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ORIGINAL RESEARCH

MHD Mode Identification from Mirnov Coils Signals in Tokamak Via Combination of Singular Value Decomposition and Hilbert–Huang Transform Analysis Methods

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Abstract
In this work, we investigate how to study the MHD activities in Tokamak plasma via the combination of singular value decomposition (SVD) and Hilbert–Huang transform (HHT) methods. We apply this approach to the Mirnov coil signal fluctuations analysis without any filtering technique. First, the principal axes (PAs) of a pick-up Mirnov signals are extracted by SVD analysis. Next, the harmonics of dominants PAs is obtained by empirical mode decomposition (EMD) analysis. Moreover, the time–frequency behavior of Mirnov signals are extracted by HHT. The proposed technique is employed to analyze Mirnov coils signals for mode type and frequency identification, especially in multimode MHD activities. We obtained Spatial–temporal structures of the Mirnov coils fluctuations in terms of correlation functions to better identification of mode number and frequencies of dominant MHD modes. We also present the results of this method applied to IR-T1 and Golem Tokamaks Mirnov coils signals. Consequently, satisfying results from SVD + HHT analysis method and spatial–temporal structures for IR-T1 and Golem Tokamaks Mirnov data observed.

Keywords SVD + HHT analysis methods · Spatial–temporal structures · Wave-like structures · Empirical mode decomposition (EMD) · Hilbert–Huang transform (HHT) · Singular value decomposition (SVD)

Introduction

Identification of MHD activities properties such as the frequency and MHD mode number is very helpful for the study and control of their danger in Tokamak plasma [1]. MHD modes activities behaviors are different in Tokamaks. All magnetic confinement experiments devices show MHD oscillations according to their physical properties [2, 3]. The MHD oscillations in these devices show a wide range of wavelengths and frequencies, and have scales and wavelengths comparable with the size of the system [2, 3].MHD mode with long wavelength (small mode number) and low frequency plays important role in the ending of the magnetic confinement and causes major disruptions in fusion reactor plasma. On the other hand, MHD mode with short wavelength (large mode number) and high frequency refers to the broadband turbulences in the plasma [2, 3].

The MHD modes may be excited in Tokamak plasma with constant frequency or with a broad range of frequencies. Additionally, two MHD modes may be excited and propagated with identical frequency. In the multimode MHD activities, these modes can be identified by expanded it into the special components which correspond to the specific structures [4].

When several modes are rotate in the MHD activities with the same frequency, the technique based on the correlation functions can be very efficient in separating them, by assuming that these modes rotate with different velocities [5].

There is some powerful spectral analysis for MHD activities studies such as short time Fourier transform (STFT) [6],wavelet transform (WT) [7] and HHT [8]. The time -frequency behavior of Tokamak signals, particularly edge fluctuations data and magnetic probe signals have been analyzed by HHT method [4, 9–15].In the fusion

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plasma experiments, the basic spatial–temporal structures of the fluctuations are presented in terms of correlation functions and wave number-frequency spectra [16].

The cross-correlation functions of a 12-tip poloidal probes data used to study the turbulence structures and their propagation across the magnetic surfaces on HT-7 Tokamak [16]. In CASTOR Tokamak, Langmuir probes data evaluated by correlation techniques. In addition, spatial wave-like structures related to potential fluctuations observed in the poloidal direction [17].

SVD can be used to magnetic field fluctuations analysis in Tokamak [18, 19]. SVD is applied to Tokamak Mirnov signals to identify MHD activities in the plasma. SVD analysis sensitivity is very high to the presence of a structure even for very low amplitude MHD mode. It means that the algorithm is smart detecting even at a small level of MHD activity as present in actual machines [20–22]. This technique does not works, if the coils are unevenly distribute in space, since the PAs are, in general, not periodic function. However, in order to obtain MHD mode numbers another technique can be used [23]

In this work, we discuss how to analyze the MHD activities fluctuations via the method of analysis that to be a combination of SVD and HHT methods.

The proposed technique employed to analyze the Mirnov coils signals to mode type and frequency identification. We use spatial- temporal structures of the Mirnov coils signals in terms of correlation functions to better identification of mode numbers and frequencies of dominant MHD modes.

The details are as follows: first, spatial PAs and temporal principal components (PCs) structures of MHD activities are obtaine by SVD. Next, harmonics of MHD modes are extracted by EMD analysis from the dominant PA. Then, the time–frequency behavior of dominant PC or one of the Mirnov signals is obtained by HHT. This analysis determines approximately the time–frequency behavior of each MHD mode. We present the results of this method applied to IR-T1 and Golem Tokamaks Mirnov coils signals to obtain mode numbers and the oscillation frequencies of MHD activities. In Sect. "Theory", the structures of spectral analysis are studied. In Sect. "Experimental Results", the experimentally raw data as measured from Mirnov coils from IR-T1 and Golem Tokamak analyzed and discussed by SVD + HHT analysis method. In the end, in Sect. "Conclusion", the conclusions are presented.

Theory

Singular Value Decompositions (SVD)

The SVD is described in details in most of the papers related to the magnetic fluctuations data analysis [18, 19].

Consider a time series of M-dimensional vectors $X(t) = [x_1(t), x_2(t), \ldots, x_M(t)]$ where the components $x_j(t)$ are simultaneous measurements of the same physical quantity at different positions (channels). (row index = time, column index = channel).

The singular value decomposition expresses X in terms of the following product of matrices$X = VSU^T$, where S is an $M \times M$ diagonal matrix $S_{ij} = \delta_{ij} s_i$ and the quantities $s_i \geq 0$ are called singular values of X, by convention given in decreasing order; V is an $N \times M$ matrix with orthonormal columns $v^j = V_{ij}$ that $v^j v^k = \delta_{jk}$ and U is an $M \times M$ matrix.

The SVD is the analogue of the similarity transformation, which diagonalize a square matrix. The SVs are the analogue of the eigenvalues, while the U columns $u^j = U_{ij}$ are the analogue of the eigenvectors. Therefore $X = VSU^T$ is equivalent to $X_{ij} = V_{ik} s_k U_{jk} = v_i^k s_k u_j^k$

Hilbert–Huang Transform (HHT)

Huang and coworkers introduced EMD method for data analysis in 1998 [8]. First, EMD decomposes the original data into a series of intrinsic mode functions (IMFs) reserving the locality of data. An IMF is any function with the same number of extrema and zero crossings, with its envelopes being symmetric about zero. EMD is an adaptive and data-driven decomposition method with a posteriori basis function derived from the data itself, and suitable for analyzing both nonstationary and nonlinear data [8]. Second, the instantaneous frequencies (IFs) of each IMFs obtained by Hilbert spectral analysis (HSA). These two separate parts are known as the HHT method.

EMD decomposes a multicomponent signal $x(t)$ into the series of amplitude frequency-modulated IMFs $c_i(t)$ and a residue component $r(t)$ via an iterative sifting process

$$x(\mathrm{t}) = \sum_{\mathrm{i}=1}^{\mathrm{n}} c_i(\mathrm{t}) + \mathrm{r}(\mathrm{t}) \quad (1)$$

where i = level index of IMF, and n = total number of IMFs. This set of IMFs contains different frequency scales, reflecting diverse oscillation modes embedded in data. A mode must satisfy two conditions to consider as an IMF: (1) the number of extrema and the number of zero crossing must be equal or differ at most by one; and (2) the mean value of the upper and lower envelope is zero.

Spatial–Temporal Spectrum Based on Correlation Function

Such spectral analysis methods can be used to discover the properties of spatial–temporal features of wave-like structures. For this purpose, the plots of empirical spatial–temporal correlation matrices are considered. There is direct correspondence between the correlation functions and the spectrum [24].

Spectral analysis of time series can be done, for example, by Fourier transform (FFT) or WT. In the spatial setting, two-dimensional spectral analysis should be used to explore both the structure and the patterns of spatial datasets. It is needed to consider a method for data analysis that is referenced in both space and time. For this purpose, we use a two-dimensional discrete Fourier transform of correlation functions matrix [5]. The Mirnov coil data for a time interval of $t_{lo} \leq t \leq t_{hi}$ is given by $\dot{B}(\theta_i, t_j)$, where θ_i are the Mirnov coil angle location and t_j are the sampled equidistantly. Consider the spatial–temporal correlation matrices:

$$R_B(\Delta\theta, \Delta t) = \sum\nolimits_{i,j} \dot{B}(\theta_i, t_j)\dot{B}(\theta_i + \Delta\theta, t_j + \Delta t) \tag{2}$$

It is expected that MHD modes produce a pattern in the correlation functions similar to a plan-wave model. Two-dimensional discrete Fourier transform of this matrix discover properties of this plan propagating waves. It should be possible to identify plane wave pattern modes as clear peaks. The peak location $(f \sim 1/dt, k \sim 2\pi/d\theta)$ shows frequency and mode number of MHD mode (f, k). Also, the shape of the poloidal-temporal correlation functions gives further information about the dynamic of the magnetic fluctuations as a function of lifetime and poloidal separation [5].

Experimental Results

Study of MHD Activities in Golem Tokamak

The first detailed of SVD + HHT analysis was carried out for the time window (17.1–17.8 ms) for the Golem Tokamak (http://golem.fjfi.cvut.cz) shot number 10579 (Fig. 1a). Golem is a small Tokamak operating at the Faculty of Nuclear Science and Physical Engineering at the Czech Technical University in Prague.

SVD analysis is done using 16 coils signals of the Mirnov probs. Figure 1 shows the singular value (SV) spectrum (mode amplitude) and the corresponding first PC and PA of SVD analysis for dB/dt signals from the 16 pickup Mirnov probes which are separated by 22.5° in this time interval. The signal from each coil can be recorded by data acquisition with 1 MHz sampling rate.

The first component of SVs has the highest singular value (Fig. 1d) and is much larger than the others. The time evolution waveform of the first PC is similar to Dirac delta function (Fig. 1b), which implies an instantaneous impact on the plasma behavior [25]. Also, the polar plot of the dominant PA corresponding to the dominant PC is shown in Fig. 1c. The poloidal MHD mode number of the dominant PA can be inferred from the number of lobes which are observed in Fig. 1c. The component of the first order spatial eigenvector (PA) in the time during (17.1–17.8 ms) is extracted by using EMD analysis (Fig. 1e, f, g). We used EMD code in Ref. [26] for data analysis. It can be seen that the MHD harmonics can be identified by EMD analysis performing on the dominant PA. The first plot (Fig. 1e) is the IMF0 of the dominant PA. This harmonic MHD mode is approximately m = 4 or m = 5. The middle plot (Fig. 1f) corresponds to the IMF1 (m = 3 MHD mode) and the last plot (Fig. 1g) shows the IMF2 (m = 1) of the dominant PA. According to the HHT analysis theory, the last IMF may be residual of the data. We see that, SVD + HHT method has succeeded in decomposing the distortion mode into its components.

In the following, we applied SVD analysis in three sampling window length 16.4–16.6 ms,16.5–16.7 ms and 16.4–16.7 ms from the Golem Tokamak Mirnov signals shot number 11688 with edge safety factor $q_a = 1.8$. The algorithm based on SVD can detect the mode while acting on a smaller time interval. Therefore, we apply SVD analysis on these overlap time intervals to show sensitivity of SVD algorithm. Figure 2c shows the polar plot of dominant PA in the time during 16.4–16.7 ms (Fig. 2a) which is extracted by SVD. Then, IMFs of this multimode MHD activity for each time interval extracted via EMD. The poloidal MHD modes m = 4 (IMF0) and m = 3 (IMF1) in the time during 16.4–16.6 ms and poloidal MHD mode m = 4 (IMF0) and m = 2 (IMF1) in the time during 16.5–16.7 ms are obtained by EMD analysis. In addition, we extract MHD modes m = 4 (IMF0), m = 3 (IMF1) in the time during 16.4–16.7 ms by EMD method. We can see that poloidal MHD mode m = 2 and m = 3 can be diagnosed by combination of SVD and HHT analysis method when sampling window length have overlap. In the time during 16.4–16.7 ms m = 3 MHD mode has frequencies between 10 and 40 kHz (Fig. 2b) that is obtained by HSA. Another low amplitude MHD mode with an intermittent frequency above 20 kHz in this time interval is observed (Fig. 2b, e). Furthermore, the typical spatial–temporal plot of the Mirnov signal fluctuations displays time periodic wave-like structures (Fig. 2d). The high correlation value of this structure is centered below 0.1 ms lifetime with

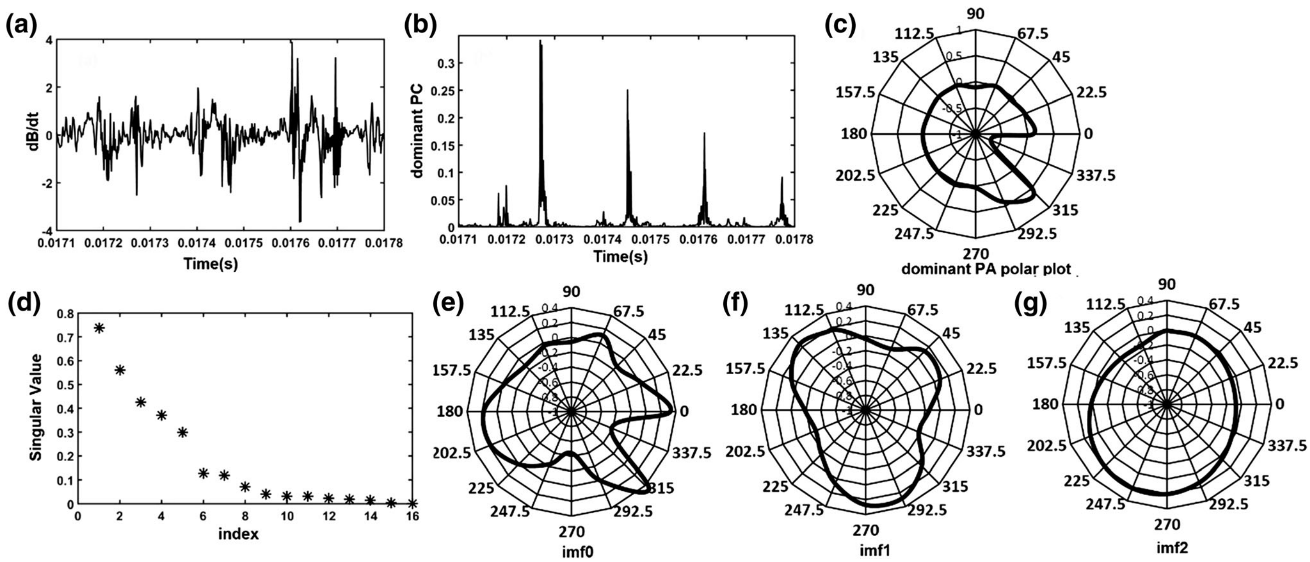

Fig. 1 **a** One of the Mirnov coil data for Golem Tokamak in expanding time (17.1–17.8 ms) shot number (10579), corresponding **b** dominant PC **c** polar plot of dominant PA and **d** singular value obtained by SVD. Corresponding IMF0 (**e**) IMF1 (**f**) and IMF2 (**g**) obtained by EMD

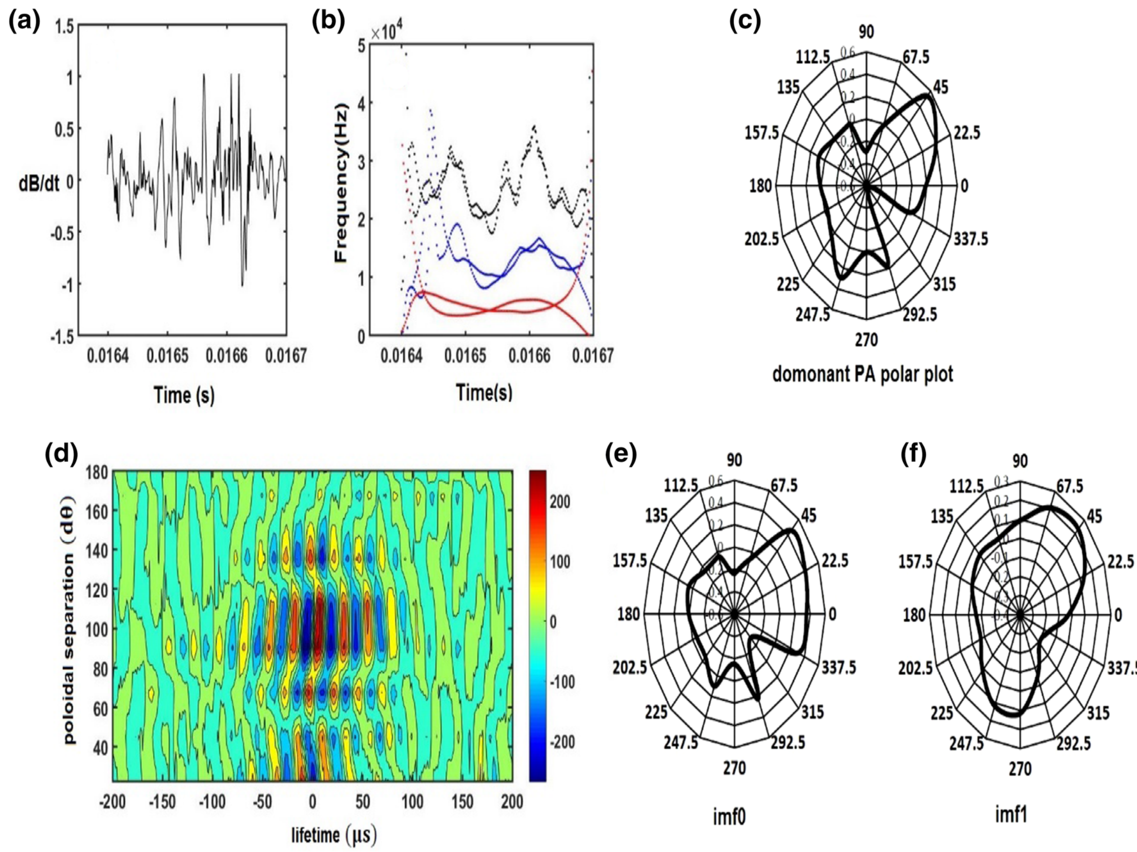

Fig. 2 **a** One of the Mirnov coil data for Golem Tokamak shot number (11688) in (16.4–16.7 ms) **b** corresponding Hilbert spectrum for the main IMFs. **c** Polar plot of dominant PA obtained by SVD. **d** Poloidal-temporal correlation function of dB/dt from the 16 pickup Mirnov probes. Corresponding IMF0 (**e**) and IMF1 (**f**) obtained by EMD

poloidal separation $d\theta$ between 80 and 120 degrees (m = 3 and m = 4 MHD mode number).

In the following, time intervals 12–14 ms (Fig. 3a) and 14–15 ms (Fig. 4a) from Mirnov coils signals shot number

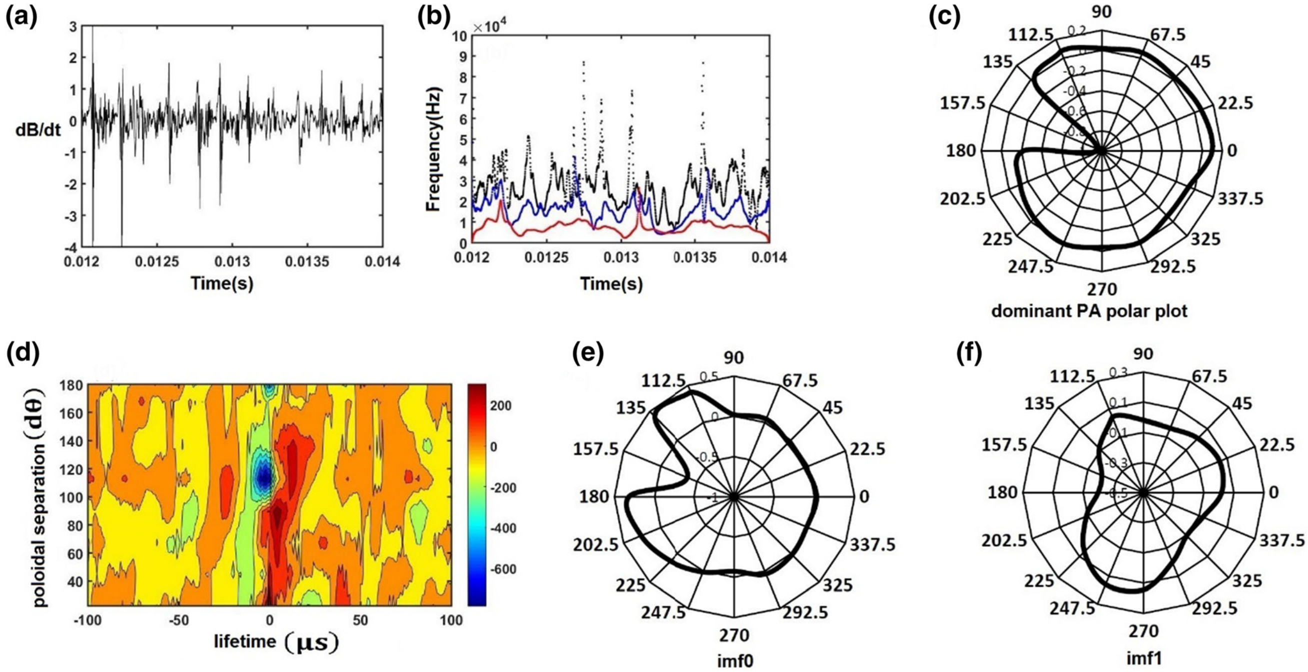

Fig. 3 **a** One of the Mirnov coil data for Golem Tokamak shot number (12562) in (12–14 ms) **b** corresponding Hilbert spectrum for the main IMFs. **c** Polar plot of dominant PA obtained by SVD. **d** Poloidal-temporal correlation function of dB/dt from the 16 pickup Mirnov probes. Corresponding IMF0 (**e**) and IMF1 (**f**) obtained by EMD

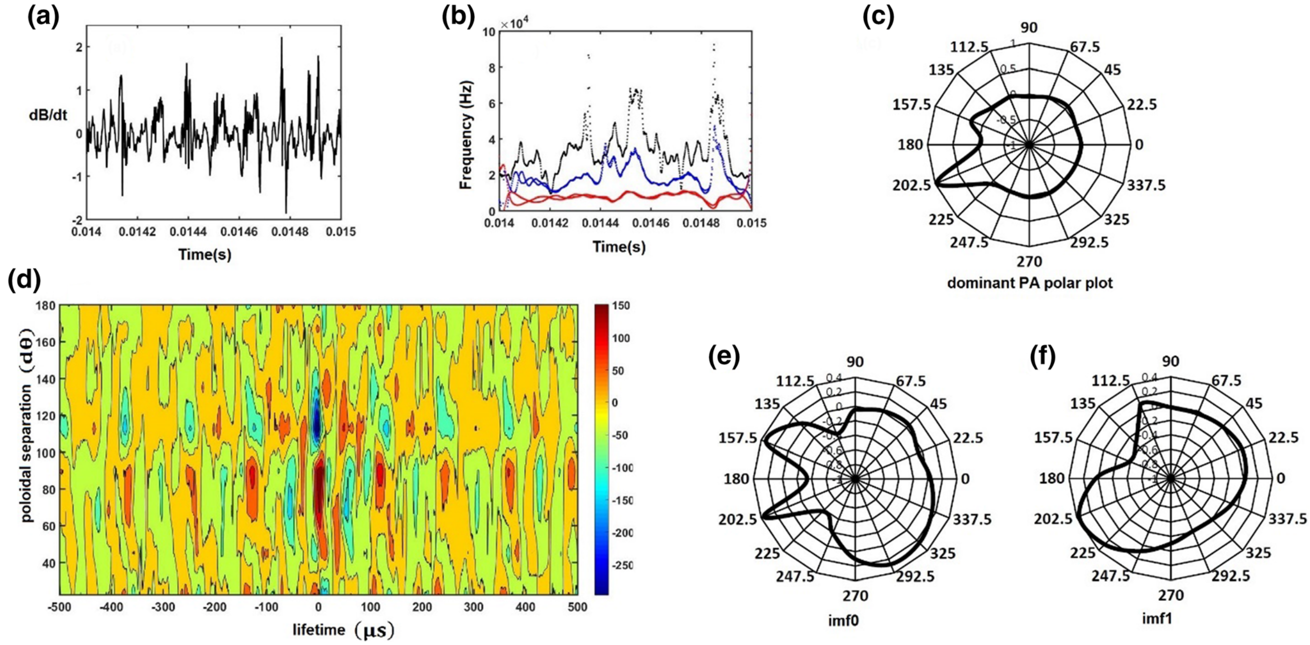

Fig. 4 **a** One of the Mirnov coil data for Golem Tokamak shot number (12562) in (14–15 ms) **b** corresponding Hilbert spectrum for the main IMFs. **c** Polar plot of dominant PA obtained by SVD. **d** Poloidal-temporal correlation function of dB/dt from the 16 pickup Mirnov probes. Corresponding IMF0 (**e**) and IMF1 (**f**) obtained by EMD

12562 are analyzed by SVD. Dominant PAs of the poloidal MHD mode, during the period from 12 to 14 ms and 14 to 15 ms are shown in Figs. 3c and 4c.

In the time interval 12–14 ms (Fig. 3), MHD mode numbers m = 4 (Fig. 3e) and m = 3 (Fig. 3f) are extracted by EMD from the dominant PA (Fig. 3c). In this time, spatial wave-like structures in term of the poloidal-temporal correlation function plot were observed in Fig. 3d. A high correlation value of this structures lower than 0.05 ms lifetime with poloidal separation $d\theta$ between 80 and 140 degrees show this wave-like structures have frequencies above than 20 kH ($f \sim 1/dt$) and the MHD mode number of this activity is m = 3 or m = 4 ($m \sim 2\pi/d\theta$). The time–frequency behavior of these MHD modes obtained by applying the Hilbert transform (HSA) on the significant IMFs of the Mirnov signals fluctuations (Fig. 3b). In this Figure MHD activities can be seen at frequencies 10–40 kHz.

In the time during 14–15 ms (Fig. 4) periodic wave-like structures (m = 4 and m = 3 MHD mode) in poloidal-temporal correlation functions plot were observed (Fig. 4d). HSA spectrum of this time interval shows these MHD activities oscillate between 10 and 40 kHz frequencies (Fig. 4b). Also, Figs.4e, f show the relative mode spectra of dominant PA, that is extracted by EMD analysis. Figure 4e is the IMF0 of the dominant PA. This harmonic MHD mode is m = 4 and Fig. 4f corresponds to the IMF1 (m = 3 MHD mode).

Study of MHD Activities in IR-T1 Tokamak with Simultaneous Application of L = 3/n = 1 and L = 2/n = 1 RHF

The IR-T1 is a conventional Tokamak with a major and a minor radius of R = 45 cm and a = 12.5 cm, respectively, and a circular cross-section without a copper shell. It has no diverter but rather uses a material limiter with a minor radius of 11.5 cm. This research Tokamak located at Plasma Physics Research Center (PPRC). IR-T1 is equipped with a poloidal Mirnov probes array consisted of 12 coils separated by 30°. These discrete Mirnov coils used to detect magnetic fluctuations and pick up the poloidal component dB/dt. The signal from each coil can be recorded by data acquisition with 2 MS/s sampling rate and 8-bit resolution.

In this section MHD activity behavior in IR-T1 Tokamak for ohmic plasma discharge (shot5-961011, Fig. 6) and plasma discharge with magnetic resonance helical field (RHF) application L = 2/n = 1, L = 3/n = 1(shot14-961011, Fig. 7) will be considered. The RHF produced by two winding with optimized geometry conductors wound externally around the Tokamak chamber with a given helicity [27]. The minor radius of these helical windings is 21 cm (L = 2, n = 1) and 22 cm (L = 3, n = 1) and also major radius is 50 cm (Fig. 5). The DC current through the helical winding is between 100 and 400 A,which is very low compared with the plasma current (20–30 kA).The RHF application in this work can be used to verify SVD and HHT combination method performance.The aim of these experiments is to understand the effect of the RHF on the poloidal MHD modes behavior.

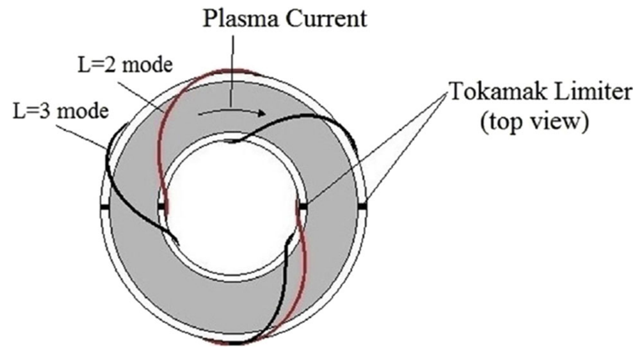

Fig. 5 Schematic illustration of IR-T1 (top view) showing the RHF system (Figure from Ref. [27])

The results of IR-T1 Tokamak experiments show an increase in poloidal m = 2 MHD mode in the presence of L = 2/n = 1 RHF and an increase of poloidal m = 3 MHD mode with the applying of L = 3/n = 1 RHF [27]. In our work, the resonance helical fields L = 2/n = 1 and L = 3/n = 1 were applied simultaneously at 25 ms for about 10 ms during the plasma current plateau in shot 14-961011 (Fig. 7). In the experiments understudy, the edge safety factor was also $q_a < 5$.

In the time during 25–35 ms with simultaneous application of L = 2/n = 1 and L = 3/n = 1 RHF, amplitude and poloidal phase velocity ($v_\theta \sim d\theta/dt$) of spatial wave-like structures in the poloidal separation ($d\theta$) between 80 and 120 degrees and $d\theta$ between 120 and 180 degrees are increased. (Fig. 7b). we observed this result in L = 3/ n = 1 RHF application in IR-T1 Tokamak [28].

Moreover, in Fig. 7b, spatial wave-like structures lower than 0.1 ms lifetime with frequency above than 10 kHz observed in the correlation figures between 80 and 120 degrees. The MHD mode number of this activity was m = 4 or m = 3.

In this Figure m = 2 MHD mode was observed related to the wave-like structures in the poloidal separation between 120 and 180 degrees. These wave-like structures disappeared for (dt) lower than 100 µs in the frequencies lower than 10 kHz (f $\sim 1/dt$) in simultaneous application of RHF (see Fig. 7b) in comparison to the ohmic plasma discharge without RHF application (see Fig. 6b).

In addition, the poloidal-temporal correlation function figures (see Fig. 7b) show that with RHF application, the MHD mode number m = 5 is disappeared in frequencies below than 10 kHz for (dt) above than 100 µs in comparison to the ohmic plasma discharge without RHF application (see Fig. 6b).

In the following, we study the spatial mode structures of MHD activity by SVD + HHT method. SVD can extract

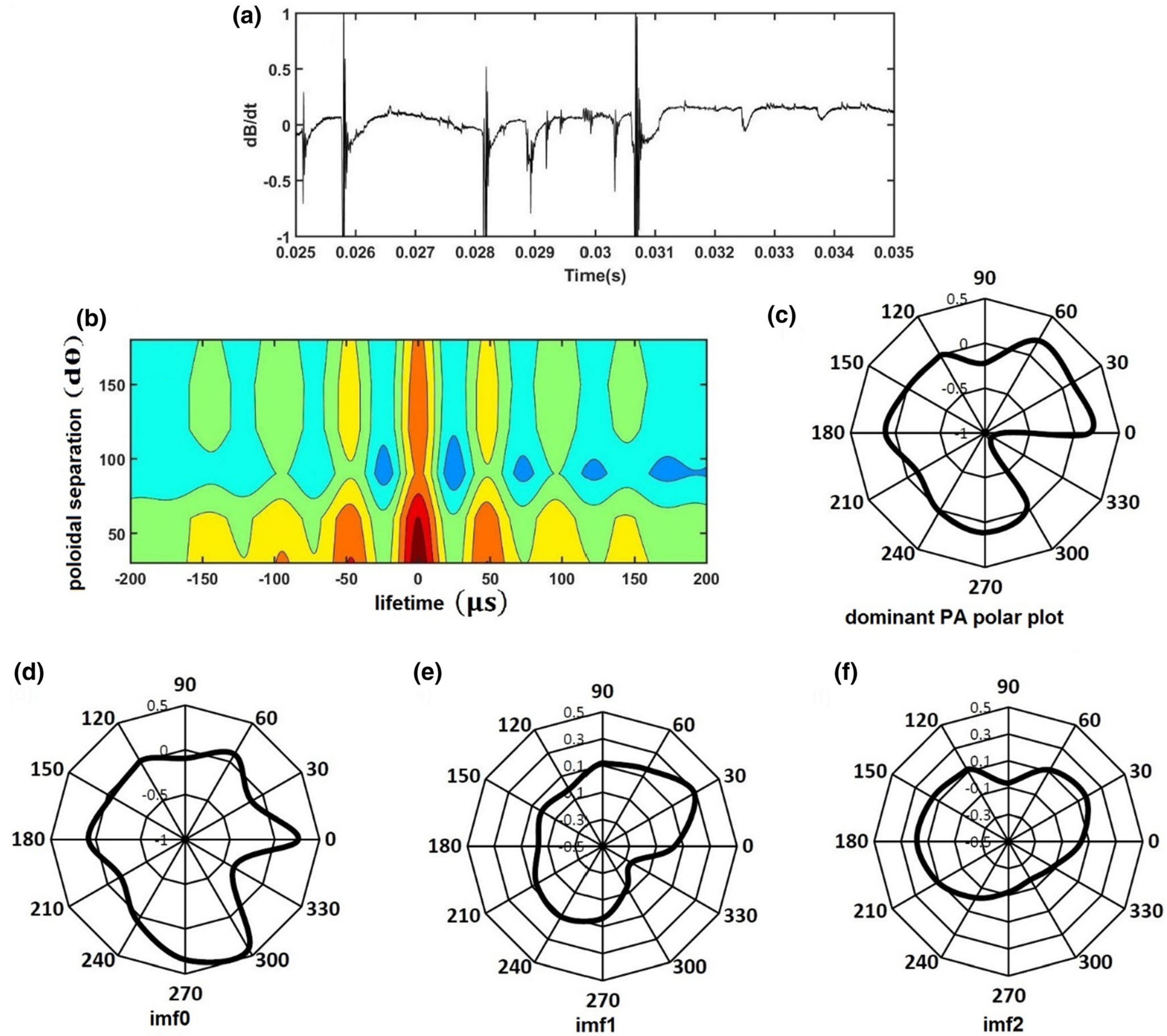

Fig. 6 **a** One of the Mirnov coil data for IR-T1 Tokamak shot number (5-961011) in (25–35 ms), **b** poloidal-temporal correlation function of dB/dt from the 12 pickup Mirnov probes. **c** Polar plot of dominant PA obtained by SVD. Corresponding IMF0 (**d**) IMF1 (**e**) and IMF2 (**f**) obtained by EMD

the spatial features of MHD modes in the form of principal axes (PAs).

For this analysis, we chose the time interval 25–35 ms from (shot14-961011) with RHF application and (shot 5-961011) without RHF application. Then, SVD analysis is done using 12 coils of Mirnov array data with (see Fig. 7c) and without (see Fig. 6c) RHF application. Dominant PAs of the poloidal MHD mode, without RHF and with simultaneous application of L = 2/n = 1 and L = 3/n = 1, is shown in Figs. 6c and 7c. In the ohmic heating discharge (Fig. 6), m = 5 MHD mode (Fig. 6d), m = 3 or m = 4 MHD mode (Fig. 6e) and m = 2 MHD mode (Fig. 6f) are extracted by EMD method from dominant PA (Fig. 6c). In the same time interval with simultaneous application of L = 3/n = 1 and L = 2/n = 1 RHF, IMF0 (m = 3 or m = 4 MHD mode number) and IMF1 (m = 2 MHD mode number) are extracted by EMD from dominant PA (Fig. 7c). We observed m = 5 MHD mode disappearing with RHF application by SVD + HHT analysis method. we have obtained these results using poloidal-temporal structures of the Mirnov coil signals in term of correlation function.

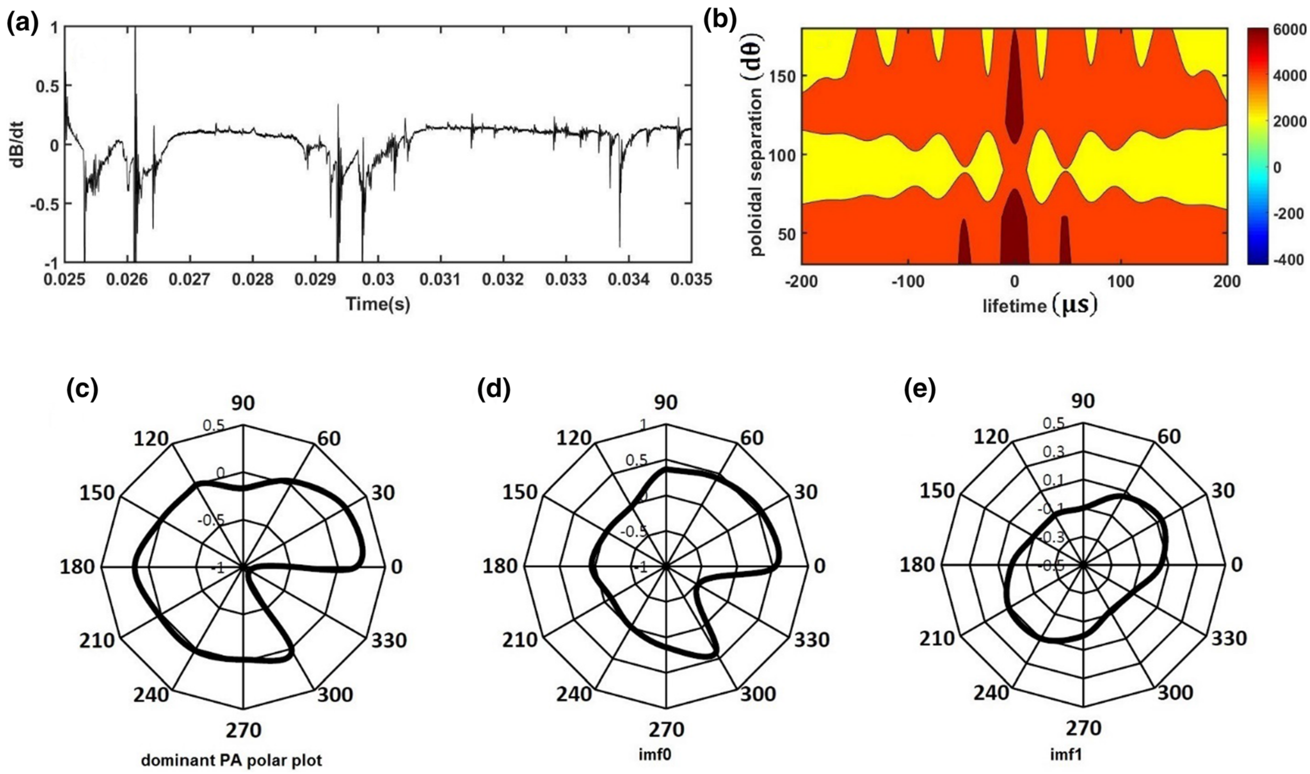

Fig. 7 **a** One of the Mirnov coil data for IR-T1 Tokamak shot number (14-961011) in (25–35 ms) **b** poloidal-temporal correlation function of dB/dt from 12 pickup Mirnov probes. **c** Polar plot of dominant PA obtained by SVD. Corresponding IMF0 (**d**) and IMF1 (**e**) obtained by EMD

Conclusion

Combination of SVD and HHT analysis methods is very effective in multimode MHD activities study. SVD analysis is very sensitive to a smaller time interval to detect even very low amplitude MHD mode. On the other hand, in the HHT analysis, the amplitude and frequency spectrum of the coupling MHD modes can be separated and MHD oscillations amplitude recognized in different periods. HHT method can extract MHD modes spectra with different amplitudes at different times. Furthermore, the instantaneous frequencies of MHD spectra can be calculated by HSA. The Poloidal-temporal correlation functions can give further information about the dynamics of the magnetic probe signals fluctuations. We use this complementary analysis method to increase the quality of SVD + HHT analysis. Spatial–temporal structures of the Mirnov coils fluctuations is used, in order to better identification of mode numbers and frequencies of dominant MHD modes. It should be possible to identify wave-like pattern modes as clear peaks. For example, rotation of the modes with the identical frequencies in the different poloidal separation in poloidal-temporal correlation functions plot is due to the coupling between modes.

It means that, in the multimode MHD activities, several modes are present and oscillate with the same frequency. A High correlation value between magnetic probes array data with most poloidal separation shows that MHD mode with small mode number (long wavelength) can be excited. Also, a high correlation value between magnetic probe with the smallest poloidal separation indicates that a large mode number (small wavelength) has been excited. Also, amplitude and poloidal phase velocity of MHD mode can be determined from poloidal-temporal correlation function plot.

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References

1. S. Elgriw, D. Liu, T. Asai, A. Hirose, C. Xiao, Control of magnetic islands in the STOR-M Tokamak using resonant helical fields. Nucl. Fusion **51**(11), 113008 (2011)
2. V. Igochine (ed.), *Active Control of Magneto-Hydrodynamic Instabilities in Hot Plasmas* (Springer, Berlin Heidelberg, 2015).
3. R.O. Dendy (ed.), *Plasma Physics: An Introductory Course* (Cambridge University Press, 1995).
4. A.M. Kakurin, I.I. Orlovsky, Empirical mode decomposition method for investigating the structure of large-scale MHD instabilities in a Tokamak. Plasma Phys. Rep. **30**(5), 370–375 (2004)

5. B.P. Van Milligen, L. García, B.A. Carreras, M.A. Pedrosa, C. Hidalgo, J.A. Alonso, E. Ascasíbar, MHD mode activity and the velocity shear layer at TJ-II. Nucl. Fusion **52**(1), 013006 (2011)
6. D. Gabor, Theory of communication. J. Inst. Electr. Eng. Part III Radio Commun. Eng. **93**(26), 429–441 (1946)
7. I. Daubechies, *Ten Lectures on Wavelets. Society for Industrial and Applied Mathematics* (Philadelphia, 1992)
8. N.E. Huang, Z. Shen, S.R. Long, M.C. Wu, H.H. Shih, Q. Zheng, H.H. Liu, The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. Proc. R. Soc. Lond. Ser. A: Math. Phys. Eng. Sci. **454**(1971), 903–995 (1998)
9. J. Terradas, R. Oliver, J.L. Ballester, Application of statistical techniques to the analysis of solar coronal oscillations. Astrophys. J. **614**(1), 435 (2004)
10. J. Kurzyna, S. Mazouffre, A. Lazurenko, L. Albarède, G. Bonhomme, K. Makowski, Z. Peradzyński, Spectral analysis of Hall-effect thruster plasma oscillations based on the empirical mode decomposition. Phys. Plasmas **12**(12), 123506 (2005)
11. A. Storelli, L. Vermare, P. Hennequin, Ö.D. Gürcan, G. Dif-Pradalier, Y. Sarazin, V. Grandgirard, Comprehensive comparisons of geodesic acoustic mode characteristics and dynamics between Tore Supra experiments and gyrokinetic simulations. Phys. Plasmas **22**(6), 062508 (2015)
12. A.M. Kakurin, I.I. Orlovsky, Hilbert–Huang transform in MHD plasma diagnostics. Plasma Phys. Rep. **31**(12), 1054–1063 (2005)
13. R. Jha, D. Raju, A. Sen, Analysis of Tokamak data using a novel Hilbert transform based technique. Phys. Plasmas **13**(8), 082507 (2006)
14. R. Coelho, D. Alves, C. Silva, Magnetohydrodynamic and turbulence activity analysis in the ISTTOK Tokamak using empirical mode decomposition. Rev. Sci. Instrum. **77**(10), 10F512 (2006)
15. Y. Liu, Y. Tan, H. Xie, W. Wang, Z. Gao, Time-frequency analysis of non-stationary fusion plasma signals using an improved Hilbert–Huang transform. Rev. Sci. Instrum. **85**(7), 073502 (2014)
16. B. Wan, Z. Chen, Y. Sun, Recent experiments in the HT-7 superconducting Tokamak. In *Fusion energy 2006. Proceedings of the 21. IAEA conference* (2007)
17. G. Van Oost, J. Adamek, V. Antoni, P. Balan, J.A. Boedo, P. Devynck, C. Ionita, Turbulent transport reduction by E $\times$ B velocity shear during edge plasma biasing: recent experimental results. Plasma Phys. Controlled Fusion **45**(5), 621 (2003)
18. C. Nardone, Multichannel fluctuation data analysis by the singular value decomposition method. Application to MHD modes in JET. Plasma Phys. Control Fusion **34**(9), 1447 (1992)
19. T.D. de Wit, A.L. Pecquet, J.C. Vallet, R. Lima, The biorthogonal decomposition as a tool for investigating fluctuations in plasmas. Phys. Plasmas **1**(10), 3288–3300 (1994)
20. C. Marchetto, G. Granucci, F. Gandini, Sensitivity Analysis of SVD algorithm for real time mode control on FTU. In *37th EPS Conference on Plasma Physics 2010, EPS 2010* (2010)
21. C. Marchetto, E. Alessi, L. Boncagni, C. Galperti, S. Nowak, C. Sozzi, Application of SVD algorithm to a set of Real Time Mirnov coil signals in FTU Tokamak. In *EPS Conference on Plasma Physic* (2012), pp. 2–64
22. C. Marchetto, F. Gandini, S. Cirant, G. Granucci, E. Lazzaro, B. Esposito, MHD structure analysis by singular value decomposition as a tool for ECRH RT-control of instabilities on FTU. In *AIP Conference Proceedings*, vol 1187, no 1 (AIP, 2009), pp. 519–522.
23. C. Galperti, C. Marchetto, E. Alessi, D. Minelli, M. Mosconi, F. Belli, S. Garavaglia, Development of real-time MHD markers based on biorthogonal decomposition of signals from Mirnov coils. Plasma Phys. Control. Fusion **56**(11), 114012 (2014)
24. N. Cressie, C.K. Wikle, Statistics for spatio-temporal data. John Wiley& Sons (2015)
25. M. Tan, H. Li, C. Tu, T. Deng, Z. Li, B. Luo, W. Ding, MHD mode analysis using the unevenly spaced Mirnov coils in the Keda Torus eXperiment. IEEE Trans. Plasma Sci. **47**(7), 3298–3304 (2019)
26. Perso.ens-Lyon.fr/patrik. Flandrin/emd
27. M.R. Ghanbari, M. Ghoranneviss, M.N. Ardebili, A new perspective on MHD mode identification of IR-T1 Tokamak plasma by frequency filtering and fitting method. Int. J. Hydrog. Energy **43**(24), 11173–11179 (2018)
28. H. Faridyousefi, M.K. Salem, M. Ghoranneviss, Study of MHD activities in IR-T1 Tokamak plasma using Hilbert–Huang transform. Braz. J. Phys. **49**(6), 864–873 (2019)