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ENHANCEMENT OF JET MACHINE INSTRUMENTATION AND COIL PROTECTION SYSTEMS

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INTRODUCTION

A new system for the monitoring of the vacuum vessel motion due to magnetic forces and thermal cycles, called Machine Diagnostic System, has been installed during the 1995-6 shutdown of JET. Due to the very high neutron fluxes expected during operation under active conditions, only passive probes, such as linear variable resistors (LVR) and strain gauges, are used. Furthermore, the planned increase of the toroidal field above 3.45T has required an extension of the protection algorithms of the existing Coil Protection System to enhance the safety of the machine.

MACHINE DIAGNOSTIC SYSTEM (MDS)

The JET vacuum vessel support and restraint system, from its initial design to the present status is shown in Fig. 1.

When the vessel is at room temperature, 66% of its weight (240 tonnes) is taken by the Octant Joint Support (OJS) springs, equipped with 16 strain gauges, and the remaining 34% by the Main Horizontal Port (MHP) springs.

The top and bottom Main Vertical Port (MVP) restraints (lockable brakes), equipped with 64 strain gauges, take most of the vertical force acting on the vacuum vessel during plasma disruptions or Vertical Displacement Events (VDEs). The axial movement of the brakes is measured with 32 LVRs.

Up to 62 LVRs are used to monitor a wide combination of radial, vertical and tangential movements of vertical ports, horizontal ports and inner walls. The radial movement of the MVPs - top and bottom - is used also to detect the rolling motion [(t-b)/2] excited by a twisting moment M_t applied to each octant. M_t is generated because the vertical force on the vacuum vessel is not in line with the reaction force of the MVP restraints [1].

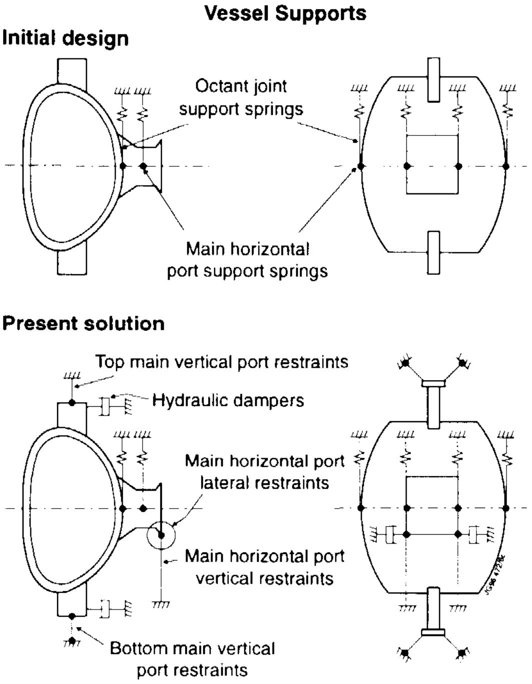

Fig.1 - JET vacuum vessel supports and restraints

The lateral restraints of the MHPs, monitored by 16 pressure gauges, have been introduced very recently to reduce the vessel sideways displacements. Four triaxial accelerometers, in the range 0 to 50g, have been installed at the MHPs of octants 2, 4, 6 and 8

The monitoring of mechanical transients of a tokamak machine is strongly affected by the time-varying magnetic fields. The noise induced by the magnetic field on the sensors is reduced by using a carrier at 5 kHz followed by demodulation.

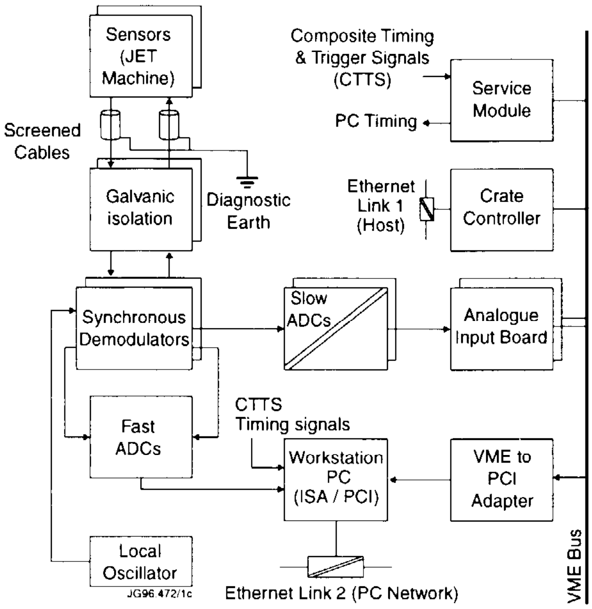

Fig. 2 - MDS hardware configuration

The demodulation is used to separate a sine wave, generally of a few mV, from a noisy signal, such as the output of a strain gauge bridge, and to determine its amplitude. In addition, the demodulators are synchronised to avoid noise generated from beating frequencies.

A new type of accelerometer and displacement sensor, insensitive to electrical noise, based on fibre optics and interferometer, is being tested for future application to JET and next step machines.

The VME based data acquisition system (Slow ADCs) is designed to sample up to 192 channels with a resolution of 16-bit. The data are sampled at 5 kHz and stored at 25 Hz every pulse and at 5 kHz in case of plasma disruption. After the pulse the data are transmitted to the host computer for the post pulse analysis. In addition, a sample of each channel is transmitted to the host continually at time intervals of 4s. The data on VME are accessible in real-time by a standard PC Workstation, via VME-PCI adapter. The PC is used for faster data acquisition (Fast ADCs) of a fewer channels, to compute power spectra and to test some fault detection algorithms, using a standard signal analysis package - LabVIEW - prior to implementation on a final target.

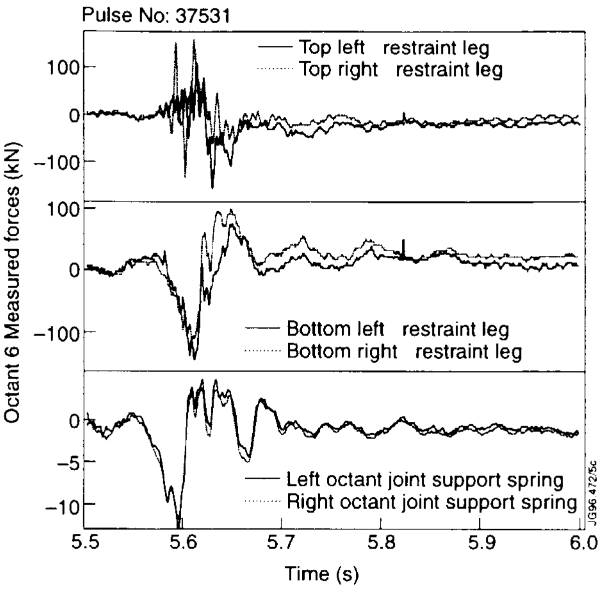

Fig. 3 - Forces on restraint legs and OJS springs

Figure 3 shows the force oscillations (ΔF) at top and bottom of octant 6 MVP restraint legs and OJS springs during an upward VDE with plasma current at 3 MA. The VDE was due to a loss of vertical stabilisation as a consequence of plasma internal perturbations. The net peak force measured on each octant varies from 200 to 300 kN with an estimated total peak force on the vacuum vessel of 2 MN. The net sideways displacement in the direction of octants 1-5 was 2.5 mm.

Figure 4 shows the variation of pressure (ΔP) in the lateral supports of six MHPs, during a plasma disruption at 3.8 MA and maximum sideways displacement of 1.6 mm. The ΔP in each lateral support is about 20 bar which corresponds to a reaction force of 14.3 kN. The peak tangential displacement - in average - is 0.6 mm. The poorly damped oscillation at 15 Hz on octant 2 right restraint is due to the rolling motion of the vessel.

The oscillation at 30 Hz on the tangential displacements has been observed also on the spectra of the radial displacements, not reported here, together with a further poorly damped oscillation at 40 Hz. These oscillations at 15, 30 and 40 Hz coincide with the 2nd, 4th and 6th harmonics estimated with a modal analysis of the vacuum vessel. Harmonics in the band 100-200Hz have been observed on the MHP accelerometer signals.

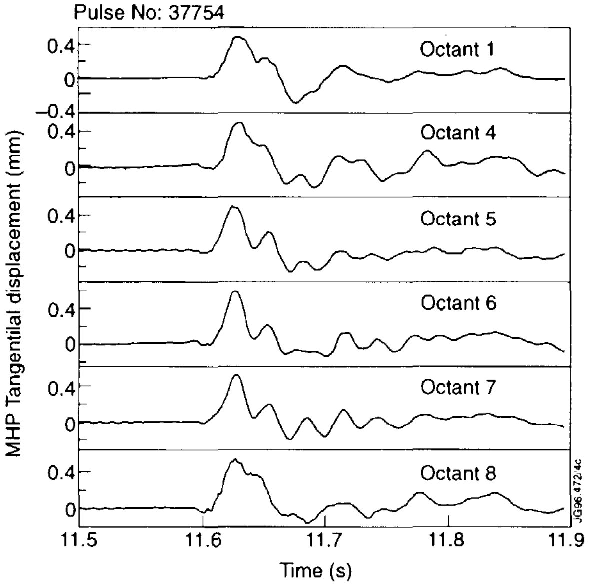

Fig. 4 - MHP tangential displacements

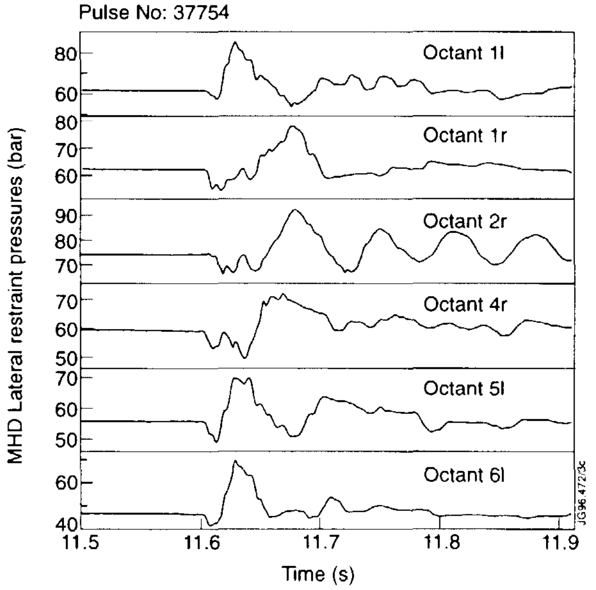

Fig. 5 - Pressure variations of MHP lateral restraints

COIL PROTECTION SYSTEM (CPS)

The system became operational in May 1994. The aim of CPS is to detect electrical faults and to protect the coils against mechanical or thermal over-stressing due to operation outside safe limits [2].

The protection implemented are: over voltage and over current for all the circuits; circuit equation simulation and comparison with the measured currents; ampere turn protection; tensile, shear and thermal stresses of poloidal and divertor coils. The protective actions include immediate removal of the voltage from the coils and circuit breaker trip.

The tensile and shear stress of the poloidal coils (P2-4) and divertor coils (D1-4) is computed as a linear combination of the vertical force, radial force and energy dissipated. The radial and vertical force of each coil are computed with flux loops and ampere turn measurements.

The main protection is implemented in VME by means of four high performance DSPs, working in parallel. About 170 electrical signals (e.g., voltages and currents) are sampled at 1 kHz and 30 thermal signals at 10 Hz. During the pulse, samples of the collected and calculated signals are simultaneously stored in 8 Mbytes of shared memory. After each pulse these are collected by the GAP programme on the host and archived. The system is backed-up by a hardware protection, incorporating over current during and outside pulses for all the circuits and over temperatures for the divertor coils.

A comparison between measured ampere turn (AT) and computed ampere turn (nI) for divertor coil D3 and a TF coil is given in Fig. 6. The maximum deviation is 1.33% for D3 and only 0.27% for the TF coil. A further reduction of the error is possible with a refinement of the compensation of the external fields.

FUTURE DEVELOPMENT

TF coil expansion. During pulses the TF coils expand in the radial direction (outward only) and in the vertical directions. This motion can be approximated, on a slow time scale, by a linear combination of the in-plane magnetic force - due to the interaction of the current with the toroidal field - and the dissipated energy.

$$\delta = K_m I_{tf}^2 + K_{th} \int I_{tf}^2 dt \qquad (1)$$

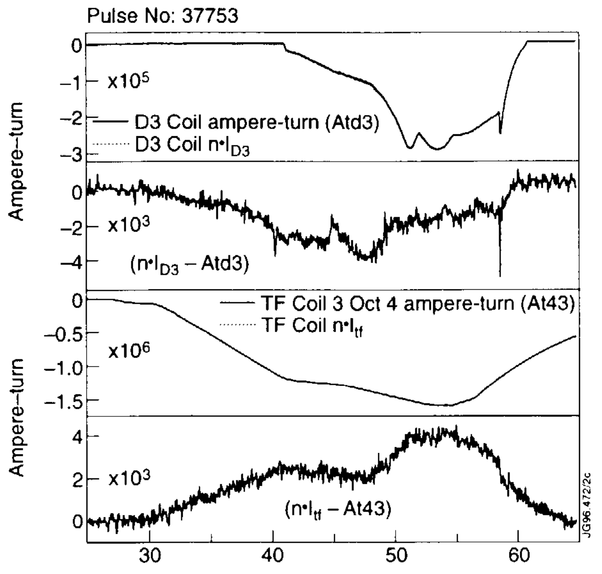

Fig. 6 - Ampere turn of a divertor and TF coil

The parameters K_m and K_{th} have been estimated experimentally for the radial displacement of 12 TF coils using a least square estimation algorithm available in MATLAB: $K_m = 28.1\Diamond 10^{-11} \pm 23\%$ (mmA^{-2}) and $K_{th} = 28.2\Diamond 10^{-12} \pm 5\%$ $(mmA^{-2}s^{-1})$. After the pulses, each coil reaches its rest position as the coil cools down. This simple model can be extended outside pulses introducing the time constant of the cooling. The monitoring in real time of such displacements is quite useful and, since it is not time critical, it has been proposed to implement it on a UNIX workstation connected to the host computer.

TF coil out-of-plane force and stress protection. Algorithms have been established for the calculation in CPS of the out-of-plane forces on the ring and collar teeth of a TF coil on the basis of the measured TF current (I_{tf}) and flux loop measurements (ϕ_{normal}). The maximum shear and tensile stress can occur at several places (at least 5 in the top and 5 in the bottom) within the coil. At each point (i) the mechanical stresses (s) can be expressed as a linear combination of the in-plane force, scaling with $I_{tf}^2 r^{-1}$, and the out-of-plane force scaling with I_{tf}.

$$s_i = a_i I_{tf}^2 + I_{tf} \sum_{k=1}^{10} b_{ik}\Phi_k \qquad (2)$$

Other effects, such as thermal gradients, are left aside. The out-of-plane forces are characterised by an irregular distribution, depending on the magnetic configuration and the real plasma parameters of each pulse, that are difficult to predict a-priori. The fluxes f_k are obtained as averages of the signals from flux loops installed on TF coils D24 and D64. The computed out-of-plane forces and mechanical stresses will be compared with two limits set at 5% and 10% above the allowable levels of stress.

P1 coil stress and controlled decay. During pulses the outward magnetic force on P1 coil is balanced by the inward pressure of the TF coils. Analytical expressions for the hoop, radial, vertical and von Mises stresses, as a function of the P1 current, ΔT and I_{tf} have been specified and are due to be implemented in real-time in CPS. The allowable limit is 60 MPa. A "coherent" decay of P1 and TF currents is required during the termination of the pulse to keep the stress in the safe region.

CONCLUSIONS

The number of sensors for the monitoring of the vacuum vessel motion has been increased substantially during the last shutdown of JET. The positive experience gained at JET with VME suggested to use the same technology, with automated fault detection, for the instrumentation of the machine. Finally, the upgrade of TF to higher fields requires the implementation, in real-time, of additional algorithms for the evaluation of the stress in the magnetising coil (P1) and TF coils.

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1. E. Bertolini et al, "Engineering analysis of JET operation", *Proc. 16th Symposium on Fusion Engineering (SOFE)*, Champaign, Illinois, USA, 1995.
2. V. Marchese et al, "Detailed design, installation and testing of the new coil protection system for JET", *Proc. 18th Symposium of Fusion Technology (SOFT)*, Karlsruhe, D, 1994.