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ABSTRACT.

In JET, the presence of an elongating quadrupolar field makes the plasma vertical position unstable. The Vertical Stabilisation (VS) system has been developed in order to keep plasmas for a time longer than the vessel field penetration time constant. This system controls the plasma vertical velocity to zero. Its present plasma vertical speed observer is affected by several problems, which reduce the operating range of the system. New hardware has been designed and is now being installed, aimed at solving some of these shortcomings. The main component is a new hybrid (digital-analogue) signal combination card, which should enable a better tuning of the VS system. In addition an increased set of magnetic measurements will be used.

1. THE VS SYSTEM

The VS is a control system dedicated to control the plasma vertical speed. It uses the measurement from a magnetic observer of the quantity $\dot{z}_p \cdot I_p$, the plasma vertical speed scaled by the plasma current, to drive a combination of poloidal coils producing radial field (Lennholm et al [1]). This allows the VS to vertically move the plasma equilibrium position, and by placing it ahead of the plasma position, in the direction of its vertical movement, the system is able to keep the plasma speed under control. At the same time VS is also slowly trying to control the average radial field close to zero, in order to avoid both displacing the plasma vertically and exceeding the limits of the power supply (Fig.1).

The present speed observer was originally designed to measure the plasma vertical moment derivative using 64 different pickups and saddles placed around the machine vessel combined using coefficients derived from the Zacharov-Shafranov equation (Shafranov et al [2]).

$$(z_p \dot{I}_p) = \frac{1}{\mu}\oint\left[z \times \frac{dB_t}{dt} - R \times \log\left(\frac{R}{R_0}\right) \times \frac{dB_n}{dt}\right] dl = \sum_n W_{pk} \times V_{pk} + \sum_n W_{sad} \times V_{sad}$$

Then the feedback quantity, the plasma vertical speed scaled by the plasma current, is calculated using this formula:

$$\dot{z}_p I_p = (z_p \dot{I}_p) - z_p \dot{I}_p$$

The present speed observer hardware uses resistor networks to create 8 combined signal parts of the vertical moment derivative calculation, and 4 parts of the plasma current derivative. These two observer signal parts are divided in components depending on the position of the sensors: top and bottom of the machine and octant 3 and 7. The vertical speed moment derivative signal is furthermore divided in combination of saddle loops and pickup coils. (Fig.2)

These signals are acquired by the VS real-time controller, a VME system composed of a network of 4 20Mhz DSPs (TMS32C40), 6 four channel 1MHz ADC cards and one DAC. (Sartori et al. [3])Together they implement a proportional plasma velocity feedback and a proportional/integral amplifier current feedback. The speed loop gain is continuously adapted to variations in the plasma growth rate by an adaptive controller.

The power amplifier, FRFA, is composed of a series of four very fast GTO H-bridge units, capable of switching in about 100ms and of driving +/-2.5KA and +/-2.5KV. Each unit is not Pulse Width Modulation (PWM) controlled, and therefore the FRFA can produce only 9 voltage levels. The switching devices, GTOs, are either working with no current or with almost no voltage across their terminal. It is only during the transition that some power is dissipated. As a result the junction temperature is proportional to the switching frequency. (Bonicelli et al [4])

VS control system and FRFA form together a bang-bang controller: when the plasma speed is above a threshold, the amplifier is switched on, until the signal has reversed and fallen below a second threshold. The resulting oscillating behaviour is the main cause of FRFA dissipation.

2. THE NEW VS ACQUISITION SYSTEM

A new analogue processing system is being developed at JET to act as a speed observer for the plasma vertical movements. This new system will combine 128 magnetic measurements taken from 4 different octants. Half of the probes are the same as those used for the old speed observer, half are taken in the same poloidal positions but from 2 new toroidal locations. As a result, for each poloidal position there are 4 different measurements distributed toroidally every 90^o.

The system will produce two outputs to the digital controller, each the linear combination of the 128 inputs. While, on one hand, this will allow replicating the present acquisition system, providing both the vertical moment derivative and the plasma current derivative, it can also be used to switch between two different sets of gains. While the VS is using the first signal with the old weights, the second channel is being set-up with the new gains; then the controller will gradually switch between the signals, thus avoiding the problem of the not simultaneous settling of all DACs.

A newly developed analogue-digital hybrid module, the UAAB, provides the services of both separately isolating 8 signals with a 100kHz bandwidth, and of combining them with variable weights. The UAAB modules are remotely controlled via a multi-drop RS485 network running at 9600 bit/s. From a VME computer with an RS232 interface it will be possible to monitor the status of the cards and to change the gains (Fig.3).

On this two wire serial network up to 255 different UAAB modules can be connected and controlled at the same time. Given the relatively low speed of the network, an average communication will normally take more than 10ms to complete. This means that it is not possible to load the gains on each card during the pulse. The same result will be obtained by instead preloading several sets of weights before the pulse on each card. The simultaneous installation of a set of weights will be achieved by broadcasting a single short command. The UAAB provides also several self-diagnostic features: its internal temperature, the quality of the supply voltages, and the measurement of its outputs and inputs.

3. THE UAAB ACQUISITION CARD

The UAAB is a module developed by UKAEA specifically for the JET VS. The main design objective was to be able to build a high density VS acquisition system with a higher flexibility and expandability. The card has been designed around the AD215 isolation chip. Providing more than 100Khz bandwidth coupled with 1.5KV isolation and integrated DC-DC converter it was the ideal candidate for the project. Its size allowed for installing 8 units on a 3U eurocard using just about 30% of the available space. The remaining area was then used to install an instrumentation amplifier on each input and to host the multiplier DACs and the power regulators. The digital circuitry had to be placed on a daughterboard (Fig.4).

The card provides two summed outputs, created as combination of 8 inputs with two internally generated offset corrections. The weights and the offsets are set by the internal 89C51 microprocessor, which is fitted with 64Kb of internal FLASH and 32Kb of RAM, enough storage space to contain more than 1000 pre-programmed weight selections. The download of the weights and the remote control of the processor are performed via a multi-drop RS485 network.

The board firmware is designed for expandability. It is possible to write a program to be run in each card. The program can be remotely installed via RS485 and the set of user commands can be expanded so that to activate the new functionality.

The card layout was also designed for flexibility and reusability. In addition to the two summed outputs, the module offers either the 8 isolated inputs or the eight weighted and isolated inputs as outputs on the backplane (selected by jumpers). By assembling the unit without daughterboad and multiplying DACs the board becomes a high-density isolator module (Fig.5).

4. LIMITS OF THE CURRENT VERTICAL STABILISATION ADDRESSED BY THE NEW SYSTEM

When JET was upgraded with internal divertor coils, in order to provide a mechanical support for the divertor tiles with the necessary mechanical precision, it was decided to insert a u-shaped toroidally continuous ring of steel. On the two sides and underneath, 4 concentric rings of copper conductors pancakes form the divertor coils, which are used to control both the strike point position and the flux expansion in the area. (See figure 6) (Garribba et al. [5])

The first problem introduced by this new configuration was that the plasma vertical moment derivative ($\dot{z}_p \cdot I_p$,) measurement had a strong pickup from the divertor current amplifier noise. Trying to correct the problem by adding a measurement of the current derivative on the support structure and on the divertor coils resulted into a failure because of the different frequency response of the different signals. The problem was partially solved by adding filters to the divertor power supplies.

The second problem was that every plasma movement induced a transitory current in both the divertor coils and the support structure. Because of this all the magnetic probes behind the divertor are shielded from promptly seeing the plasma movement. This filtering effect on part of the speed observer measurements meant that the overall signal was distorted and delayed, thus affecting the

VS performance. Eventually a solution was found where the signal combination of the pickups on the bottom of the machine was discarded: it provided a fast signal, but with a strong coupling with the plasma current derivative and radial moment derivative. The new acquisition system, providing independent weighting of each coil, should allow the development of a better solution.

The new divertor configuration has allowed physicists to operate the machine with plasmas with much higher elongation (up to 1.9) and higher triangularity (up to 0.5), both of which significantly increase the plasma instability growth rate (up to $500\mathrm{s}^{-1}$). Stabilising these equilibria requires a fast plasma speed measurement, which cannot certainly be obtained using probes placed outside the machine vessel. (Vessel time constant of about 3ms). For this reason a speed observer using only internal pickup coils will be studied.

Often, some plasma magnetic events act as disturbances to the control system, causing the FRFA temperature to raise up to the tripping point. These disturbances act by either adding to the velocity signal and therefore anticipating the switching, or by directly driving the FRFA output. n=2 MHD activity is the most usual sources of this noise.

A generic MHD disturbance component can be modelled as $D_{M,N} = \mathrm{Re}\{A \cdot e^{j2\pi ft} \cdot e^{jM\varphi} \bullet e^{jN\theta}\}$ where φ is the poloidal angle and θ the toroidal one. In the new speed observer four measurements displaced at 90° toroidally and at the same poloidal position are summed with equal weights. The resulting MHD noise can be modelled as follow $A \cdot e^{j(2\pi ft + M\varphi)} \bullet [1 + e^{jN\pi/2} + e^{jN\pi} + e^{jN3\pi/2}]$. Table 1 shows the effect of the signal combination on the mode amplitude . The new vertical speed observer, by summing four octants measurements, will be insensitive to all the modes n, m but those with a toroidal number multiple of four.

A different source of disturbance is the ELM. Small and frequent ones can cause the FRFA to overheat. A work by Hofmann et al. [6] has demonstrated that by choosing the right gains the observer can be made relatively more insensitive to these disturbances. Giant ones tend to create a big disturbance that put the plasma far out of equilibrium. In these circumstances VS is sometimes incapable of keeping the plasma vertical position.

5. DISCUSSION

After commissioning of the new system, for the following months the new system will be operated as an open loop speed measurement and occasionally as a feedback quantity during specific time windows. Once all the problems had been ironed out and a standard setting had been found, the new system will completely replace the old one. From then on, JET operational range will be increased: n=2 MHD will be eliminated as cause of vertical control failure. The disturbances caused by ELMs should also be reduced, since being local, are equivalent to a combination of MHD disturbances. In addition, new weights for the observer will be studied, with the hope of better handling both ELMs and highly shaped plasmas.

Recent experiments have shown that by switching off the VS for 1ms during and after a medium ELM, the overall plasma behaviour was better controlled. In some cases, after a giant ELM, the plasma started ramping vertically with a steady speed for several milliseconds, while at the same time the FRFA was applying maximum voltage to the coils. Both behaviours certainly seem inconsistent with an unstable plasma vertical position. Are all these problems caused by the shortcomings of the speed observer? Is the speed observer mistaking the plasma current derivative and the plasma radial speed with a vertical speed? The new observer will also be used to try to answer these questions.

ACKNOWLEDGEMENTS

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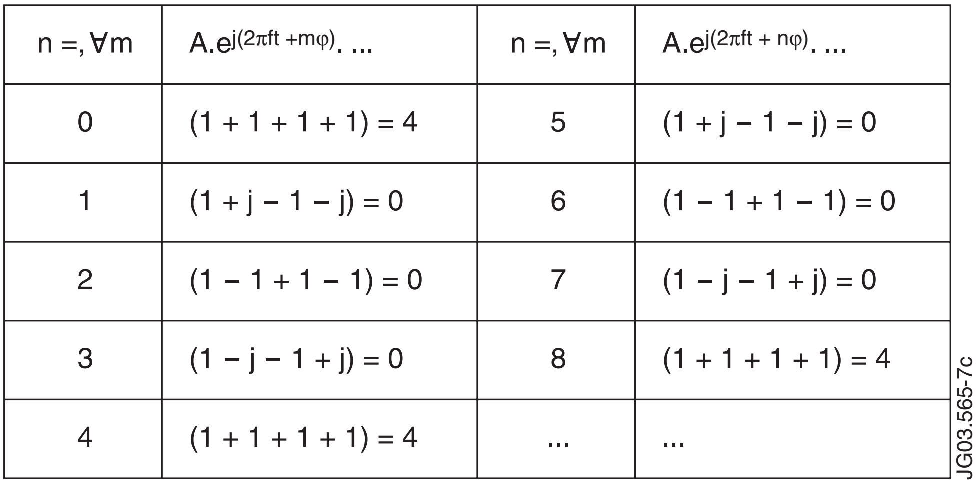

$n =, \forall m$	$A.e^{j(2\pi ft + m\varphi)}. \ldots$	$n =, \forall m$	$A.e^{j(2\pi ft + n\varphi)}. \ldots$
0	$(1 + 1 + 1 + 1) = 4$	5	$(1 + j - 1 - j) = 0$
1	$(1 + j - 1 - j) = 0$	6	$(1 - 1 + 1 - 1) = 0$
2	$(1 - 1 + 1 - 1) = 0$	7	$(1 - j - 1 + j) = 0$
3	$(1 - j - 1 + j) = 0$	8	$(1 + 1 + 1 + 1) = 4$
4	$(1 + 1 + 1 + 1) = 4$	...	...

Table 1: The mode rejection at different values of the toroidal mode number N.

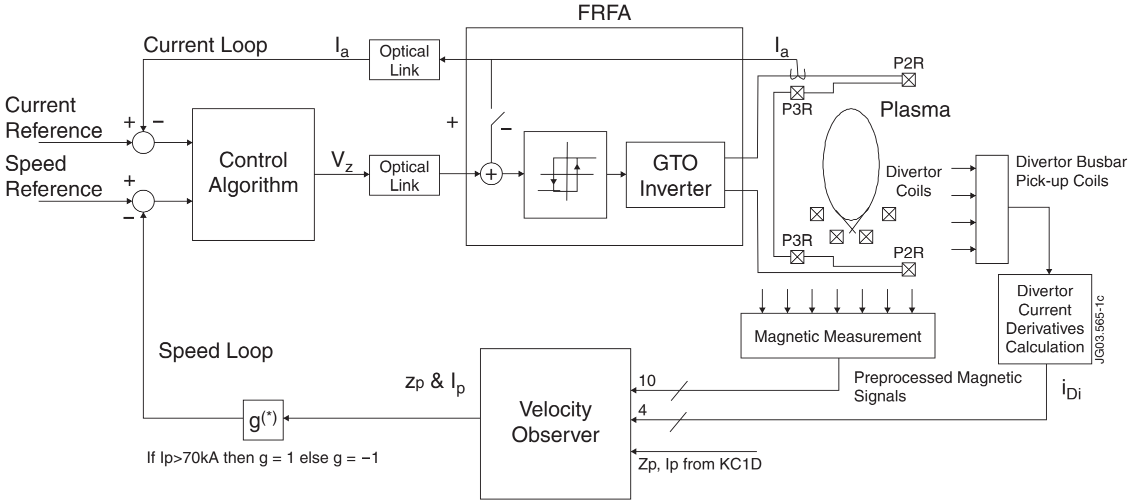

Figure 1: The block diagram of the VS System including the amplifier and the plasma.

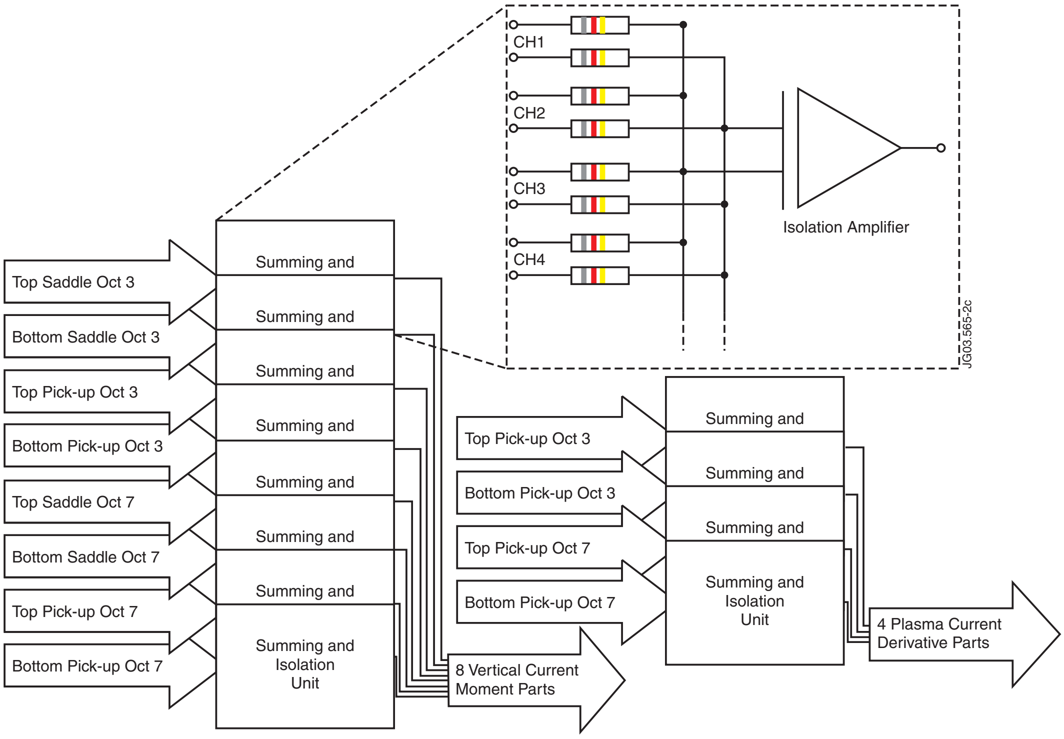

Figure 2: Old speed observer. Each summer is made by passively combining signals using resistors.

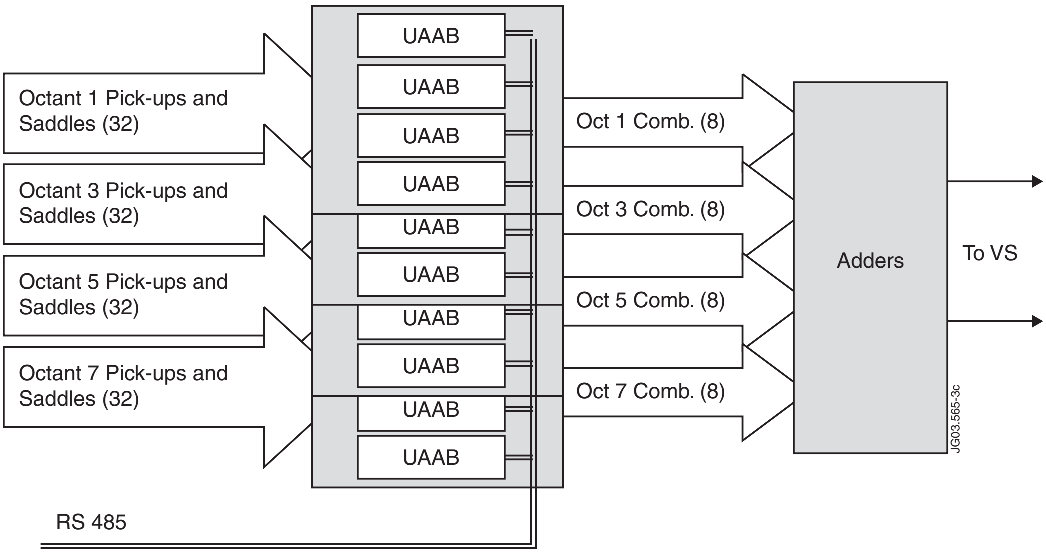

Figure 3: The new VS acquisition system composed of UAABs, separately isolated, variable weight summers.

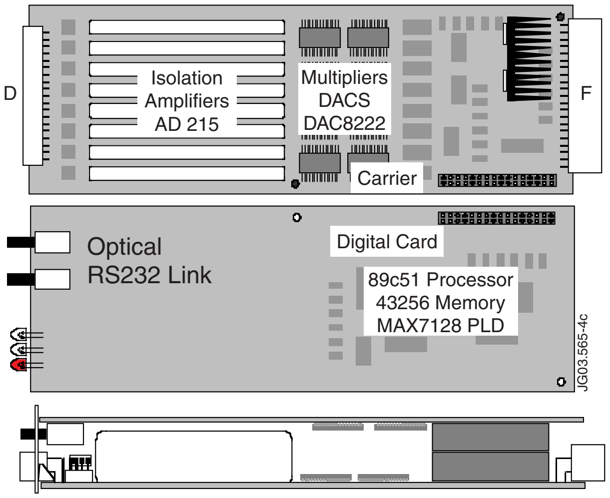

Figure 4: The layout of the UAAB module. On the top the analogue board, in the middle the digital controller and finally the assembled module seen from its top side.

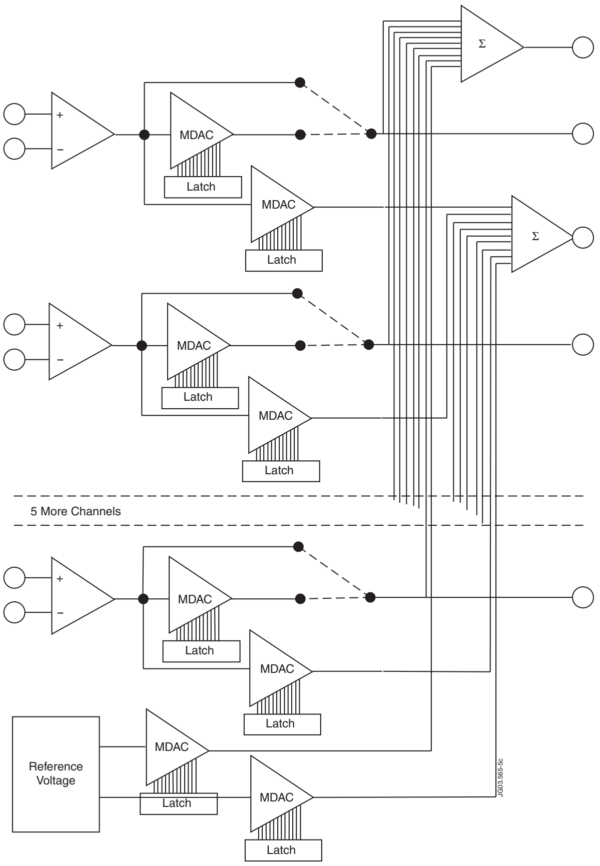

Figure 5: The block schematic of the analogue part of the UAAB module.

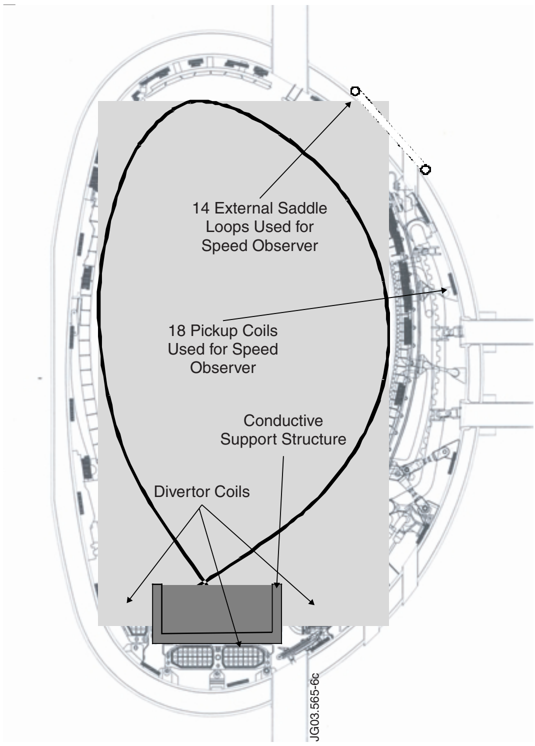

Figure 6: Picture of the Jet machine cross section. Note on the bottom the divertor support structure and the 4 power coils.