35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-5.047 (2008)

Comparison Between an Experimentally Estimated and a Finite Element Model of RFX-mod MHD Active Control System

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Introduction

RFX-mod is equipped with an active system for the control of MHD instabilities, consisting of 192 saddle coils, uniformly distributed on the outer side of the support structure, 192 power amplifiers independently feeding the saddle coils, and an array of 192 sensors for each component (b_r, b_ϑ, b_φ) of the magnetic field. In the past years, a multi-input multi-output (192x192) dynamical model of the system has been derived by identifying the transfer function matrix $\mathbf{M}(j\omega)$ from the coil currents to the flux measurements according to the black box paradigm [1]. On the whole, the model can well reproduce the evolution of the flux at the sensors from the applied currents, the applied voltages and in closed loop operations, too. However, the accuracy decreases for a number of locations near regions with local cuts and vacuum portholes and for m=0, low n current patterns. A possible explanation could be that, in the model derivation, simplifying hypotheses have been made, with the aim of saving machine experimental time (for taking the measurements) and to limit the resulting model size. However, in view of an optimisation of the control system, the residual errors present in the model can no longer be acceptable. To achieve a more accurate evaluation of the active coils-sensor probes couplings, new measurements have been performed, aimed also at determining coupling terms originally supposed negligible. Moreover, an activity has started to compare the couplings estimated from measurements with the corresponding ones evaluated by the finite elements code called Cariddi [2]. This activity has two goals: on the one hand, it allows benchmarking the RFX-mod geometrical model used by Cariddi with experimental data, on the other hand, it can provide further "virtual measurements" useful to improve accuracy of the active system dynamical model. The validation of the geometry is also a preliminary step for its use in studying the resistive wall modes (RWM) with the CarMA computational tool [3], whose adaptation to RFX-mod is currently in progress.

Models description

Being both the number of inputs and outputs equal to 192, a total of 36864 scalar relations are in principle required to describe the system. Each one of these relations, referred to as couplings in the paper, is itself a single-input single-output dynamic system which describes the effects of a given saddle coil current on the flux measured by a given radial field sensor.

In the Cariddi implementation of the finite elements approach, the model is derived by applying the Galerkin method to an integral formulation of the eddy currents problem in the frequency domain. In particular, a two-component electric vector potential $\mathbf{T}$ is introduced to express the current density $\mathbf{J} = \nabla \times \mathbf{T}$ in terms of edge elements [2]. The resulting algebraic system of equations is

$$\begin{cases} j\omega \mathbf{L}_{ss} I_s + j\omega \mathbf{L}_{sc} I_c + \mathbf{R}_s I_s = 0 \\ j\omega \mathbf{L}_{cs} I_s + j\omega \mathbf{L}_{cc} I_c + \mathbf{R}_c I_c = V_c \\ j\omega \mathbf{L}_{ms} I_s + j\omega \mathbf{L}_{mc} I_c = V_m \end{cases} \tag{1}$$

The suffix (s,c,m) stands for passive conducting structures (vessel, shell, and mechanical structure), active coils and measurement coils, respectively. The quantities I_s, I_c represent currents in the passive structures and in the active coils, while V_m, V_c represent the voltage at the terminals of the measurement and the active coils, respectively. Simple algebraic manipulations of (1) allow to find the mathematical expression of $\mathbf{M}(j\omega)$, which is the equivalent mutual inductance between the active and the measurement coils including the effect of passive structure shielding.

$$\mathbf{M}(j\omega) = \mathbf{L}_{mc} - \mathbf{L}_{ms}(\mathbf{R}_s/j\omega + \mathbf{L}_{ss})^{-1}\mathbf{L}_{sc} \tag{2}$$

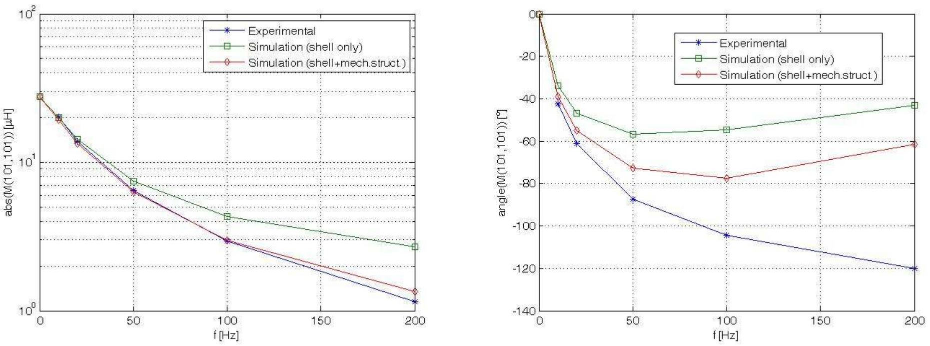
In the black-box approach the same couplings have been described directly by transfer functions of different order, from 0 to 3, depending only on the frequency response data. No physical meaning is associated to the corresponding states: a comparison with Cariddi is then possible only in terms of output quantities.

To achieve an overall assessment of the behaviour of the two models a conveniently aggregate representation of the data has been envisaged. At the same time an accuracy criterion to cancel couplings with negligible contribution was also defined.

Comparison

The qualitative agreement of the two models is generally good, even if the refinement of the RFX-mod load assembly mesh is still ongoing. Figure 1 shows the agreement of the experimentally measured coupling of coil (26,1) with the underlying sensor (26,1) and those calculated by Cariddi using different meshes (shell only or shell and mechanical structure). The finer mesh has 24360 elements, giving rise to 10780 discrete unknowns. The influence of the mechanical structure is apparent, while the contribution of the vacuum vessel (not reported in the figure) seems less significant. Modelling a specific system input-output dynamic with more accuracy could require the inclusion in the geometrical model of finer details such as the diagnostic and pumping portholes; this would increase even further the number of discrete unknowns.

As an example of the details currently reproduced by the models, different inductance maps are plotted in Figure 2. In this kind of pictures each pixel represents a coupling and its colour is in relation to the logarithm (base 10) of the coupling normalised magnitude. Cariddi calculated



(a) Real part (b) Imaginary part

Figure 1: Comparison of coupling (26,1)-(26,1) as measured and calculated by different runs of Cariddi.

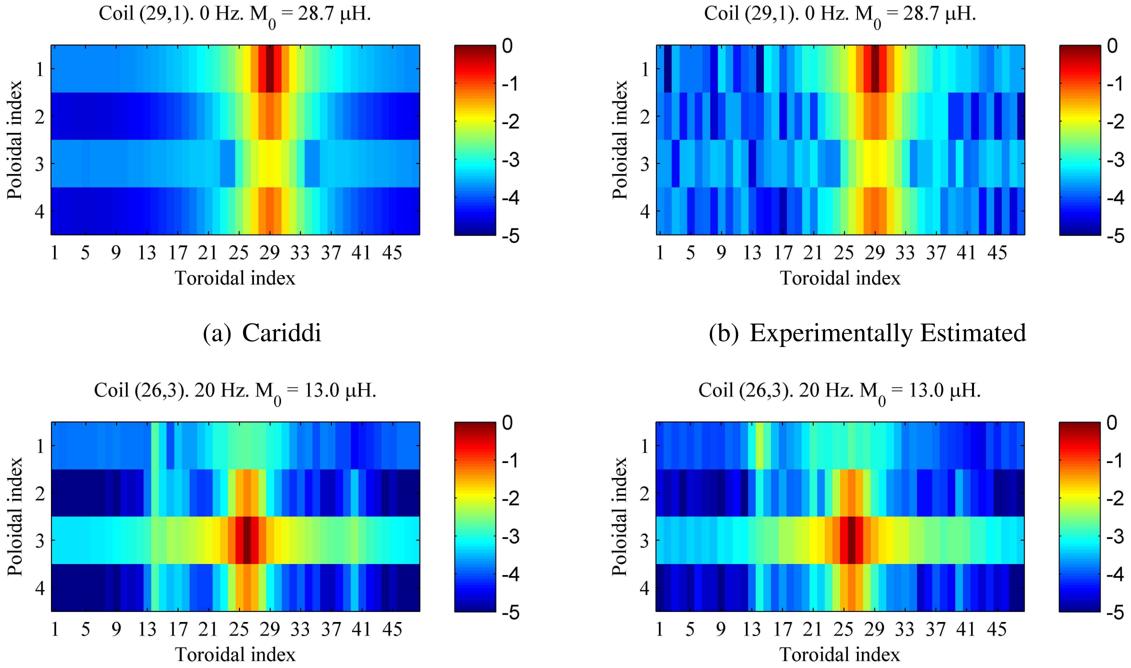
couplings are on the left column while experimentally estimated couplings are placed on the right. The steady state case of coil (29,1) is presented in the first row, whereas the second depicts the 20 Hz case of coil (26,3). M_0 is the inductance value corresponding to 1. Cases (a) and (c), compared to (b) and (d) show a good qualitative agreement. Steady state measures (b) seems affected by a background noise of about $10^{-3} - 10^{-4}$ the size of the coupling with the underlying sensor. Picture (c) shows that Cariddi can effectively take into account local effects such as the support structure and shell poloidal gaps (visible around toroidal index 16), a second poloidal gap of the support structure (toroidal index 40), and the inner toroidal gap of the shell (poloidal index 3).

The pattern of the flux depends on the selected coil and changes with the frequency. In these conditions it is not immediately obvious if and which couplings can be neglected to simplify the model. For example, case (d) shows a notable effect of coil (26,3) on sensor (14,1) which is a quarter of machine far apart. Most of, if not all, the saddle coils have a measurable effect on that sensor.

A coupling is considered to be negligible if its contribution to the overall cumulative sum of the ordered couplings (which should be null with the present sensors geometry) is small. The cumulative sum of the couplings of saddle coil (29,2) is plotted in Figure 3. A number of 52 couplings are required to lower the residual to less than 1%, 112 to fall within the 0.1% band of the final value. Overall, in between 50 to 60 couplings per saddle coil seem to be required to reproduce the exact dynamic at the sensor while satisfying the condition on the solenoidality of the magnetic flux.

Conclusions

The two models show a good qualitative match and a good quantitative agreement at low frequency. The comparison of the coupling amplitudes above 20 Hz is also encouraging, but



(a) Cariddi (b) Experimentally Estimated

(c) Cariddi (d) Experimentally Estimated

Figure 2: Flux maps examples.

the disagreement on the phase is still significant. For this reason work on the refinement of the RFX-mod mesh is ongoing.

References

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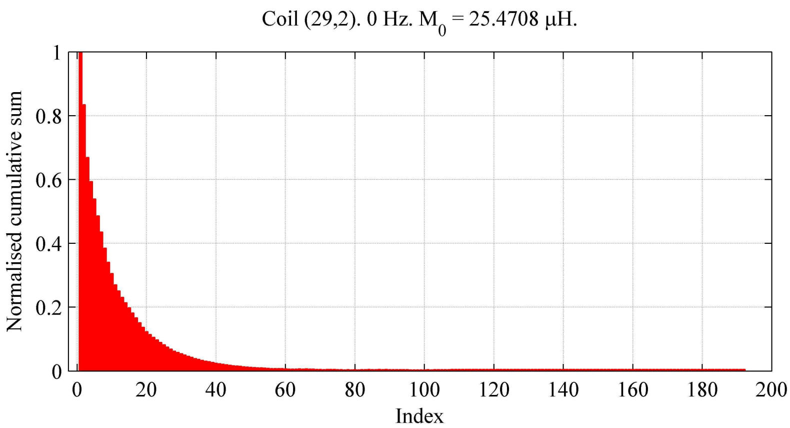

Figure 3: Couplings cumulative sum