MIMO MODELLING AND DESIGN FOR MHD MODES CONTROL IN RFX-MOD

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OUTLINE

- Overview of the MHD active control system modelling in RFX-mod

  - Dynamic model of the active coils system

  - Dynamic model of the coil-sensor couplings

- Experimental determination of model parameters

  - Model validation results

- Design of a MIMO dynamic decoupler

  - Singular Values Decomposition analysis of the coil-sensor dynamic model

  - Design of the dynamic decoupler

  - Simulation results

- Conclusions

Active Coils and Passive Structures Models
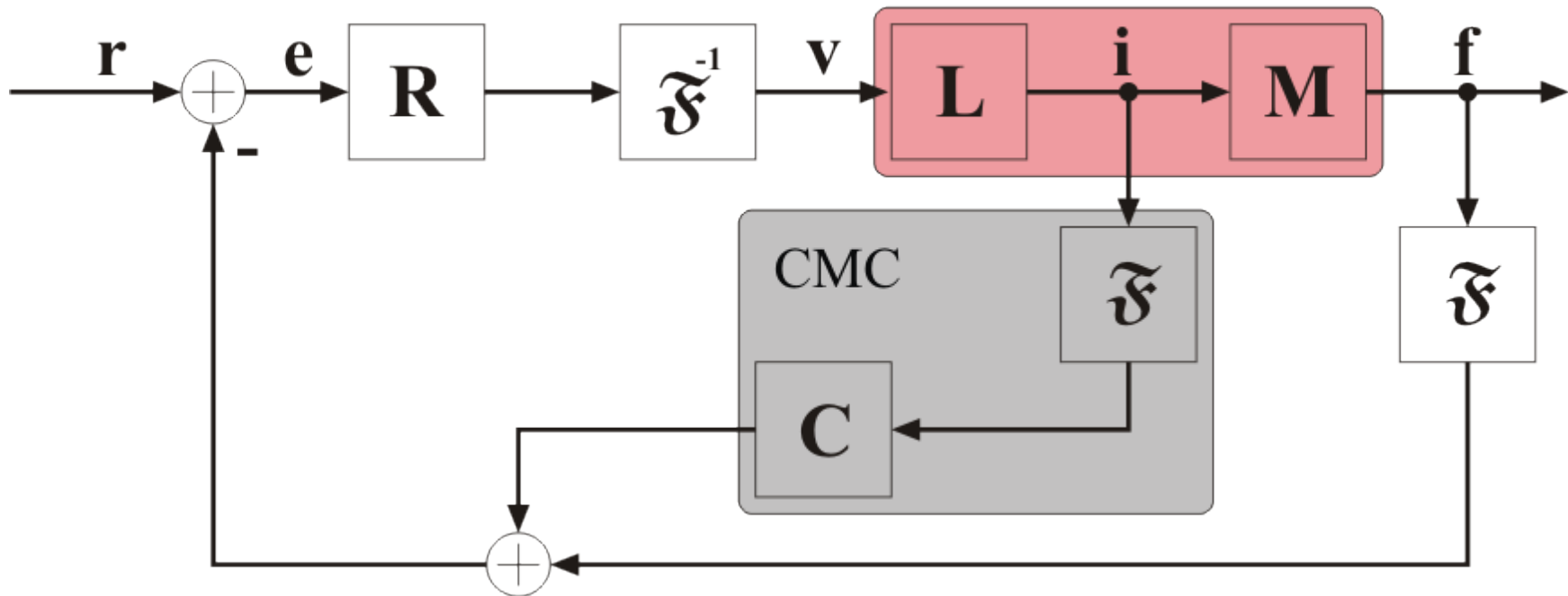
- L is the model of the active saddle coil system
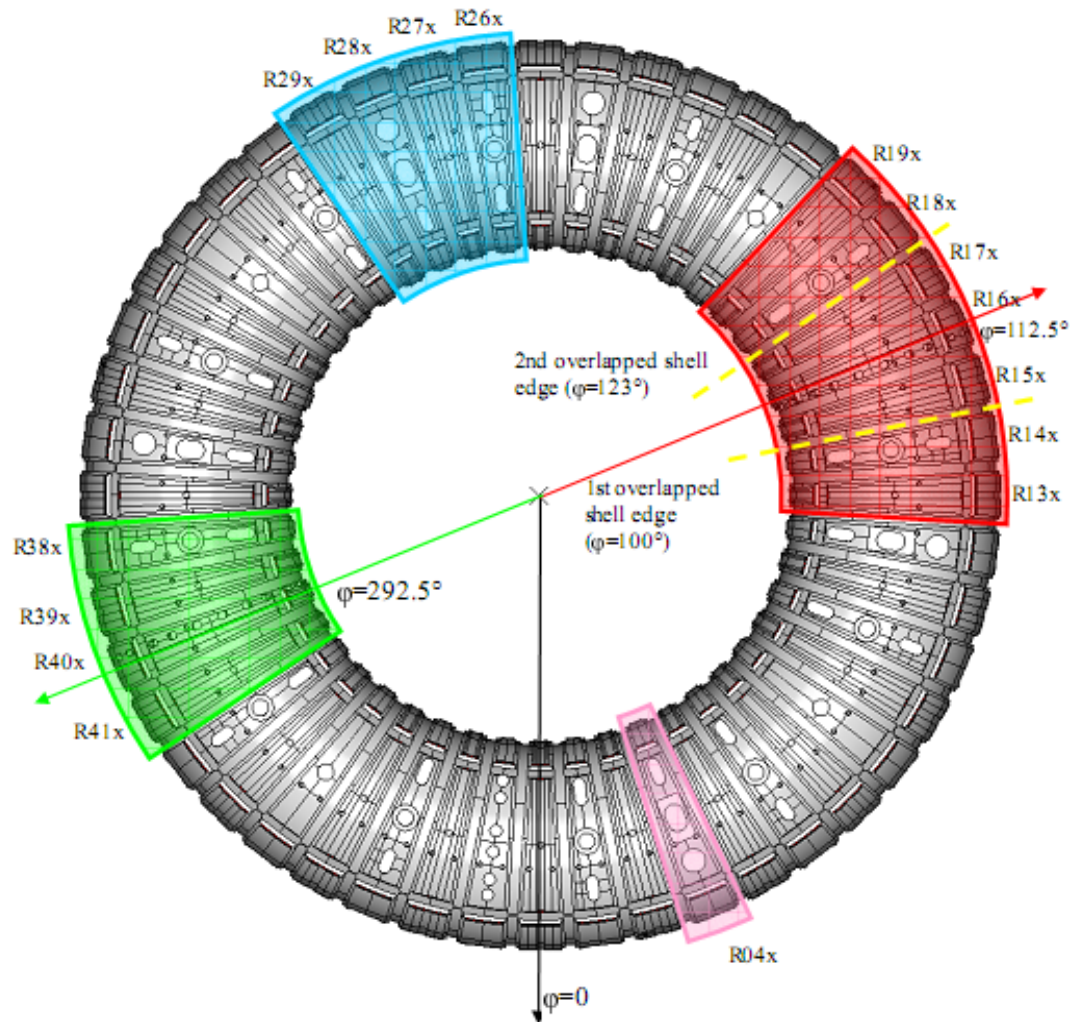- M is the model of the coupling between active coils and sensors

Experimental data acquisition for system characterization

- Since the coils are mounted on two overlapping conducting structures the coupling and the dissipative parameters depend on the frequency.

- Experimental data to compute the coupling terms between active coils and between active coils and sensors were collected at frequency $f=w/2p=[10, 20, 50, 100, 200]$ Hz.

- To investigate on non-axisymmetric effects due to the load-assembly, data were collected in sections of the torus both with and without special features (structure poloidal gaps, shell poloidal gap with overlapped edges).

- Overlapped gap zone (red): $86.25° <= \varphi <= 138.75°$

- Structure 2nd gap zone (green): $273.75° <= \varphi <= 303.75°$

- First "standard" zone (blue): $183.75° <= \varphi <= 213.75°$

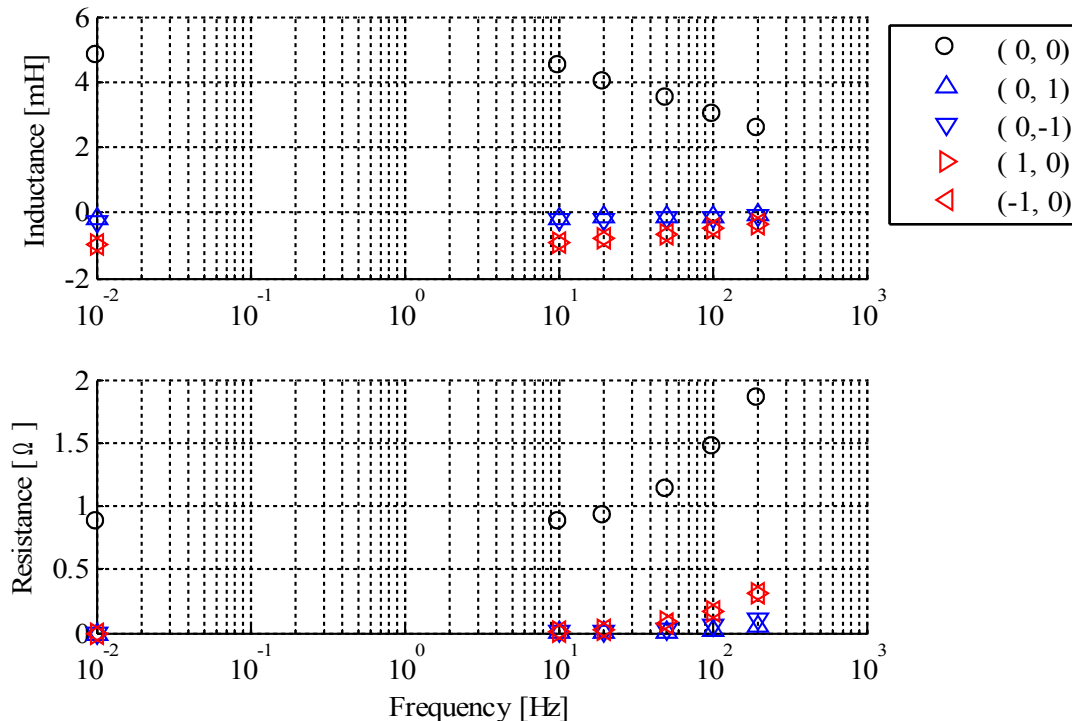- Second "standard" zone (pink): $\varphi = 22.5°$

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- The "off-diagonal" dissipative terms are associated only to the passive structures, which react to the currents induced in the surrounding active coils, as well.

- The coupling terms are singled out by a couple of numbers, where the digits 0 e ±1 mean invariance and increment/decrement along the toroidal (first digit of the couple) and poloidal (second digit of the couple) direction.

- The relative weight of self and mutual inductance is apparent and, in particular, the greater importance of the coupling with the toroidally adjacent coils, consistently with the longer length of the poloidal leg, can be appreciated.

Self inductance and resistance of coil (26,2); mutual inductance and mutual resistance of the same coil with the adjacent ones.

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Computation of active coil-sensor couplings
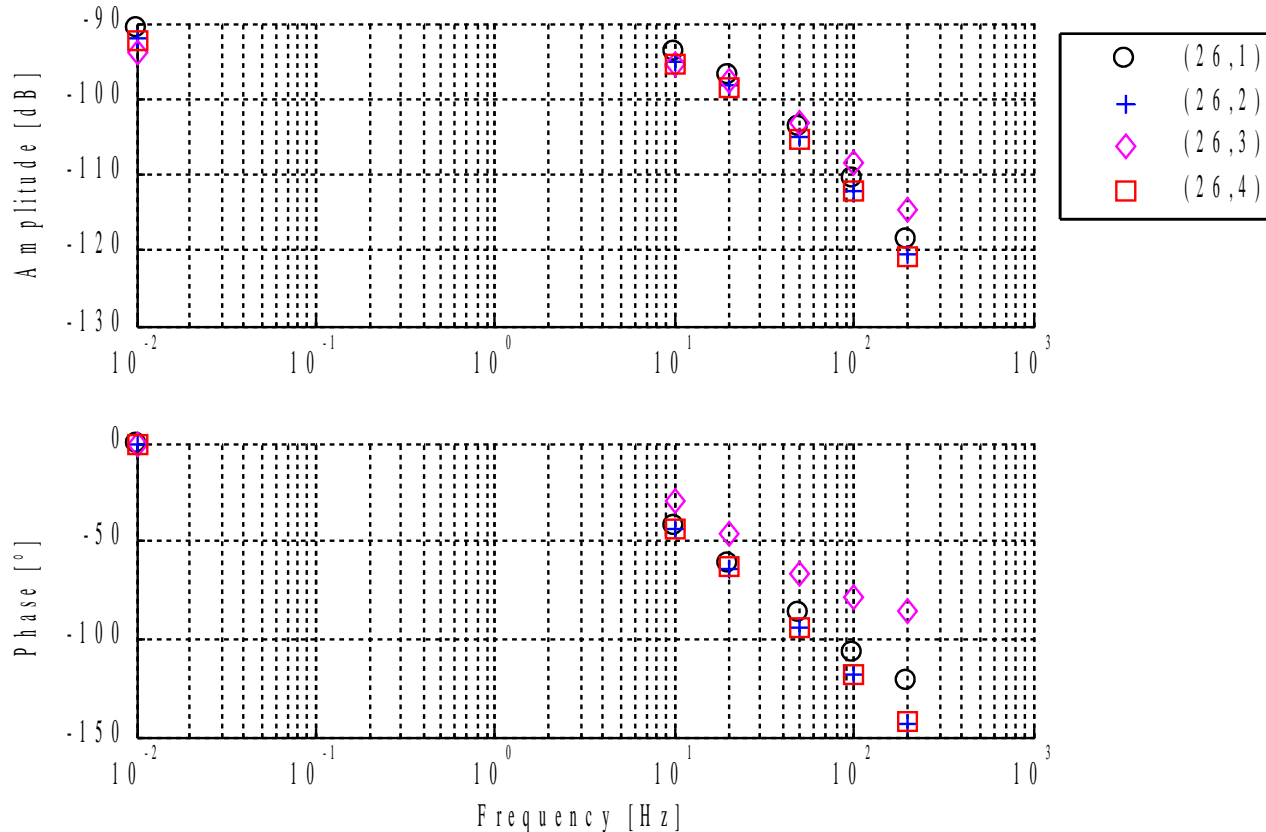
At high frequency the presence of the inner equatorial gap compensates for the reduced size of the inner coil-sensor couple, the corresponding mutual inductance resulting larger than the others where the shielding of the passive structures is more effective.

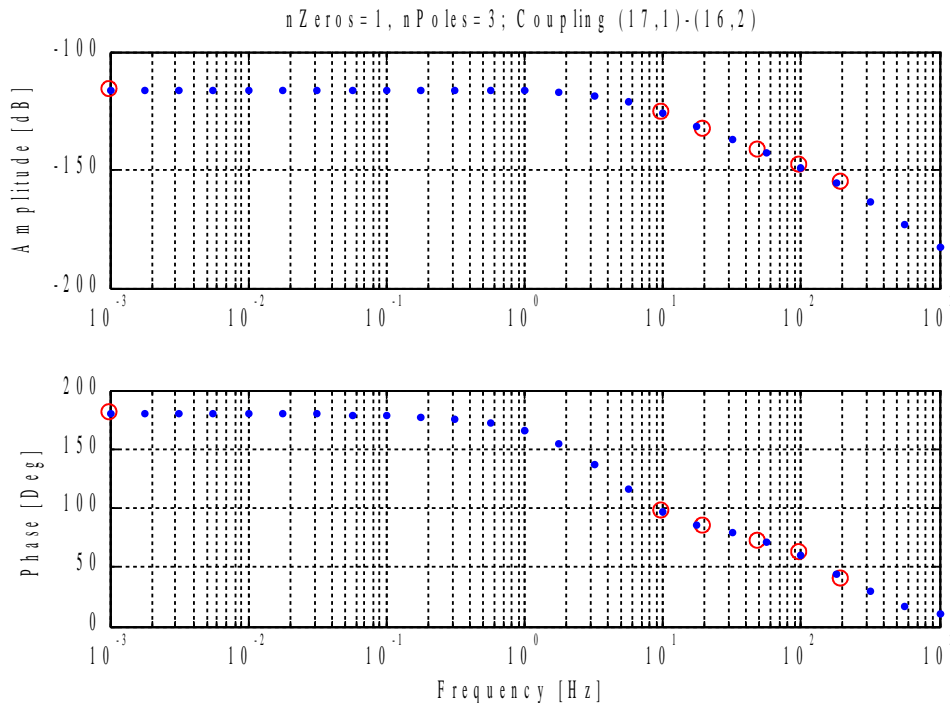**Mutual coupling of the coils in the poloidal array 26 with the underlying sensor.**
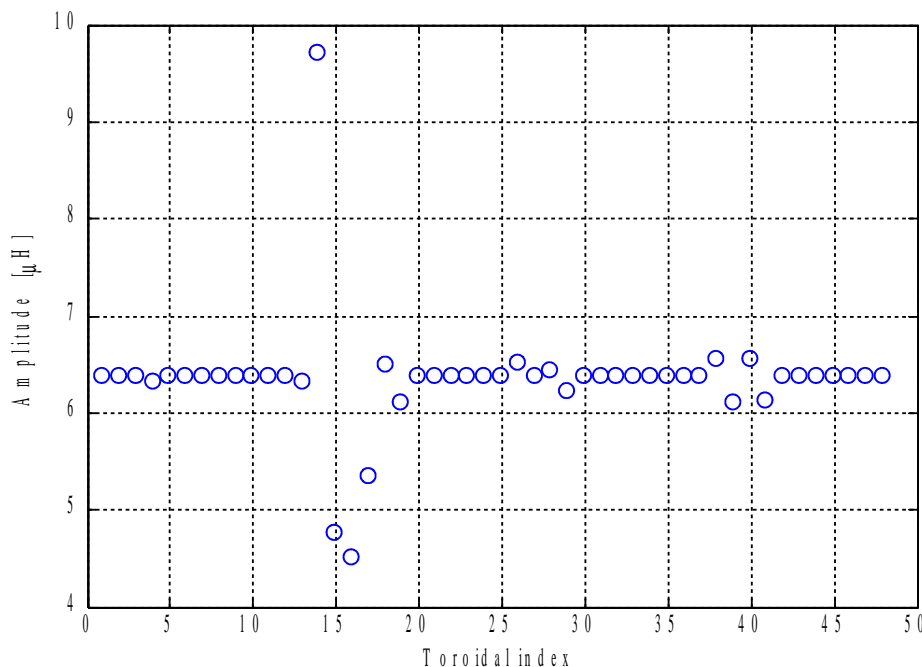
Mutual coupling of the outer coils with the underlying sensors at 50 Hz

- The most significant differences are near the structure and shell poloidal gaps

- (14,1) is the highest since there is no short-circuit element in the inner shell edge on its right side.

- The following three mutual inductances are the lowest, as the corresponding couples face the shell overlapped edges with the outer one regularly short-circuited.

- Lower deviations in the section of the structure second poloidal gap; the largest two terms result (38,1) and (40,1), the former couple encircling a pumping port and the latter spanning the poloidal gap.

- The average values of the "standard" zone appear at the other positions.

nZeros=1, nPoles=3; Coupling (17,1)-(16,2)

Frequency response relative to the coupling between coil (16, 2) and sensor (17, 1). Model (blue point), measured (red circle).

- Automatic evaluation of the coil-sensor transfer functions. It is based on a MATLAB toolbox routine providing the numerator and denominator coefficients of the transfer function which best fits in a least square sense an assigned set of experimental frequency response data. According to the couple coil-sensor, a different number of zeros and poles of the transfer functions was necessary to achieve the best fitting.

- In order to achieve a satisfactory agreement in reproducing the time evolution of the magnetic flux as many as 52 coil-sensor mutual inductances were considered in the final version (reaching a number of about 6000 states). The dynamic and steady state errors are generally about 5%, which was assessed sufficient for the design and performance analysis of an active control system of MHD modes.

Computation of active coil-sensor couplings

Logarithmic normalised magnitute [log10(abs(M)/max(max(abs(M))))] at 20 [Hz]
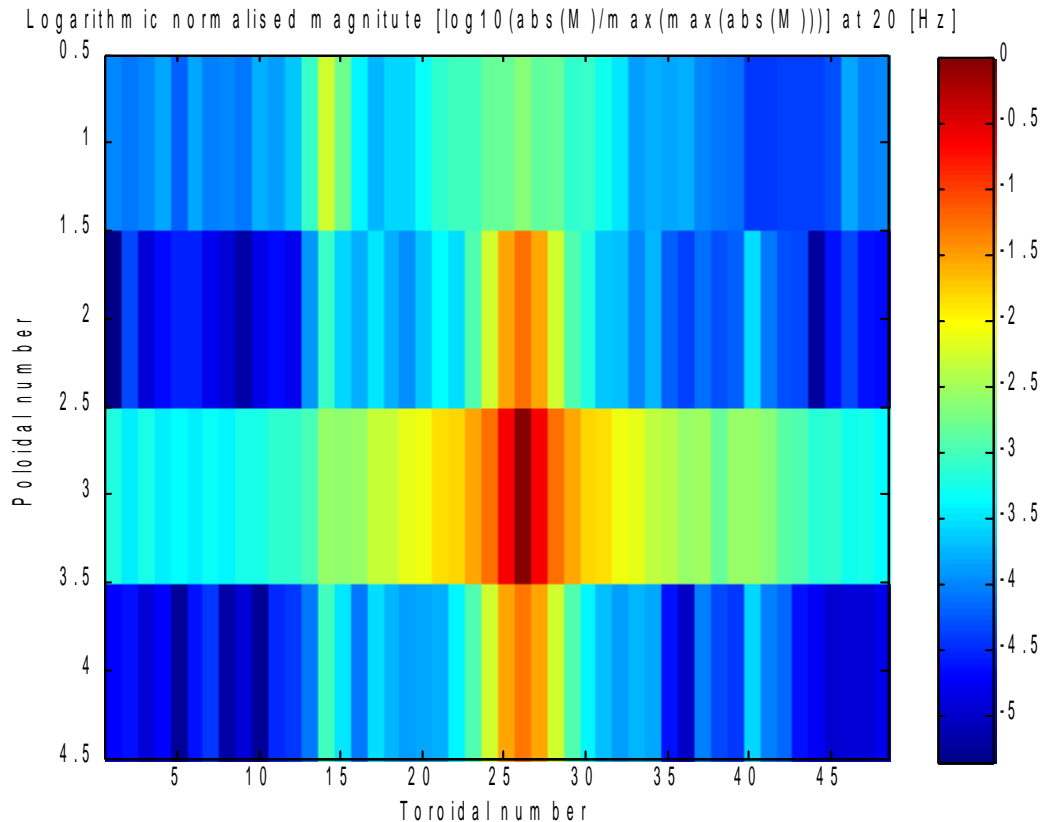
- It is worth while noticing how far the effect of a coil can propagate to less shielded sensors. In the figure the case of sensor (14,1) and sensors spanning the toroidal inner gap are shown.

- Each sensor measure is clearly affected by many "small" (~1% of the overlying coil) contributions.

- They add up with the same sign for coil current distributions with low m and n.

Computation of active coil-sensor couplings

Logarithmic normalised magnitude [log10(abs(M)/max(max(abs(M))))] at 200 [Hz]
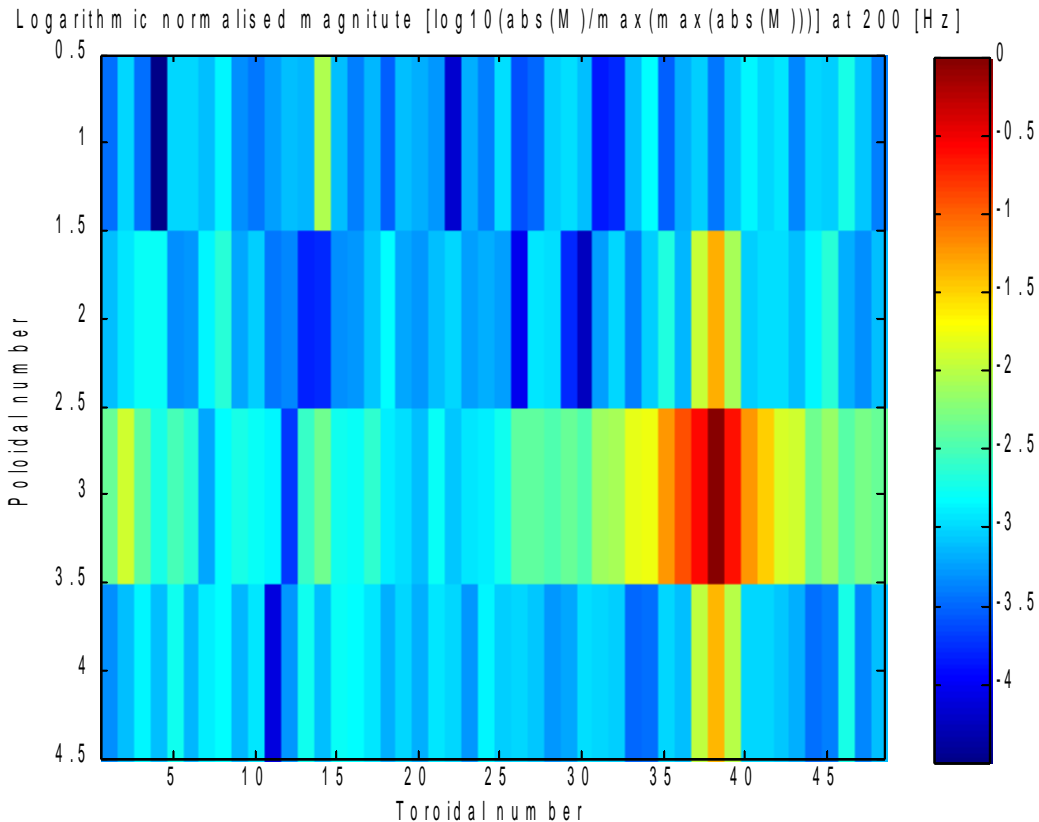
- Another example is given for shot 22470.

- The coil (38,3) was fed at 200 Hz. The same effect of the anomalous position (14,1) is visible notwithstanding the lower signal to noise ratio and the distance.

- The active coil parameters (inductances and resistances) exhibit a much lower dependence on the frequency than the mutual couplings between the active coils and the sensors.

- A constant matrix representation for the active coils parameters could then be chosen, while the full transfer function matrix was needed to reproduce the behaviour of the coil-sensor couplings. A more convenient and numerically robust state representation was then derived and used to build the MIMO model.

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Coil (46,1)   Coil (46,2)   Coil (14,3)   Coil (14,4)
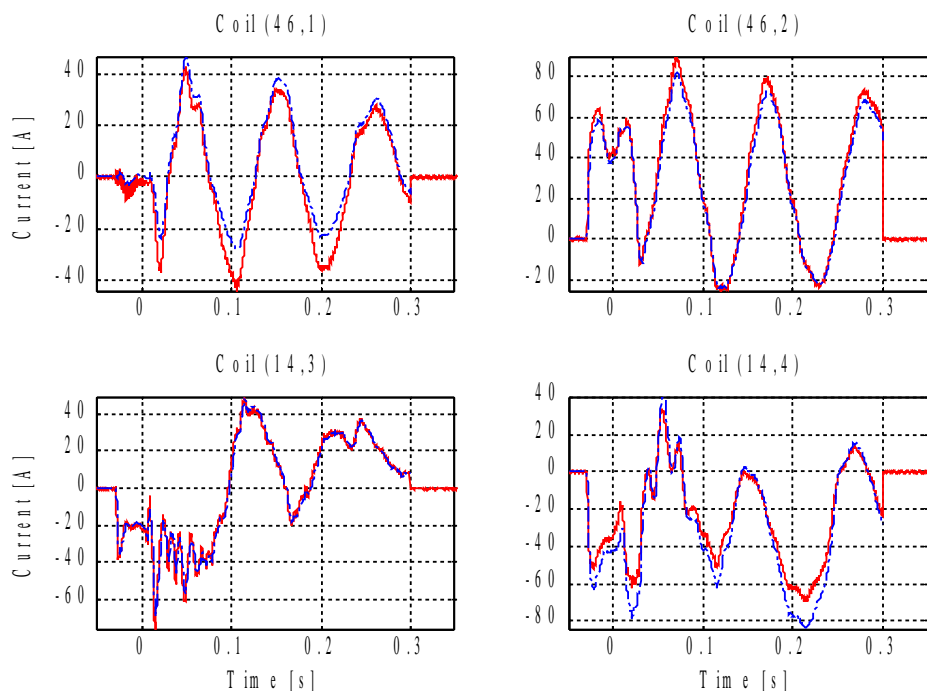
Comparison between model (blue dashed) and measured (red) saddle coil currents in a shot with plasma.

- In the presented case (Shot #17523: a 10 Hz rotating field imposed in a plasma shot with virtual shell) the 10 Hz values of inductance and resistance were used to make up the matrices. The agreement is satisfactory confirming that the number of 5 coupling terms between active coils is sufficient and that it is an acceptable assumption to neglect the coupling between plasma and active coil currents.
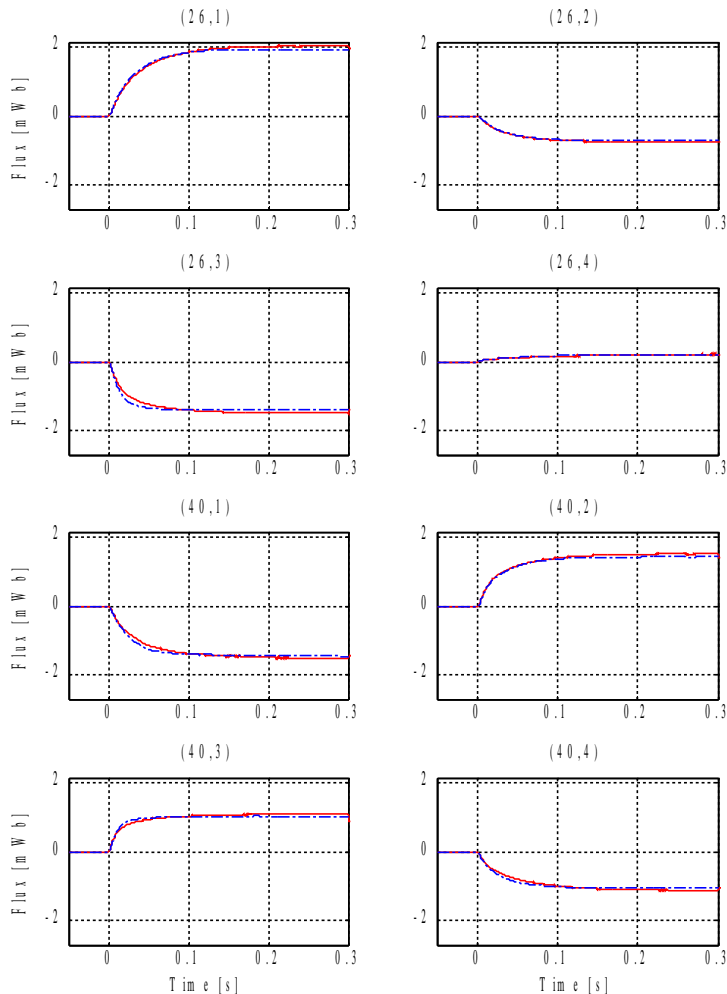
- Tests executed applying the measured coil currents as system inputs and evaluating the radial components of the magnetic field as model outputs.

- In the figure fluxes measured in shot #17136 (m=1, n=2 mode) by 4 poloidal arrays of saddle probes are compared with the corresponding model outputs.

- Similar successful validation procedures have been carried out in order to test the model in virtual shell closed loop operation.

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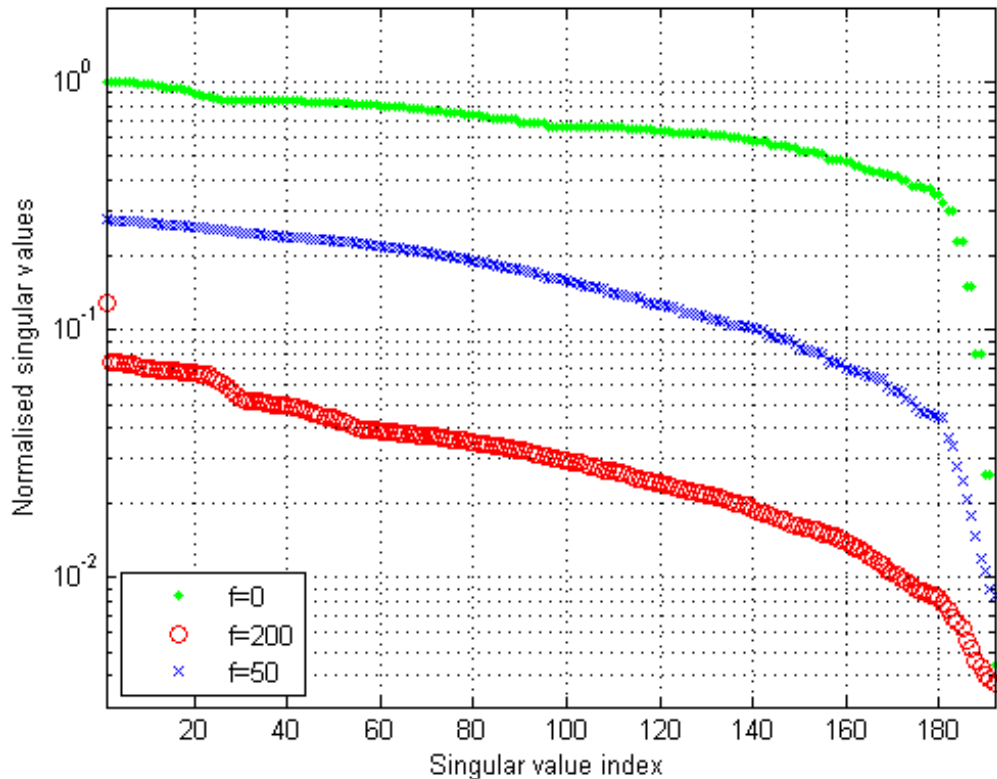
- The input and output singular vectors can be interpreted as coil current and flux distributions, respectively.

- The Singular Values give a measure of the system effectiveness in creating different magnetic flux distributions.

- Since the input and output singular vectors are very close in the case of RFX-mod, only the input ones are shown in the following figures.
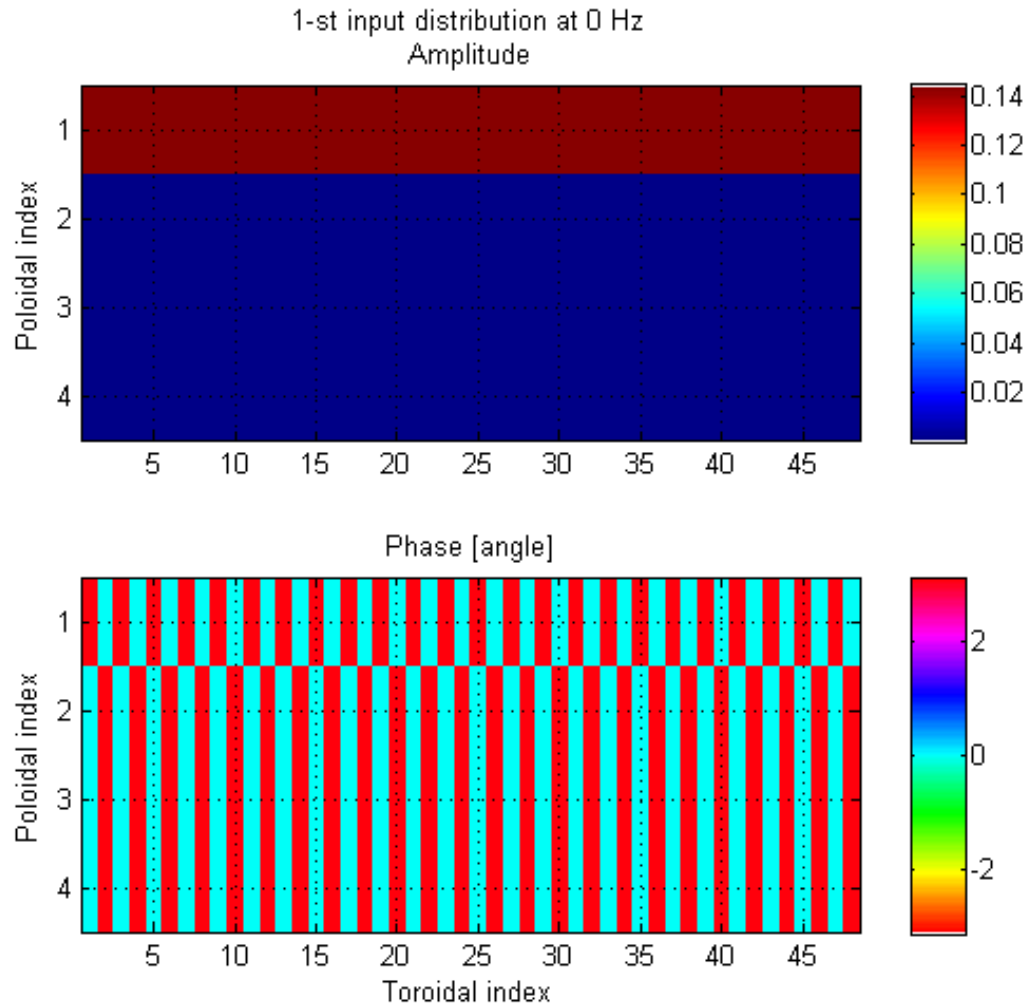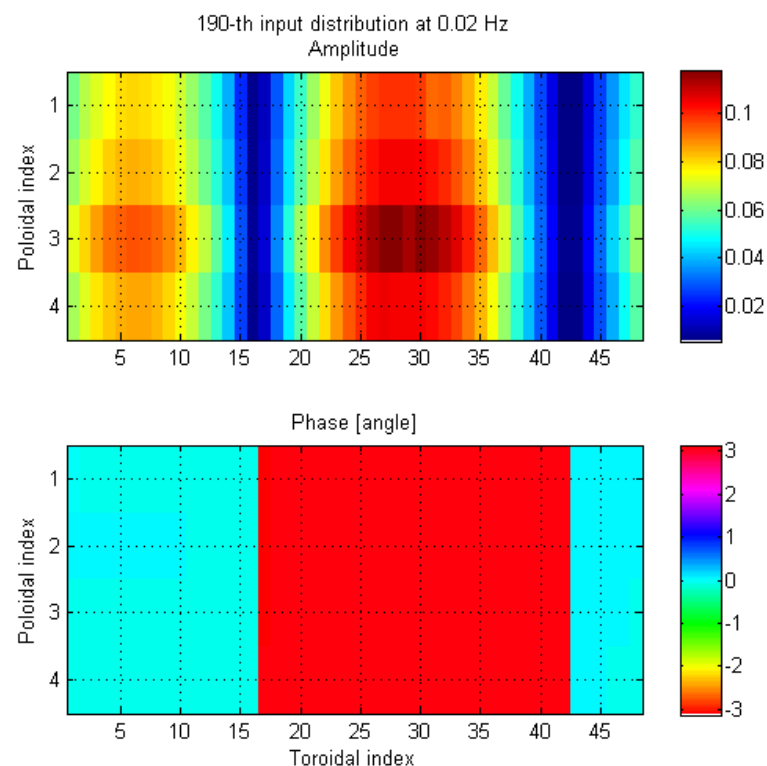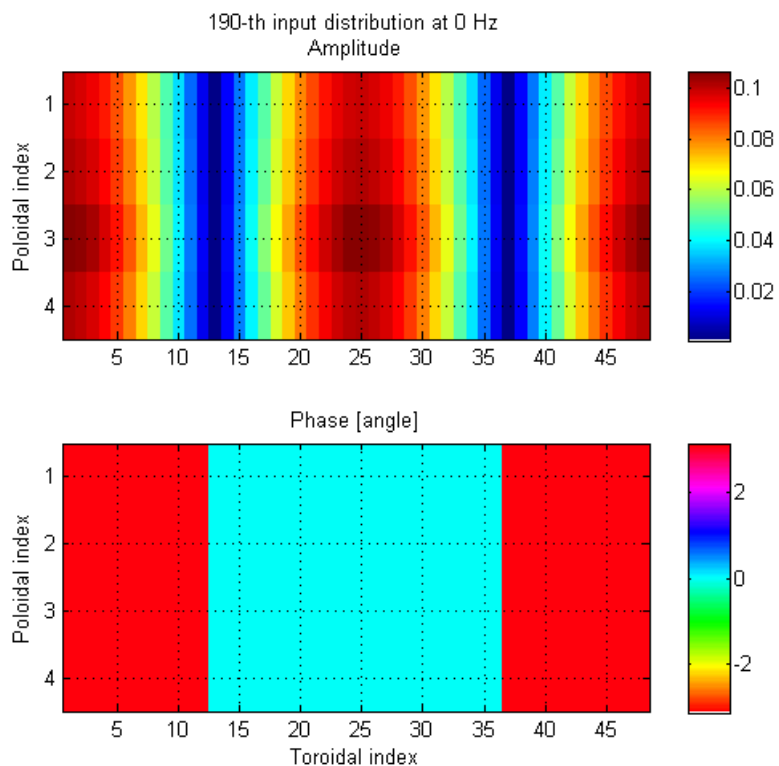
- An example of the most effective distribution is given in the figure.

- It consists in feeding the outer toroidal array with alternate sign and it does not correspond to any modal distribution.

- The SVD analysis results to be a useful tool to get an insight into the physical properties and limits of the system.
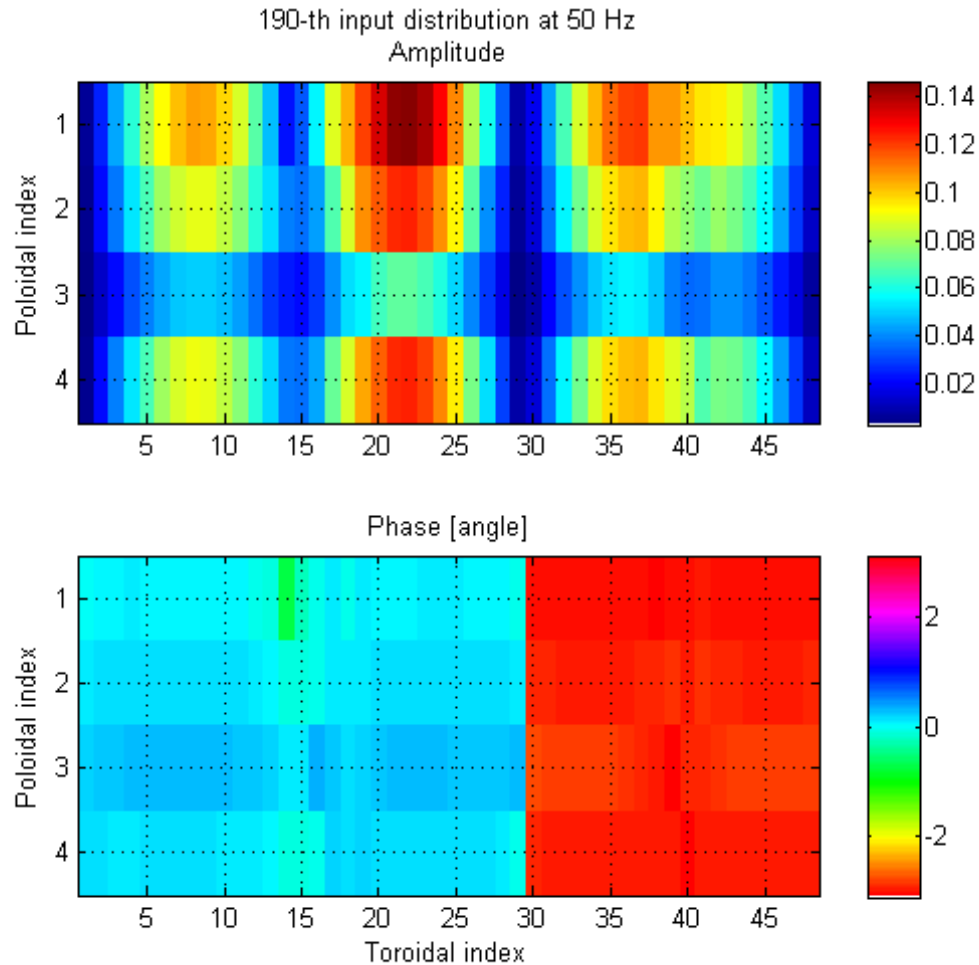
- Two more examples of distributions are here presented to highlight the effect of neglecting small coupling terms in calculating the svd decomposition.

- In this case the most ineffective one is shown: it is very close to a m=0, n=1 modal distribution.

190-th input distribution at 50 Hz

- The figure shows the increasing effect of the toroidal disuniformity in making a distribution ineffective at increasing frequency. A distribution aimed at keeping the flux at zero along the equatorial gap and in the region near the sensor (14,1) is ranked in the lowest positions.

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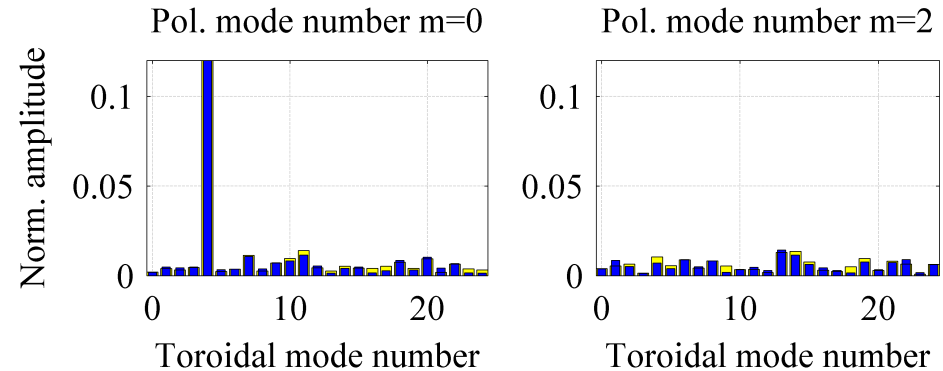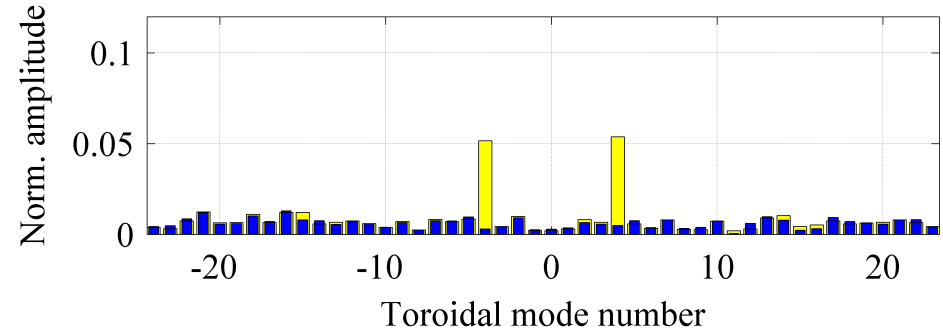
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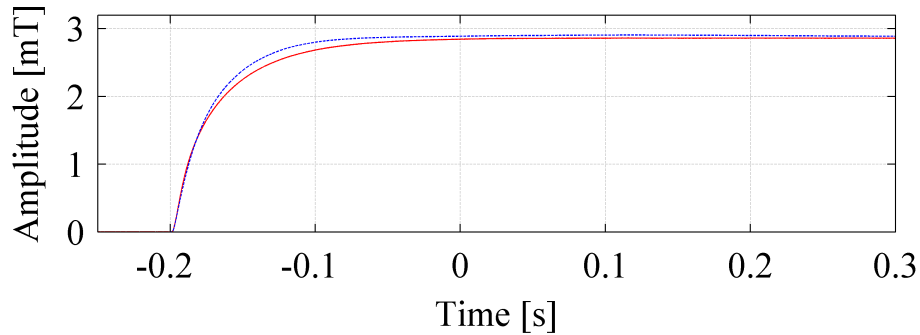
Mode numbers m=0, n=4

Mode numbers m=1, n=-4
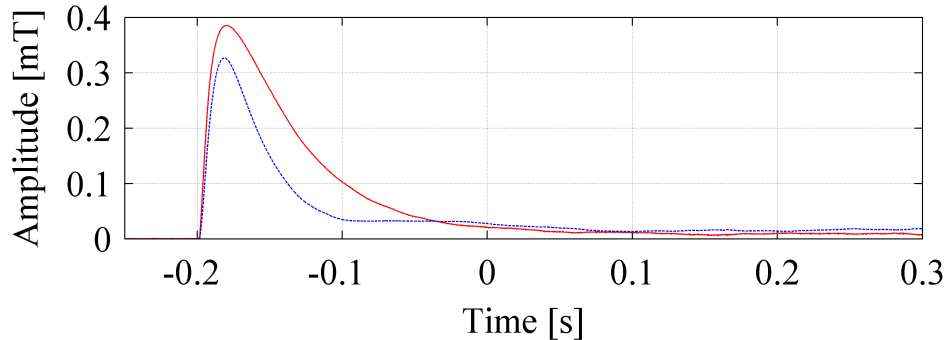
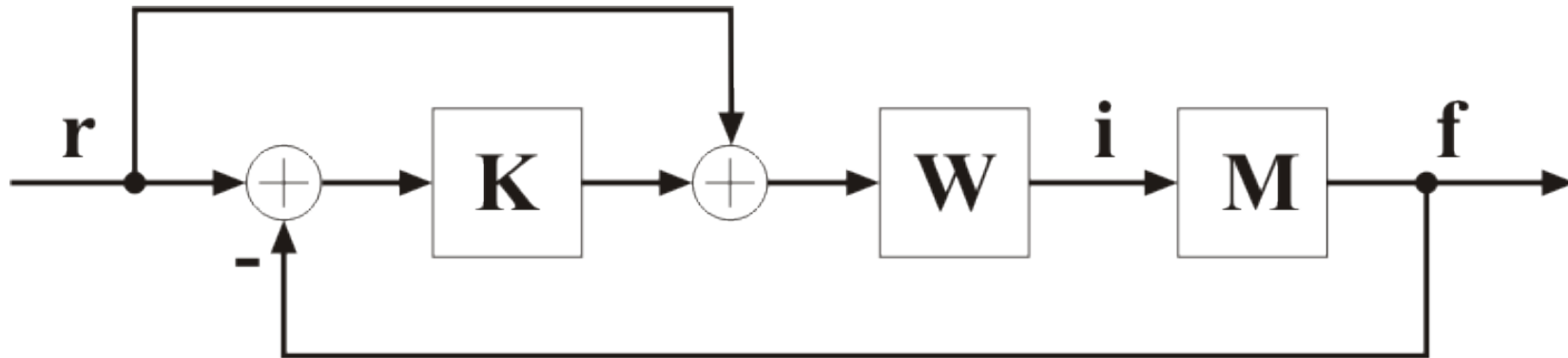Poloidal mode number m=1

Pol. mode number m=0

Pol. mode number m=2

Shot 19552: computed (blue dashed) and measured (red) evolution of spectral component m=0, n=4 and m=1, n=4.

Comparison between the normalized amplitudes of the spectral components in shot 19552 (blue) and shot 19539 (yellow).

$$M(j\omega) = \begin{bmatrix} U(j\omega) & u_{192}(j\omega) \end{bmatrix} \begin{bmatrix} \Sigma(j\omega) & 0 \\ 0 & \sigma_{192}(j\omega) \end{bmatrix} \begin{bmatrix} V(j\omega) & v_{192}(j\omega) \end{bmatrix}^{H}$$

$$W(j\omega) = V(j\omega)\Sigma^{-1}(j\omega)U^{H}(j\omega)$$

- The decoupler W has been calculated through a pseudo-inversion of the model M instead of a standard inversion because the last singular value is ideally equal to zero.

- This is a consequence of having a set of sensors exactly covering a closed surface.
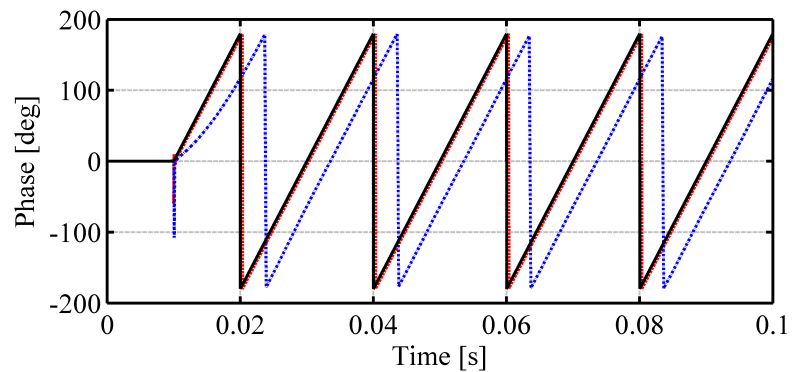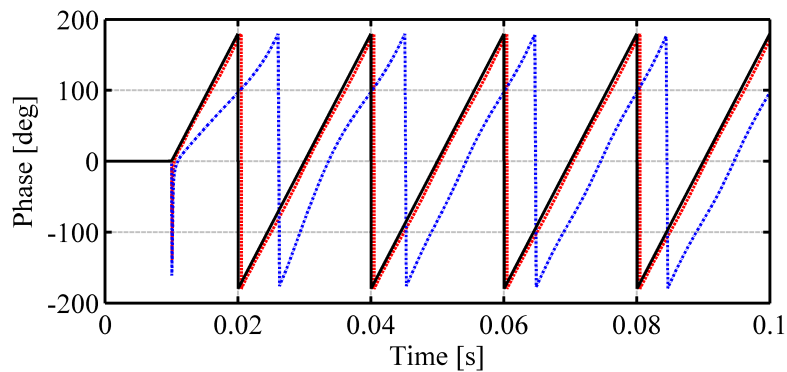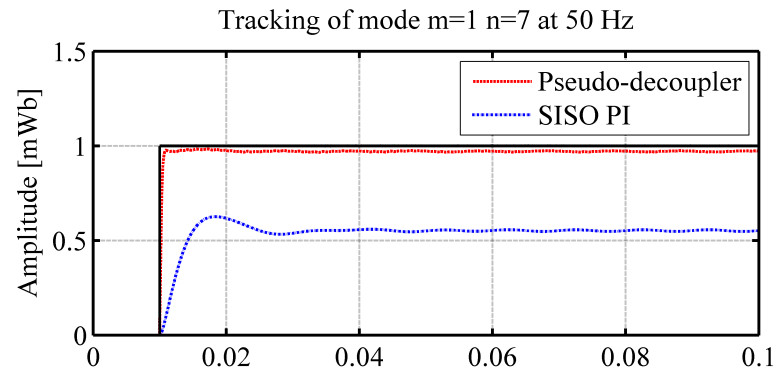
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Dynamic Decoupling

Rejection of mode m=0 n=4 at 20 Hz

Rejection of mode m=1 n=7 at 20 Hz
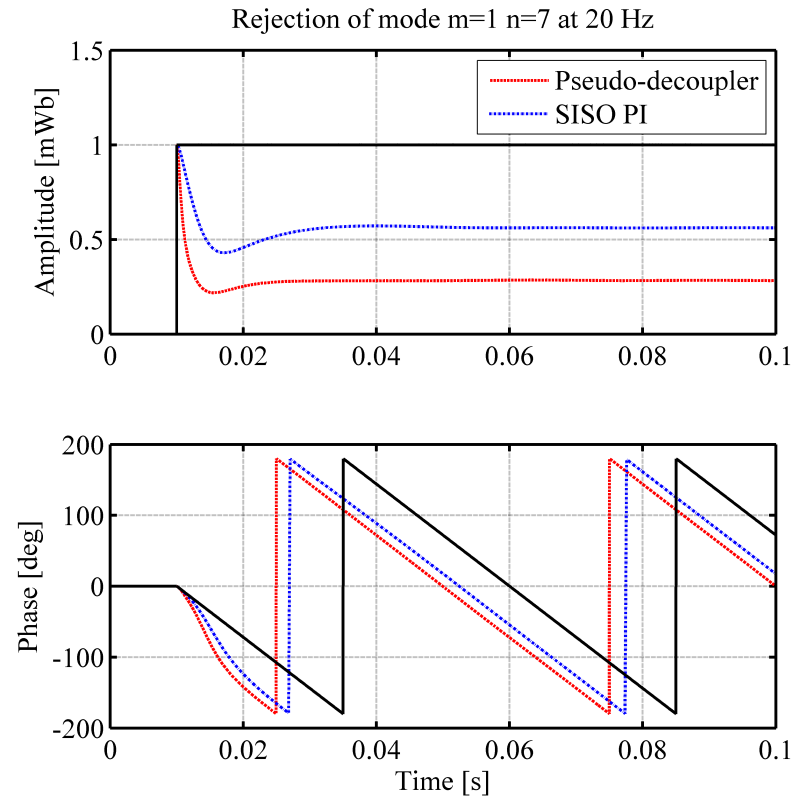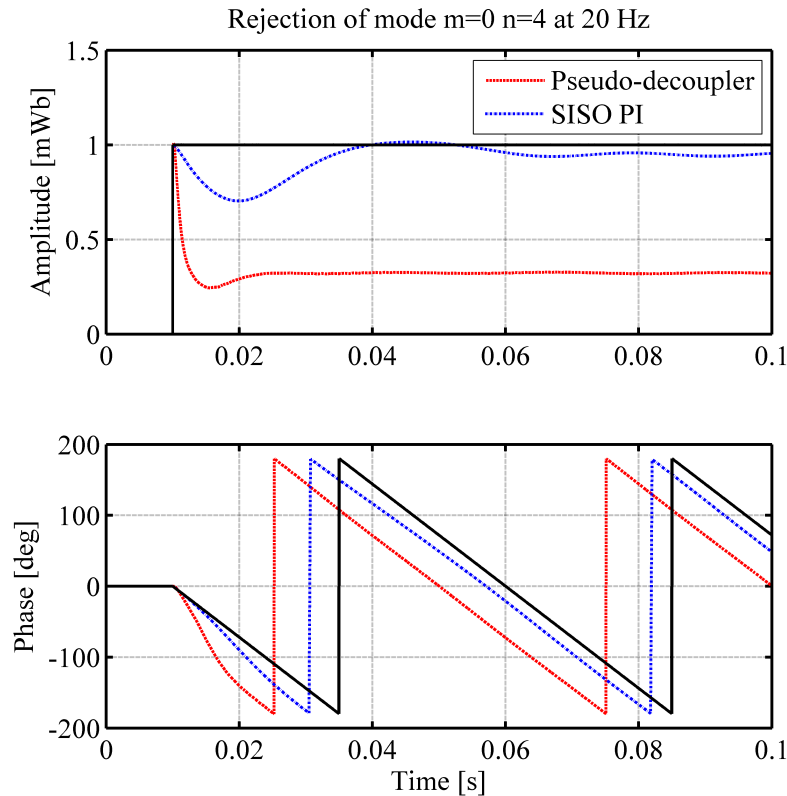
- Simulations of mode tracking and mode rejection: a comparison between a controller with dynamic decoupler and now operating, SISO approach designed, PI regulator

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Tracking of mode m=0 n=4 at 50 Hz

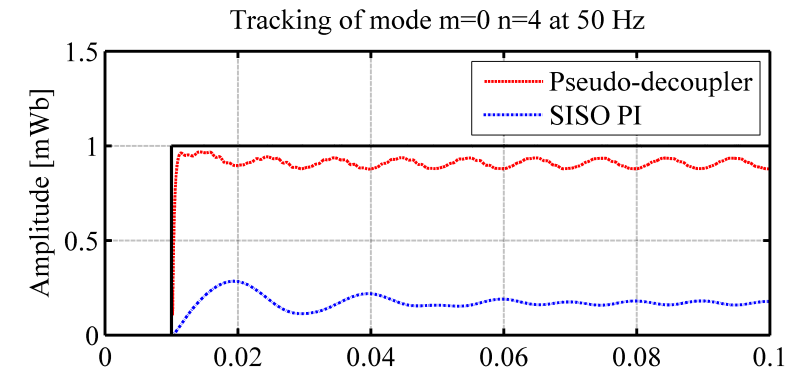Tracking of mode m=1 n=7 at 50 Hz

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CONCLUSIONS

- A MIMO full electromagnetic dynamic model of the MHD mode control active control system has been derived starting from the experimental data

- SVD analysis turned out to be a useful tool to gain insight on the system properties and limits

- A MIMO dynamic decoupler has been designed on the basis of the model

  - Simulations show promising results in terms of system tracking and rejection capability

  - Implementation activity started and experimental tests are foreseen in the next year