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MSE diagnostic signal processing using software Phase Locked Loop and Empirical Mode Decomposition

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1 – Introduction

The continuous progress in fusion plasma technology and comprehension of the stability and confinement properties of Tokamak fusion plasmas offers encouraging support for the success of ITER. Plasma diagnostics are essential for real time plasma control and the reconstruction of important plasma radial profiles such as the ion/electron temperatures and densities, ion toroidal angular rotation, the plasma current density and the safety factor *q(R)*. The latter two, in particular, are essential for the assessment of the discharge operational regime (ohmic, reversed shear or hybrid) and for the integrated plasma modelling. Probing directly inside the plasma, the Motional Stark Effect (MSE) diagnostic is one of the best techniques to evaluate the radial q-profile[1]. In the MSE diagnostic installed at JET[2], the direct determination of the magnetic field pitch angle is made measuring the polarisation angle of the $+\pi$ component of the Stark splitting of the Balmer D_α emission from deuterium atoms injected by the heating neutral beams[3]. Polarised light from all 25 spatial channels, covering the full outboard minor radius, is intensity modulated at characteristic frequencies, 20 and 23 kHz, by two photo-elastic modulators (PEMs). Making use of a set of 25 Avalanche Photo Diodes (APDs) and associated fast tunable narrow band filters, one gets Amplitude Modulated (AM) (at harmonics of the PEM modulation frequencies)[4] electrical signals which are then digitized at 250 KSample/s.

2 – Software PLL implementation and pitch angle processing

The following sub-section describes the kernel of the MSE diagnostic signal processing including the PLL algorithm, the basis of the pitch angle calculation. Sub-section 2.2 addresses the pitch angle post-processing used not only to improve signal to noise ratio but also to provide the user the capability of selecting relevant time scale events.

2.1 - Phase-Locked Loop and Amplitude extraction

The quality of the inferred pitch angle ($\gamma = B_\theta/B_\varphi$) depends strongly on the algorithm used for the determination of the amplitudes of the DC, 23, 40 and 46 kHz frequencies (due to the particular MSE setup at JET) present in the APD signals. A PLL is suitable for this purpose and in JET, the software approach has been preferred. Since the PEMs retardance varies as *cos(cos(*ωt*))*, it is possible, with appropriate Band-Pass Filters (BPFs), to extract, from the digital reference signals, waveforms corresponding to odd and even harmonics of the fundamental excitation frequencies. Since the waveforms are not normalised, as an alternative to performing a least square fit with a fixed frequency (20 and 23 kHz), we have found more appropriate to obtain the instantaneous phase (φ) of the desired harmonics. A 500 Hz band-pass FIR is firstly applied (centred about each pertinent frequency) and the correspondent analytical signal is built using the Hilbert transform. Mixing the *cos(*φ*)* and *sin(*φ*)* signals with the APD and extracting DC yields the in-phase and quadrature amplitudes of the required frequencies. At this point, standard decimation is performed to 1 kSample/s. Extraction of the harmonic amplitudes requires minimisation of the quadrature signals. In our implementation, a simple (shot and channel dependent) linear regression yielding $tan(\theta_{Rot})$ is done on the I-Q plot in order to apply a rotation matrix to both in-phase and quadrature amplitude signals, guaranteeing optimal performance for every shot/channel in a fully automatic way. We could also use the Hilbert transform to extract the relevant instantaneous amplitudes of the BPF APD components, without resorting to the PEMs excitation waveforms. However, an offset in the extracted amplitudes due to rms noise effects and an inadequacy to follow sign changes in the amplitudes (in particular the 23 kHz but also in the 46 kHz harmonics) are significant handicaps that discourage such a scheme.

A Matlab based Graphical User Interface (GUI)) has been developed for reading/processing JET MSE data, making use of MDSplus and the above PLL. Since the full record of 750 kSample signal is read/processed for each channel, benchmarks indicated an average of 10 minutes to extract the complete set of amplitude signals required for each shot. A significant improvement in the overall performance is achieved with an implementation of the Local Area Multicomputer Message Passing Interface environment for Matlab, with a fully portable MPI standard compliant Application Programming Interface. The processing is spread over 5 nodes, taking advantage of the JET Analysis Cluster (JAC), yet constrained by the limited amount of Matlab licenses, yielding an average computational elapsed time of the order of 4 minutes for typical JAC usage.

2.2 - Pitch-angle Post-processing

In JET, the magnetic field pitch-angle (γ) can be extracted using the following relation:

$$\tan(2\gamma(t)) = \frac{C_{21}A_{DC}(t) + C_{22}A_{23}(t) + C_{23}A_{46}(t) + C_{24}A_{40}(t)}{C_{11}A_{DC}(t) + C_{12}A_{23}(t) + C_{13}A_{46}(t) + C_{14}A_{40}(t)},$$

where $A_{xx}(t)$ are the *xx* component amplitudes mentioned previously and C_{ij} are diagnostic calibration coefficients[5]. It is important to offer the user the capability of selectiveness in terms of relevant time scales of the γ evolution. The limitation of 3000 samples discourages the use of linear phase (FIR) filters and conventional (moving average) smoothing of data provides inadequate frequency response. Empirical Mode Decomposition (EMD)[6] is a powerful method for extracting individual frequency events in the time domain, acting as a user-interactive adaptive filter bank. Through a *sifting* process, a signal is decomposed into elementary signals, called Intrinsic Mode Functions (IMFs) with the same length as the original signal and meaningful instantaneous frequency, plus a residue (basically the DC signal trend). Orderly subtracting IMFs from the original signal gradually removes distinct time scale events whilst preserving local signal trend. A good example of EMD performance is shown in Figure 1, where only the highest frequency IMF (1st out of a total of 6 IMFs plus the residue) is removed from the original signal. Since EMD is a signal dependent process, increasing the time window of interest will, in general, result on an increasing number of IMFs and some frequency leakage among neighbouring IMFs. Therefore, the relevant IMFs containing the time scales of interest to the user may differ, depending on the signal length and stopping criteria[7].

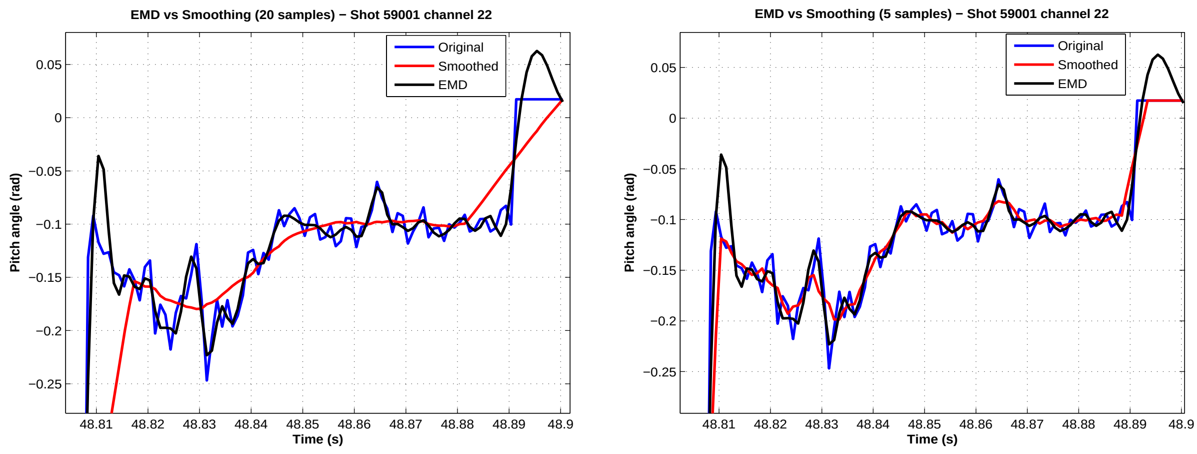

Figure 1 – Comparative performance between EMD and boxcar smoothing 20 ms (left) and 5 ms (right)

3 – Application to equilibrium reconstruction

The MSE signals processed with the EMD technique in a time scale of one millisecond, have been used as constraint for EFIT code in JET discharge 66558. The reconstructed equilibrium profiles are shown in Figure 2. Here the red traces represent the profiles obtained using the EMD technique, while the blue curves corresponds to profiles where the MSE data was smoothed to 20 milliseconds (partly to attenuate the 50 Hz component, and correspondent harmonics, arising from modulation of the NBI power waveform) which is a routine procedure at JET. From Figure 2 it is possible to observe very little changes in using both methods. For this time slice some evidence (by means of Alfvèn cascades activity) to support a slightly reversed q-profile would be possible, therefore one cannot rule it out completely.

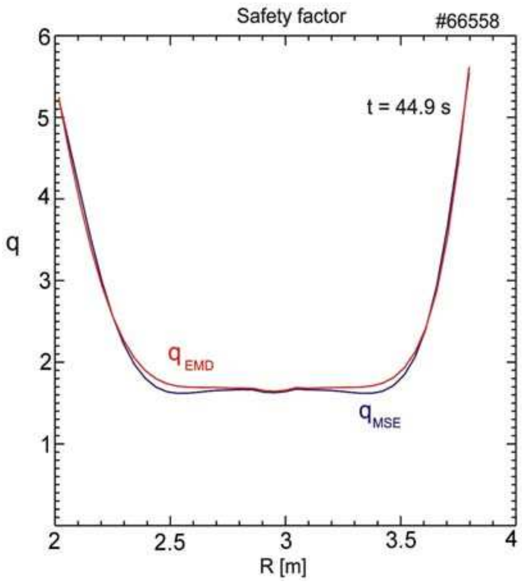

Figure 2 – Equilibrium reconstruction profiles with MSE data smoothed to 20 milliseconds (blue curve) and processed with the EMD technique (red curve) in 1 millisecond time scale.

4 - Conclusions

The software PLL scheme described here allows for frequency jitter tracking in a bandwidth of 500 Hz as opposed to the (fixed frequency) least-square fit currently applied. In addition, optimal quadrature minimisation is guaranteed for every channel/shot reducing error propagation in the pitch angle and q-profile calculation. The EMD technique can be used offline as an alternative to the conventional smoothing of MSE data improving high frequency filtering performance whilst preserving local signal trend. Future work involves the application of EMD to pulses where the detrimental effect of ELMs in the MSE signals is most severe. This technique has already been applied successfully for similarly fast events (turbulence) in the ISTTOK tokamak[8].

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