MHD control system optimization to RFX-mod real passive boundary

L. Pigatto\textsuperscript{1}, P. Bettini\textsuperscript{1}, T. Bolzonella\textsuperscript{1}, G. Marchiori\textsuperscript{1}, F. Villone\textsuperscript{2}

\textsuperscript{1} Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA),
Corso Stati Uniti 4 - 35127 Padova, Italy

\textsuperscript{2} Ass. Euratom/ENEA/CREATE, DIEI, Università di Cassino e del Lazio Meridionale, Italy

Introduction The RFX-mod experiment is well suited to test innovative MHD control techniques thanks to the flexibility of its 192 independently fed saddle coils that play as actuators in a feedback loop with over 600 magnetic field sensors, including 192 saddle sensors\cite{1}. This configuration has been successfully applied to the mitigation of potentially dangerous instabilities such as Tearing modes\cite{2} and Resistive Wall Modes\cite{3} \cite{4}. The actuator grid, wrapping the whole RFX torus, produces a Fourier spectrum that is influenced by geometrical aspects, such as toroidicity of the boundary and shape of actuators. These aspects, as well as the passive structures electromagnetic characteristics, can be evaluated and accounted for through the measurement of actuator-sensor couplings. During real time operations taking into account all the possible actuator-sensor couplings is a particularly challenging task that involves the use of a 192x192 time dependent decoupler\cite{5}. The simplest coupling approximation in both experiments and simulations is obtained with the identity matrix. This approximation corresponds to the assumption that each actuator is only coupled with its underlying sensor. To test the quality of such an assumption the quadratic Total Harmonic Distortion parameter is introduced:

\[
THD = \frac{\sum_i B_i^2 - B_{\text{target}}^2}{B_{\text{target}}^2}
\]  

where \(B_i\) are the amplitudes all the produced Fourier harmonics, measured by saddle coil sensors, and \(B_{\text{target}}\) is the desired one. In order to reduce the distortion of control signals, matrices with a certain number of non-zero off-diagonal elements can be implemented, these representing the coupling of each actuator with the surrounding sensors. Such a matrix can be calculated by evaluating the mutual actuator-sensor inductances for a given set of frequencies both experimentally and from the numerical plant model given by the Cariddi code\cite{5}, which gives a 3D eddy current problem solution for the RFX-mod active structures and copper shell with toroidal and poloidal gaps. Since model obtained from Cariddi includes neither the vacuum vessel nor the support structures, experimentally acquired mutual inductances are expected to account for the presence of these structures. In the following work different coupling strategies have been tested with a dynamic simulator of RWM open and closed loop stability\cite{6}.
Limiting decoupling examples

As a first approach to the problem a simple open-loop scheme has been considered: feeding the 192 saddle coils with a single harmonic reference and observing the harmonic content of the output magnetic flux. The main objective of this work is to improve the quality of this harmonic content by introducing different strategies to take into account the actuator-sensor couplings.

In the aforementioned dynamic simulator the plant (i.e. numerical model of passive and active structures) is given in state-space representation with saddle coil current as input signal. As for the matter of decoupling, two limiting cases can be considered: the static actuator-sensor couplings and the so-called infinite frequency limit, in which case the decoupling matrix will be named $D$ as the input-output matrix in state-space theory. This latter case should work better when the working frequency approaches the infinite limit. To probe this limit a scan in reference frequency has been run and the results compared in terms of total harmonic distortion. As expected, when using the $D$ matrix, the harmonic distortion of the output is lower for higher frequency references. In Figure 1 the effect of the $D$ matrix can be appreciated: for 100 Hz and 50 Hz requests the regime harmonic distortion is lower with respect to the identity matrix decoupling, while for the static step reference case the opposite situation is obtained.

Tests have been run for the step reference, i.e. zero frequency limit, using both experimental and modeled actuator-sensor mutual inductances. In this way good results in terms of harmonic distortion reduction can be obtained with the experimentally calculated matrix in particular, thus achieving for an $m=1$, $n=-6$ reference, a significant reduction of the relative amplitude of other undesired poloidal components $m=-1$, $m=0$, $m=2$, in agreement with the results already available from [4]. For the aforementioned matrices, as well as for the following results, a note should be made concerning normalization. The coupling values obtained by inverting the mutual inductance matrix have been normalized to a chosen value for the sake of simplicity. Since the decoupling matrix acts as a recombination of the input reference for each actuator, non-normalized values would have introduced an unnecessary scale factor in the chain. Therefore each decoup-
Figure 2: (a) Total harmonic distortion obtained from simulations with D matrix, Max normalized and Identity. (b) Zoom of the first 50 ms.

The matrix has been normalized to its maximum value, i.e. the strongest coupling. The effect of the D matrix during the first few milliseconds should be noted, Figure 2b. This matrix is in fact well suited for the initial time lapse when the penetration of high order harmonics occurs.

Finite frequency value decoupling

One possible approach is to use the model couplings in the building of a decoupling matrix that can be expressed, for a given frequency $\omega$, as:

$$K(\omega) = \left[ C(i\omega - A)^{-1}B + D \right]^{-1} \quad (2)$$

which can be obtained by changing from standard state-space notation (with matrices A,B,C,D) to a transfer function representation of the system. Alternatively the experimental mutual couplings can be implemented, thus obtaining good results in comparison with real data. These couplings intrinsically include the effect of non-uniformities of the toroidal boundary not contemplated in the model. Good agreement with experimental results can be obtained for the
production of an almost monochromatic (1,-6) step. The experimentally calculated decoupling matrix reduces the m=0 sideband both in simulation (Figure 3) and experiment (Figure 4). The numerical couplings from Cariddi have been used in the generation of a 50 Hz m=1, n=-7 harmonic. An expected improvement towards monochromatic harmonic content is obtained.

Conclusions
Simulated and experimental data show that the mutual couplings, obtained for RFX-mod thanks to dedicated experiments, can help in the task of producing monochromatic fields or, in general, in following as much as possible a given reference. The dynamical model implemented for this work has allowed the testing of various decoupling strategies, the most significant of which have been presented. The global effect of decoupling is clear in the reduction of sideband amplitude with respect to the main harmonic and the relevance of transients has been highlighted. Interesting future developments could extend the frequency range so far studied, improve the predictive capabilities of the dynamic model and consider the effect of coupling when reconfigured actuator arrays are implemented [7].

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References