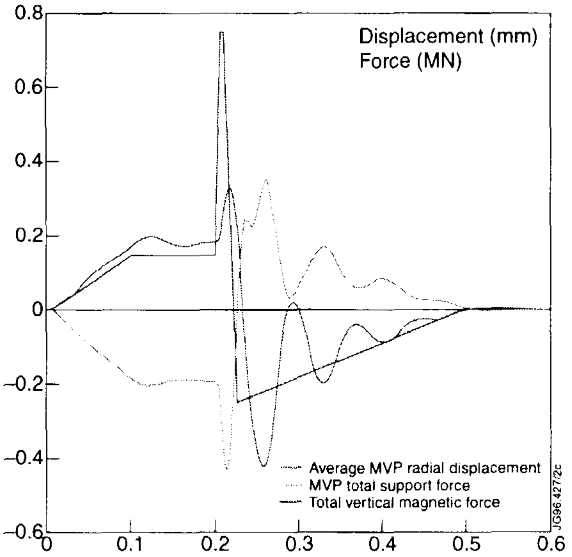

Fig. 2 - Dynamic simulation of vessel rocking motion for a reference case with ΔF=1 MN

displacement swing and the MVP vertical support force swing $\Delta\delta_{MVP}/\Delta R_{MVP}$ is in the range 0.95~1.35 mm/MN, depending on the application point of the resultant ranging from A to B (i.e. going farther from the rotation centre, as shown in Fig. 1). Likewise, the amplification ratio between the magnetic and support force swings $\Delta F/\Delta R_{MVP}$ ranges from 0.8 to about 2.0. This kind of information can be used to deduce the total plasma force for a particular pulse, on the basis of deflection and support force measurements. The stresses at the base of the port have been calculated for many configurations and in the worst expected case, that is a force swing of 11 MN applied in B predicted by MAXFEA for a 6 MA VDE, they would cause a strain not larger than 0.5%. This level of stress could be withstood without danger for 1000+ events.

2.2 Non-axisymmetric effects

Observation of MVP support forces and displacements has led to an estimate of toroidal asymmetries. Deviations from average of strain gauge signals giving support force on each octant up to ±50% were measured, while deviations in the displacement signals are much smaller because of the "equalising" effect of the torsional stiffness of the vessel. Dynamic mechanical simulations indicate that in order to explain these asymmetries a peaking factor[1] of the order of 2 has to be expected in the toroidal distribution of magnetic force. This non-uniformity in the loading has little influence over the rocking motion and the related stresses; however, it may have a localised impact on in-vessel components.

3. SIDEWAYS VESSEL DISPLACEMENTS

3.1 Mechanical analysis of sideways events

According to a model proposed by P Noll [3], the sideways force F_{SW} responsible for the observed horizontal movements of the vessel could be assumed proportional to the difference of plasma moment between opposite octants in the *perpendicular* direction, $\Delta(I_{PLA}z_{PLA})_{PERP}$. This difference, in turn, is directly related to the difference in vertical force applied to the Vessel $\Delta F_{V,PERP}$, which in turn scales with the measured difference in reaction force $\Delta R_{MVP,PERP}$, through a coefficient depending on the vessel's dynamic response. Considering in the first approximation the vessel like a rigid, single d.o.f. system and integrating the sideways impulse equation[2] between the start of the instability τ_0 and the time τ_{peak} when maximum sideways δ_{SW} displacement is reached and the velocity is null, one can see that:

$$\int_{\tau_0}^{\tau_{peak}} (F_{SW} - R_{SW} \_ D_{SW})dt = \int_{\tau_0}^{\tau_{peak}} m dv = 0 \quad \Rightarrow$$

$$\int_{\tau_0}^{\tau_{peak}} F_{SW} dt \propto \int_{\tau_0}^{\tau_{peak}} \Delta R_{MVP,PERP} dt = \kappa\delta_{SW}$$

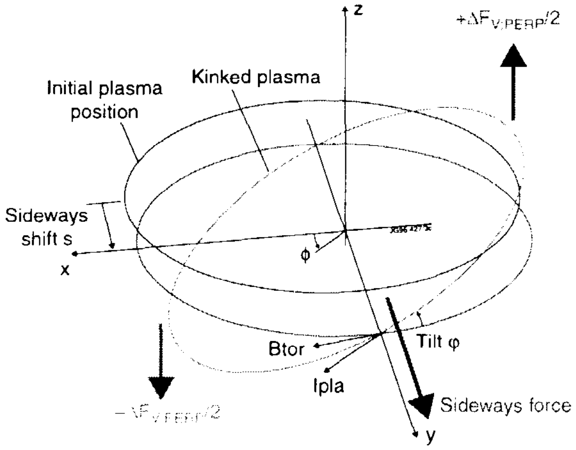

Fig.3 - Kink model for the sideways forces

where it has been reasonably assumed that both the sideways elastic reaction force of the supports R_{SW} and the damping force D_{SW} increase linearly with the amplitude of the displacement. This kind of approach lends itself to relatively easy order-of-magnitude checks: for example, the F_{SW} time scale for pulse 34078 (worst case so far with δ_{SW}=5.6 mm) as estimated from the history of $\Delta R_{MVP,PERP}$ is about 20~30 ms, corresponding to a dynamic amplification factor of ~0.3. Considering that the sideways support stiffness is R_{SW}/δ_{SW}=100 kN/mm and the natural

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[1] Defined as the ratio (max. peak amplitude)/(average amplitude)

[2] Making use of the integrated support force difference signal provides an automatic way of smoothing noisy signals, minimising at the same time the effects of any additional higher frequency modes.

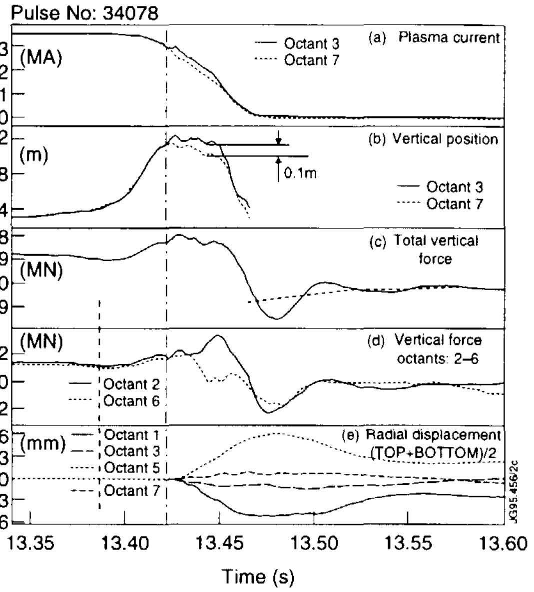

Fig.4 - Experimental data for JET pulse 34078

frequency is about 3 Hz[3], this leads to an estimate F_{SW}=~2 MN (consistent with previous magnetic force calculations [2]). Another interesting correlation comes from the calculation of the proportionality coefficient κ for some JET pulses, which gives consistently $\kappa=\Delta R_{MVP,PERP}/\delta_{SW} \approx 1.5$ kN·s/mm. However, this result is observed only for pulses characterised by sideways displacements > ~4 mm, all of which occur approx. in the direction from Oct.5 to Oct.1. In other cases, where the n=1 mode is probably not locked (or the dynamic response of the vessel to higher modes is not sufficiently attenuated, so that $\Delta R_{MVP} \approx 0$) such correlation is notdetectable. The response of the vessel to rotating forces or asymmetric MHP restraints may account for this, but further analysis is needed.

3.2 Implications of sideways motions for other structural components

The presence of sideways forces raises the question of checking their effects not only on the Vessel, but also on all other components that could react such forces. Basically, all axisymmetric loads are reacted by the poloidal coils, while non-axisymmetric ones seem to be taken up by the toroidal system. According to the above mentioned n=1 kink model, the reaction forces applied to the TF coils might have a sinusoidal distribution which should be evaluated by means of a full 3D simulation. The horizontal resultant of such reaction should ultimately be taken by the P1 coil and the iron limbs, and an assessment of their effects is needed.

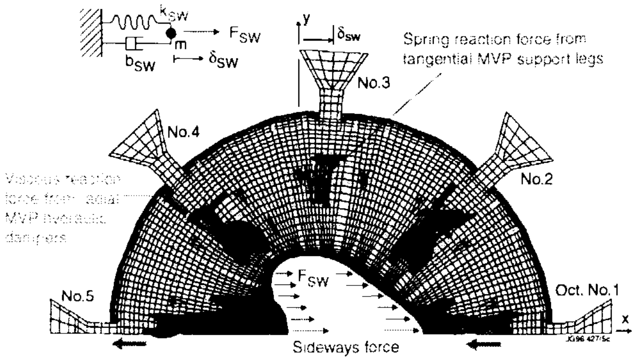

Fig.5 - FE 180° model showing sideways deformation of the Vacuum Vessel

4. CONCLUSIONS

- Mechanical analysis of forces and displacements of JET components (primarily the Vacuum Vessel) can be used "backwards", in order to estimate the characteristics of the magnetic loads that caused them.
- The worst plasma instability that can be reasonably predicted could be sustained by the Vacuum Vessel for ~1000 pulses without any danger of structural damage or vacuum leak. No realistic load can cause failure of the whole Vessel, even if localised force peaks have produced many minor damages in the past and careful analysis is being devoted to in-vessel components [2]. The fatigue life of the MVP root remains the primary concern, especially considering that the machine has already operated considerably above the original design goals and will be probably required to do so for some time to come.
- The effects of non-symmetric reaction forces should certainly be included in the assessment and specifications of any Tokamak machine.

REFERENCES

1. E Bertolini et al, Engineering experience in JET operation, this conference
2. E Bertolini et al, Engineering analysis of JET operation, Proceedings of SOFE '95
3. P Noll et al., Present understanding of electromagnetic behaviour during disruption in JET, this conference

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[3] these values have been observed experimentally and confirmed by FE analyses