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Mirnov coil data analysis for tokamak ADITYA

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Abstract. The spatial and temporal structures of magnetic signal in the tokamak ADITYA is analysed using recently developed singular value decomposition (SVD) technique. The analysis technique is first tested with simulated data and then applied to the ADITYA Mirnov coil data to determine the structure of current peturbation as the discharge progresses. It is observed that during the current rise phase, current perturbation undergoes transition from $m = 5$ poloidal structure to $m = 4$ and then to $m = 3$. At the time of current termination, $m = 2$ perturbation is observed. It is observed that the mode frequency remains nearly constant (≈10 kHz) when poloidal mode structure changes from $m = 4$ to $m = 2$. This may be either an indication of mode coupling or a consequences of changes in the plasma electron temperature and density scale length.

Keywords. Mirnov coils; tokamak; mode structure; singular value decomposition.

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1. Introduction

Structure of magnetohydrodynamic (MHD) modes has always been an interesting study in tokamak devices [1]. It is well known that Mirnov oscillations with poloidal and toroidal mode numbers m and n, respectively, are created by perturbation of current channel on rational magnetic surfaces. The coherent structure of such rotating modes can be obtained by poloidal and toroidal arrays of Mirnov coils inside the tokamak vacuum vessel. The data are acquired at fast sampling rate in order to follow the rotating modes. The Mirnov signals are oscillating time series from which the overall structure is extracted. A look at the time traces of Mirnov coil signals may sometimes be sufficient to determine the mode number, particularly when only a single mode is present. However, the signal can be complicated when several modes are significant and they are interacting. In such a case, two numerical techniques have been developed to determine the mode numbers and the coherent mode structure [2,3]. In the first method, mode number and structure are determined by obtaining phase angles from a set of Mirnov coils at the frequency of interest. At this point, attempt is made to find the best fit to the phases. This involves finding the optimal parameters m, λ, n and δ_0 such that $\zeta = m(\theta - \lambda \sin\theta) + n\phi + \delta_0$ approximates the phase data. Here, $\lambda = (\beta_p + l_i/2 + 1)\epsilon$ is a free toroidal correction to the geometry of the mode and the off-center position of the mode with respect to the vessel center; β_p, the poloidal beta; l_i, the internal inductance; $\epsilon = r/R$, the inverse aspect ratio; δ_0, a phase constant and θ, ϕ are the poloidal and toroidal angles of location of the Mirnov coils. It is assumed here that each mode (m, n) has a distinct frequency and the method fails in the presence of the mode coupling. A typical nature of mode coupling is indicated by the two or more modes having the same frequency [2]. Another uncertainty is due to the statistical nature of the curve fitting procedure. In the second method, a correlation analysis is done in space rather than in time. In this method, singular value decomposition (SVD) is applied to a time space matrix of multichannel Mirnov coils data. The singular values (SVs) and principal axes (i.e. eigenvalues and eigenvectors) contain the information about MHD mode. The principle axes corresponding to the largest SVs determine the most important modes in the signal. Mode structure can be seen by a polar representation of principal axes vs probe positions. This is a relatively recent technique which effectively filters the uncorrelated noisy data. In this method, two or more modes with the same mode numbers but different frequencies are seen as a single mode distorted in time. Two or more modes with different mode numbers but having the same frequency (as in the mode coupling) are identified by SVD as a single mode with a distorted non-sinusoidal eigenvector in space. Thus, a distorted mode structure indicates presence of mode coupling.

In this paper, we apply the SVD technique to ADITYA discharges to characterise the presence of various MHD modes. A typical ADITYA discharge is selected which has indications of the presence of several modes in the discharge. The physical picture of the evolution of the discharge is well understood. The organization of this paper is as follows: Section 2 describes the method. Section 3 presents application of this method on ADITYA multichannel Mirnov coils data followed by conclusion in the last section.

2. Method

An $N \times M$ rectangular matrix X is formed by M-channels of N data points (i.e. row index = time, column index = channel). The SVD of X can be expressed in terms of the following product matrices:

$$X = VSU^T,$$

where V is an $N \times M$ orthonormal matrix, U is an $M \times M$ orthonormal matrix and S is an $M \times M$ diagonal matrix. SVD is analogous to the similarity transformation which diagonalizes a square matrix. The SVs are the analogous to eigenvalues, while the columns of matrix U are analogous to the eigenvectors. The columns of matrix U are called the *principal axes*, form an orthonormal basis on which the signal is decomposed. Moreover, since most of SVs are very small compared to a few dominant ones, it describes the features of whole signal. Also, the matrix product *VS* are the principal components (PCs) of X. They give the time evolution of the signal along the corresponding principal axes.

A numerical test have been carried out to see the strengths and weaknesses of the method. An artificial time series in the following form [3]

$$X_{ij} = \frac{1}{\sqrt{N}} \sum_l a_l \cos\left[\frac{2\pi m_l}{M}(j-1) + \phi_l - 2\pi\nu_l t_s (i-1)\right] + \eta\sigma_{ij},$$

i.e. a superposition of cosinusoids of mode number m_l rotating having frequency ν_l and amplitude a_l, with an additional white noise σ_{ij} of amplitude η was considered. The signal was detected at M equidistant poloidal positions with a sampling time t_s. Algorithm

Table 1. Summary of parameters used to generate signal for numerical test of SVD analysis, $M = 8$, $t_s = 10^{-3}$, $N = 8192$.

m_l	a_l	$\nu_l^{\dagger}$	ϕ_l
1	1.00	20.0+6.0t	0.00
2	0.60	50.0−1.2t	0.50
3	0.20	90.0−7.6t	0.33
noise	0.05	–	–

†Signal is generated with frequencies slowly drifting in time.

was written in MATLAB (a mathematical and graphical package) script using its in-built mathematical routines. Various parameters used to generate the signal is given in table 1.

This test signal was preprocessed to remove the mean and linear trends; otherwise the first SVD components would be just the trend itself. Algorithm for SVD analysis is found correct as the results for numerical test signal have been reproduced as in ref. [3].

It is also checked that two or more modes with the same mode number but different frequencies will be seen as a single mode distorted in time. Also, two or more modes with different mode numbers but having same frequency and with constant amplitude ratios will be identified by SVD as a single mode with a distorted, non-sinusoidal eigenvectors in space. This is because the off diagonal phase relationship in the covariance matrix do not vary in time and so they do not average out to zero. Therefore, SVD method must be used carefully for real Mirnov data.

3. Analysis of Mirnov coil data

In ADITYA, a garland of 15 tangential magnetic probe is installed to detect poloidal magnetic field, $\dot{B}_\theta$ inside the vacuum vessel. Since the frequency of rotating islands is typically in between 1 and 20 kHz, magnetic probe signals have been digitized at a sampling frequency of 40 kHz. Stored binary data is read through MATLAB script. For very large Mirnov coil amplitudes, either because of plasma position and shape or because of ballooning effects on the outboard sides, mode determination could be wrong as this can confuse the interpretation of eigenvectors. Hence all the signals have been normalised in the range -0.5 to 0.5 before performing SVD.

We have chosen shot #6579 to analyse for the analysis of MHD modes using SVD technique described in §2. Out of 15 probes, 12 probes have been used for the analysis because other 3 probe connections were broken and hence discarded. In figure 1, plasma current (in the unit of 10 kA) and loop voltage are plotted alongwith one of the Mirnov coils raw data. The points (1), (2) and (4) on the loop voltage trace are marked to indicate sudden bumps in loop voltage. Because of high frequency (600 Hz) pickup from the ohmic power supply, these bumps are not clearly marked as in other tokamaks [4]. In other tokamaks, these bumps have been related to the penetration into or ejection of poloidal flux from the plasma. There is an increase in the Mirnov signals corresponding to these points (see figure 1). The time-frequency analysis of the Mirnov signal is carried out using short-time FFT (MATLAB routine SPECGRAM). Figure 1(c) shows that the frequency of the Mirnov oscillations remain nearly constant (in the range of 10–12 kHz). The constant frequency

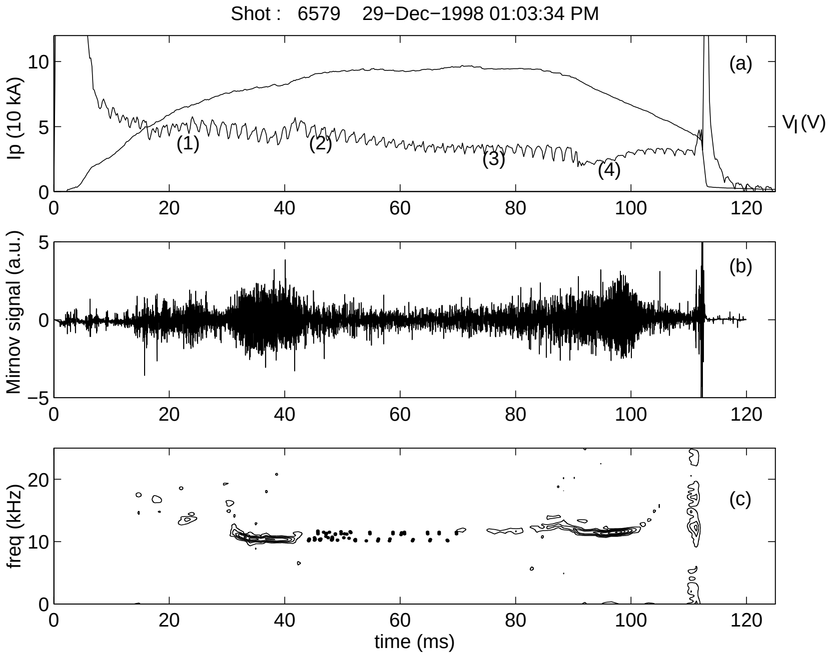

Figure 1. ADITYA discharge # 6579: (**a**) Plasma current (in the unit of 10 KA) and loop voltage (in volts). (**b**) One of the Mirnov coils raw data. (**c**) Time-frequency spectrum of a Mirnov signal indicating the dominent frequency component present in the signal.

of the Mirnov signal, in spite of obvious signature of change in the mode structure (e.g. bumps in the loop voltage signal) indicates presence of mode coupling.

We have carried out SVD analysis of Mirnov coil data from 12 pickup coils to understand the progress of tokamak discharge. In addition, data from pickup coils are also analysed at point (3) in the loop voltage trace where no conspicuous change in loop voltage is seen. Figure 2 shows the result of SVD analysis of pickup coil data during the rise phase (points 1 and 2) of the discharge. It is observed that the plasma current makes transition through $m = 5$ and $m = 4$ modes when the currents exceed 58 kA and 83 kA respectively. From the estimates of edge safety factor (q_a), these cross over take place at $q_a = 5$ and $q_a = 4$ respectively. In the standard tokamak discharge, these phases correspond to the current penetration and sharpening of current density profile. Although we do not have a direct measurement of either current density or temperature profile, we speculate a standard picture of tokamak discharge for ADITYA.

Figure 3 shows the result of SVD analysis for a nearly flattop phase and a current termination phase (points 3 and 4 respectively on the loop voltage trace). In these phases, the poloidal mode structure is 3 and 2 respectively (see figures 3(c) and 3(f) respectively). It is clearly seen that the current termination is preceeded by large increase in Mirnov signal (see figure 1) whose mode structure is $m = 2$. In the standard tokamak discharge, large increase in $m = 2$ signals has been observed as precursor activity to either a density limit

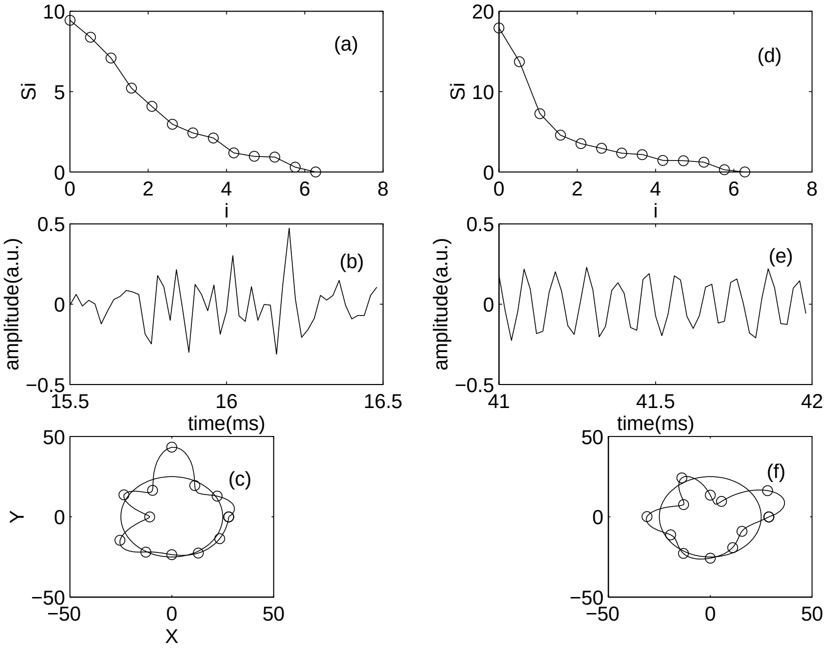

Figure 2. SVD analysis for ADITYA shot $\#6579$: (**a**) Spectrum of singular values, S_i vs i. (**b**) Temporal structure of the mode. (**c**) Spatial structure of $m = 5$ mode for time point (1) shown in figure 1. (**d**) spectrum of S_i vs i. (**e**) Temporal structure of the mode. (**f**) Spatial structure of $m = 4$ mode for time point (2).

disruption or a current limit disruption [5]. In the absence of additional diagnostic information, it is not possible to make such conclusion for ADITYA. We have carried out similar SVD analysis of many ADITYA discharges which confirm a standard picture of tokamak discharge for current rise, flattop and current termination phases.

We have also carried out the mode structure analysis of the data presented in this paper using the conventional methods [6]. The mode numbers are found to be an error of $+1$. This uncertainty arises because of the difficulty in correctly estimating the phases from the FFT as well as the statistical nature of the curve fitting.

It is possible to speculate on why the mode frequency remain constant when mode structure changes from $m = 4$ to $m = 2$. In the beginning the observed mode frequency of $\approx$ 10 kHz may belong to $m = 4$ (for electron temperature, $T_e = 250$ eV, density scale length, $L_n = 10$ cm and radius of mode rational surface, $r = 20$ cm). However, as the discharge progresses, the electron temperature may increase and the density scale length may decrease giving the same frequency for the lower mode numbers.

4. Conclusion

SVD technique is a powerful tool which has been applied to the magnetic probe signals at ADITYA tokamak. We have analysed Mirnov coil data of ADITYA discharges during the

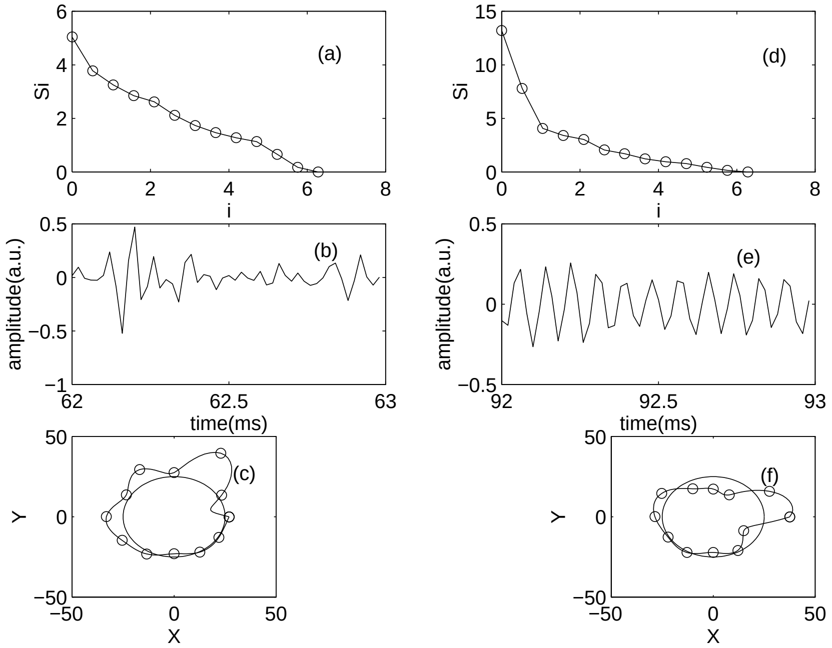

Figure 3. SVD analysis for ADITYA shot #6579: (**a**) Spectrum of singular values, S_i vs i. (**b**) Temporal structure of the mode. (**c**) Spatial structure of $m = 3$ mode for time point (3). (**d**) Spectrum of S_i vs i. (**e**) Temporal structure of the mode. (**f**) Spatial structure of $m = 2$ mode for time point (4).

current rise, flattop and current termination phases. The current rise phase exhibits signatures of current penetration indicated by progressively decreasing poloidal mode numbers. The $m = 3$ modes are observed at the current flattop phase and the current termination is accompanied by nearly exponential increase in $m = 2$ activity. We observe that the mode frequency remains nearly constant (≈10 kHz) when poloidal mode structure changes from $m = 4$ to $m = 2$. This may be either an indication of mode coupling or a consequences of the change in plasma electron temperature and density scale length. In future, it will be possible to combine these informations with other diagnostic signals and characterise the tokamak discharges.

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