Analysis of W7-AS Mirnov data using SVD and correlation techniques

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Introduction: The modular stellarator W7-AS is equipped with three poloidal arrays of Mirnov probes, two with eight, one with sixteen coils measuring the rate of change of the poloidal magnetic field. Data are acquired at a rate of $333kHz$ and $250kHz$, respectively. Analysis comprises SVD, correlation and Fourier techniques. The aim is to identify MHD instabilities, the influence of which on stellarator confinement is often unclear.

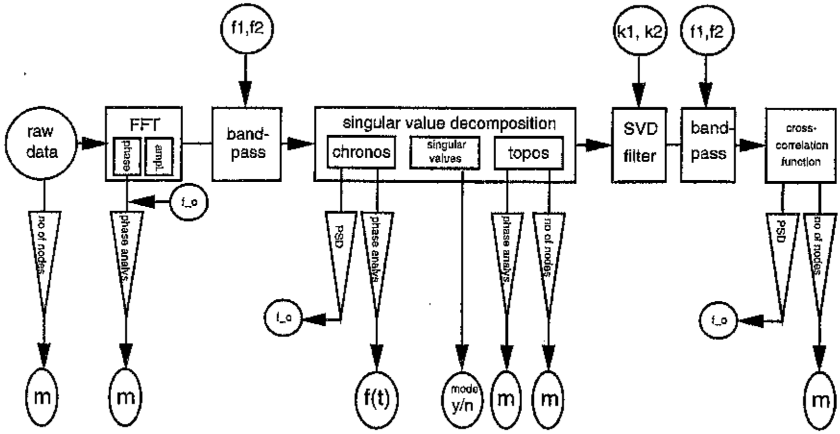

Fig. 1: Schematic of mode analysis: circles indicate input data/parameters, boxes represent entities of different decompositions. Triangles describe ways to analyse the decomposition entities, e.g. *power spectral density or phase analysis of SVD chronos. Output data are represented by 'eggs'. Further explanations see text.*

Data Analysis: Raw data are FFT'd and band-passed to eliminate parasitic signals such as pick-up from the thyristors of W7-AS' power supply.

Singular value decomposition (SVD) or biorthogonal decomposition (BD) [1] splits a matrix $\mathbf{X}$ $(M \times N, M > N)$, containing N time series of M samples of N probes into three matrices: $\mathbf{U}(M \times N)$, $\mathbf{V}(N \times N)$, and a diagonal $\mathbf{S}$.

$$\mathbf{X} = \mathbf{U} * \mathbf{S} * \mathbf{V}^{\dagger} \tag{1}$$

The columns of $\mathbf{V}$ are spatial "eigenvectors" or *topos* (figs. 2c, d), the columns of $\mathbf{U}$ are temporal "eigenvectors" or *chronos* (figs. 2e, f), ordered with respect to variance ("importance") which is reflected by the monotonuously decreasing singular values contained in $\mathbf{S}$ (fig. 2b).

If two of the singular values are approximately equal, the corresponding *topos* and *chronos* describe one single, but rotating perturbation. In that case, the *topos* reveal the dominant m (figs. 2c, d), as does the relative phase of the two neighbouring *topos* (figs. 2g, h), which is analysed in the same manner as phases obtained from FFT [3] The relative phase of the corresponding *chronos* yields a time–resolved frequency [1] (figs. 2i, j).

In our example, SVD components with $k \geq 4$ will contain mostly noise (see the discussion in [1]). A non-Fourier noise–filtering may thus be obtained if the higher order singular values are set to zero when reconstructing $\mathbf{X}$ according to eq. (1).

The normalised cross correlation function (NCC) [2] is calculated from SVD–filtered data using selected *topos* and *chronos* $k_1 \dots k_2$ *. Probe 1 (outboard midplane, fig.3a) serves as a reference channel and $j = 1 \dots N$:

$$c_{1j}(p) = \frac{1}{2\,M+1} \sum_{i=-M}^{M} x_1(i) x_j(i-p) \tag{2}$$

The correlation diagram, *i.e.* a plot of $c_{1j}(p)$ *vs.* the time lag p and the probe position reveals the frequency, the sense of rotation and the dominant poloidal harmonic m (figs. 2k, l, o, p).

For the frequencies of maximum power spectral density yielded by the coherence spectra and the spectra of the relevant *chronos*, m is obtained by FFT phase analysis** [3].

A comparison with calculated phases or correlation diagrams which are obtained using the assumed m and the straight field line angle θ^* from the vacuum configuration is often extremely helpful. Such calculations are shown in figs. 2g, h, o, p as dashed curves and in figs. 2k, l as overlayed solid curves.

Result of the analysis example: We state the presence of two different modes. The first one rotating in the *ion* diamagnetic drift direction (fig. 2k) is possibly a beam-driven GAE mode. The power spectral density of its two *chronos* is very sharply peaked at $37kHz$. The poloidal structure appears to be more consistent with $m = 4$ (see figs 2g,

*An FFT band-pass filter may be used additionally.

**This is not shown here, but looks essentially the same as figs. 2g, h k, o), although the correlation diagram exhibits some distortions (fig. 2k). The second mode with $m = 3$ rotates in the *electron* diamagnetic drift direction (fig. 2l). The power spectrum reveals a rather broad peak about $25kHz$.

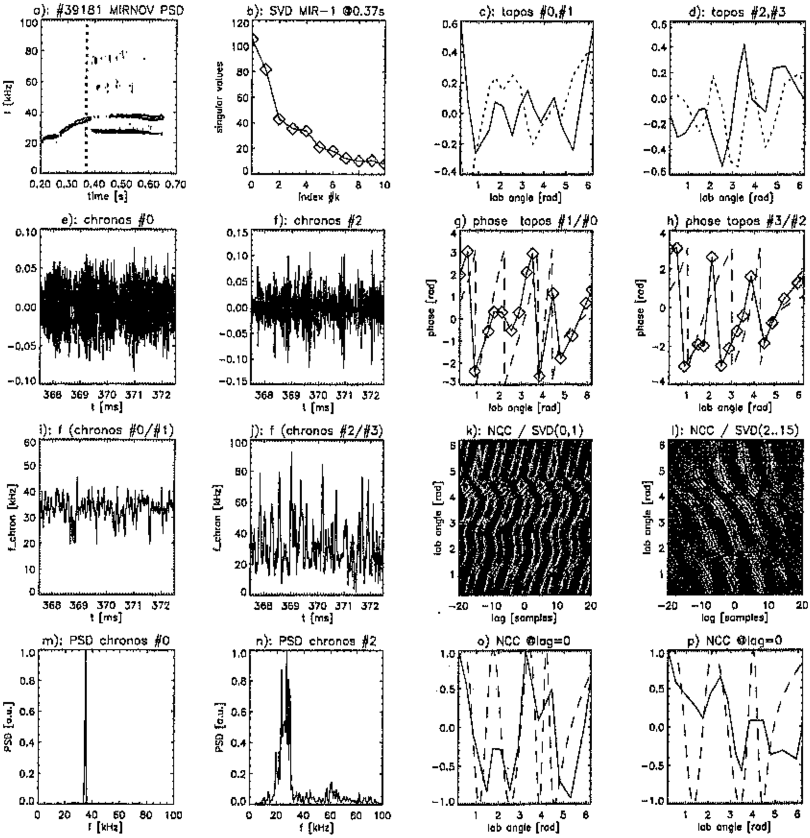

Fig. 2: Mirnov analysis of W7-AS discharge # 39181, a purely NBI heated D plasma: $P_{NBI} = 0.5MW$*, line density* $\approx 4 \cdot 10^{19} m^{-2}$*, central electron temperature* $\approx 700eV$*, extraordinary good energy confinement of* $\tau_E \approx 40ms$ [4] *in spite of comparatively strong MHD activity. Data were taken with the 16-probe array (compare fig. 3a) at a sampling rate of* $250kHz$*. 1000 samples centered about 370ms were selected. Further explanations see text.*

Reliability: Any difficulties arising from noisy data are presumably circumvented by the use of the analysis procedure described above. Persisting problems are essentially caused by geometry, *i.e.* by a too high m, a too great distance between the probes and the source of the magnetic signal or by inadequate poloidal positions of the probes.

In order to quantify these limitations, time series of simulated Mirnov signals have been produced for the 16-probe array (fig. 3a). Based on theoretical equilibria, modes with $m-$ numbers between 2 and 6 at different radial positions $2cm \leq r_{eff} \leq 15cm$ have been simulated. The degree of agreement of the analysis result with the actual m is displayed in fig. 3b. Identification of modes with $m \geq 6$ is impossible, due to the short decay lengths of high multipoles. It is feasible to identify $m = 5$ if the perturbation is located at $r_{eff} \geq 12cm$. If the mode is located inside $r_{eff} \approx 10cm$ which is frequently the case for GAE modes [5,6], $m = 3$ and $m = 4$ may already be hard to distinguish.

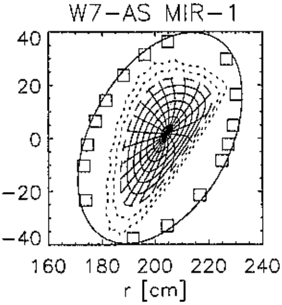

Fig. 3a: array of 16 $\dot{B}_\theta$-probes (MIR-1). Contours indicate flux surfaces of a sample vacuum configuration. The dashed contour corresponds to $r_{eff} \approx 17cm$.

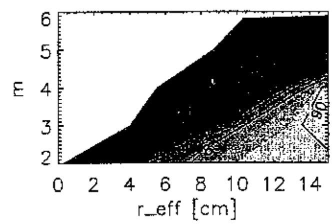

Fig. 3b: fraction of correctly determined poloidal harmonics m as a function of r_{eff} and m. Contours represent levels of 10% to 90% agreement.

References:

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[2] **Press, W H** et al.: "Numerical Recipes in FORTRAN", 2nd Ed., Cambridge (1992)

[3] **Harley, T R** et al.: Nuclear Fusion, **29** (5) p771 (1989)

[4] **Stroth, U** et al., this conference

[5] **Weller, A** et al., this conference

[6] **Goerner, C** et al., this conference