Inclusion of 3D wall effects in MHD feedback control for RFP and tokamak plasmas

P. Piovesan[1], A. Soppelsa[1], D. Fabris[1], J. Hanson[2], Y. In[3], N. Marconato[1], L. Marrelli[1], P. Martin[1], M. Okabayashi[4], L. Piron[1], H. Reimerdes[2], T. Strait[5], D. Terranova[1], F. Villone[6]

[1]Consorzio RFX, Padova, Italy; [2]Columbia University, New York, NJ, USA; [3]FARTECH, Inc., San Diego, CA, USA; [4]Princeton Plasma Physics Laboratory, Princeton, NJ, USA; [5]General Atomics, San Diego, CA, USA; [6]CREATE, University of Cassino, Italy

The wall of any magnetic fusion device is composed of various 3D structures, such as large portholes, gaps, coil feeds, and other features. These can affect plasma stability, inducing magnetic field errors, coupling different modes, or increasing their growth rate. These effects should thus be considered in any MHD feedback control approach. Examples of how the dynamic response of a 3D wall can be included in MHD feedback control are presented, both for reversed-field pinch (RFP) and tokamak experiments in RFX-mod and DIII-D.

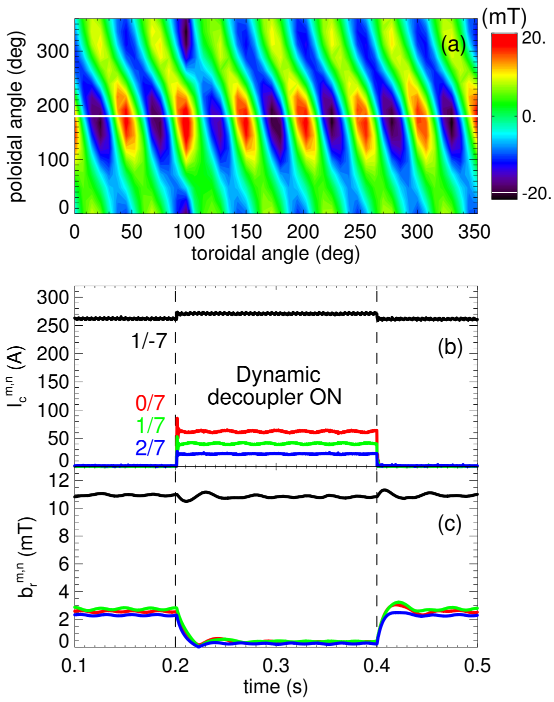

Figure 1. (a) Contour plot of the edge B_r as a function of the poloidal and toroidal angles for a RFX-mod dry shot with a m=1/n=-7 coil current perturbation rotating at 20Hz. (b) Coil current and (c) B_r amplitudes of the 1/-7 (black), 0/7 (red), 1/7 (green), and 2/7 (blue) harmonics for the same dry shot. The dynamic decoupler is active in the time interval 0.2-0.4s.

RFX-mod is equipped with a magnetic feedback system composed of 192 active coils fully covering the torus and of 192 magnetic field sensors. At plasma currents above 1MA, a m=1/n=-7 helical equilibrium with good confinement properties spontaneously forms in RFX-mod [1]. This self-organized state can be robustly controlled by imposing 3D boundary conditions (b.c.) on the radial magnetic field at the plasma edge through magnetic feedback [2]. The feedback action is distorted by the dynamic response of the 3D wall to the externally applied fields.

Figure 1 shows the radial magnetic field produced by a 1/-7 coil current rotating at

20Hz, as measured inside the shell in a dry shot. B_r is strongly perturbed at θ=180° by the presence of an equatorial gap in the wall. As a result, spurious B_r harmonics with m=0,1,2/n=7 are produced, as shown in Figure 1(c). It is expected that with plasma such error fields may in some way perturb the 1/-7 helical state and hence should be avoided.

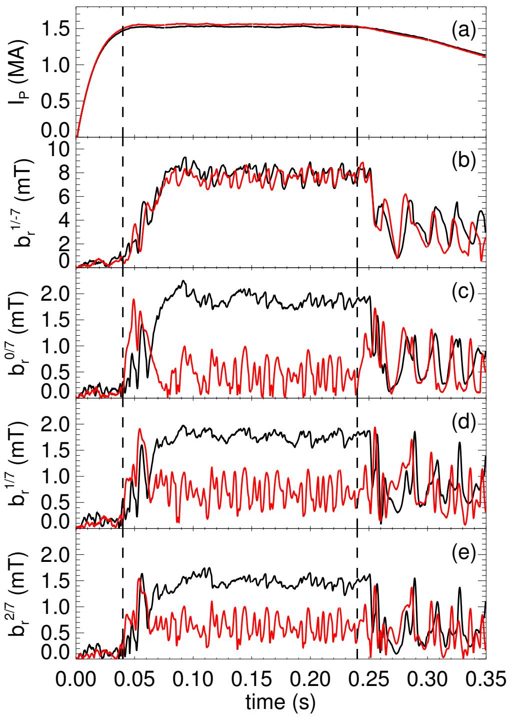

Figure 2. (a) Plasma current and B_r amplitudes of the (b) 1/-7, (c) 0/7, (d) 1/7, and (e) 2/7 harmonics for two similar RFX-mod discharges with helical boundary conditions rotating at 20Hz applied from 0.05 to 0.25s. Discharge #28784 (black lines) has no dynamic decoupler, while discharge #28764 (red) has the dynamic decoupler active from 0.04 to 0.24s.

The wall dynamic response has been first characterized by measuring the active coil-sensor couplings as a function of frequency in vacuum. An algorithm that includes this information and decouples the wall response, called dynamic decoupler (DD), was developed [3] and tested in RFX-mod both in vacuum and with plasma [4]. Figures 1(b) and 1(c) show the effect of the application of the DD in vacuum. The error field at the gap is strongly reduced in the time interval 0.2-0.4s by a proper combination of coil current harmonics and a rather pure 1/-7 B_r harmonic can be produced inside the wall at the sensor radius.

The DD has been then tested in plasma discharges where a helical b.c. was applied to control the 1/-7 helical equilibrium, as shown in Figure 2, similarly to what described in [2]. In this case the 1/-7 mode is maintained into rotation at 20Hz in the period 0.05-0.25s. In discharge #28784 (black lines) no control is applied on the m=0,1,2/n=7 error field harmonics, which have a finite amplitude. The DD is applied instead in discharge #28764 (red lines) in a pre-programmed manner and the m=0,1,2/n=7 B_r harmonics are significantly reduced. The residual error field amplitude is probably due to variations in the 1/-7 mode amplitude, which can not be compensated using pre-programmed waveforms. They may be further reduced by a DD running in real time with fast enough response.

The plasma response to the m=0,1,2/n=7 harmonics was estimated solving the toroidal Newcomb equation with edge B_r and B_t measurements in input, as described in [5]. The m=0,1,2/n=7 mode eigenfunctions for the two above discharges with and without the DD are shown in Figure 3. The 0/7 eigenfunction is reduced mainly in the edge region. The core part is in fact not associated with the error field, but it is produced by toroidal coupling with the 1/-7 mode [5]. The whole 1/7 eigenfunction is significantly reduced, while no big effect is observed on 2/7 one. The m=2 harmonic though may be affected by aliasing problems in the measurements, which are limited to four probes in the poloidal direction. The effect of the DD on the overall discharge performance is being investigated in ongoing experiments.

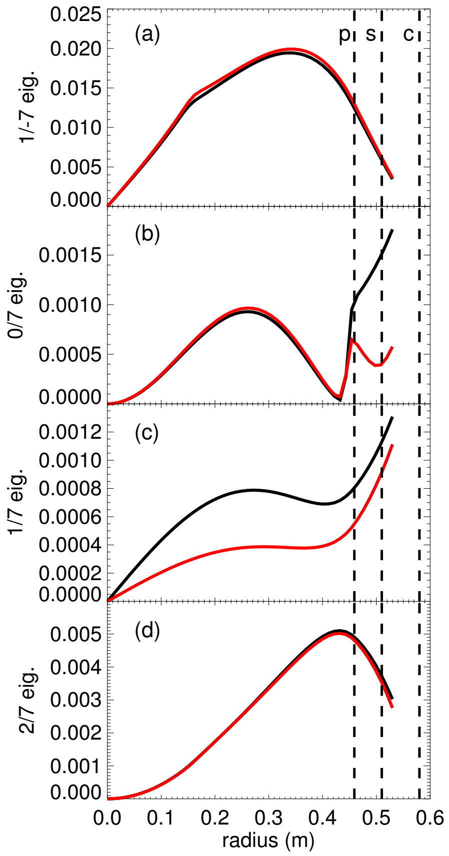

Figure 3. Eigenfunctions of (a) the 1/-7, (b) 0/7, (c) 1/7, and (d) 2/7 harmonics for the two RFX-mod discharges introduced in Figure 2 (the same color coding holds). The vertical dashed lines indicate the plasma surface (p), the B_r sensor (s), and the active coils (c) radii.

RFX-mod can be run also as a low plasma current tokamak [6]. A DD similar to the one tested in the RFP case is being developed. The aim is to control the 2/1 mode without producing spurious harmonics with m=1 and 3, which may excite resonant modes.

The possible effects of a frequency-dependent response of the 3D wall during MHD feedback control are also being investigated in the DIII-D tokamak [4]. Usually the DC coupling to the active and axi-symmetric coils is subtracted in real time from the n=1 B_p sensor signals to estimate the plasma response, which is then used as feedback variable in MHD control experiments in DIII-D [7]. A frequency-dependent sensor compensation scheme based on transfer functions between active coils and sensors measured in dry shots has been developed and tested in this device.

The wall dynamic response has been shown to affect the sensor compensation, both for dynamic error field correction and fast magnetic feedback control of unstable n=1 modes [4]. Not including these effects may introduce unwanted error fields that can affect plasma stability, especially in high-β discharges, an example of which is reported in Figure 4. In this case a n=1 resistive-wall mode is driven unstable through coupling with an off-axis fishbone and eventually leads to a β collapse, described also in [7].

The DC compensated B_p n=1 amplitude (in black, used in the discharge) and the AC compensated one (in red, calculated offline) are compared in Figure 4(d). A small discrepancy exists between the two estimates. In particular the DC compensation introduces an error in the feedback variable that oscillates in time and is probably amplified by the plasma. In fact, the n=1 B_p amplitude is initially reduced by the feedback action, but then slowly increases again. The feedback coil current, shown in Figure 4(c), increases in time trying to compensate it, up to the point where it saturates. The n=1 mode is then no more controlled and terminates the high-β phase.

The example discussed above shows the importance of including AC effects for magnetic feedback in high-β discharges, where even small error fields can be strongly amplified. Experiments using AC compensation in various palsma conditions may given important information on the importance of such 3D wall effects.

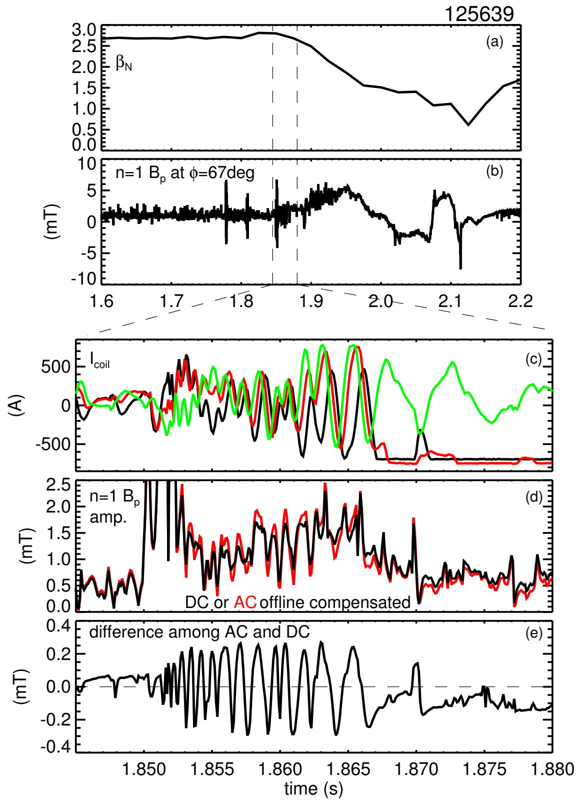

Figure 4. (a) β_N and (b) n=1 B_p for a DIII-D discharge in which the high-β phase is interrupted by a n=1 RWM driven by a q=2 fishbone at t=1.85s. (c) I coil currents, (d) n=1 B_p amplitude with DC (black) and AC compensation (red), and (e) difference among the same two amplitudes during the n=1 mode growing phase.

The experiments described in this paper show that similar effects are introduced by the 3D wall structures in RFP and tokamak experiments. Such effects are due to the distortion of the eddy currents induced in the wall by time-varying currents either in the active coils or in the plasma. They depend strongly on frequency and can be characterized and accounted for by accurate measuring and/or modelling of the active coil-sensor couplings.

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