A Fast Reconstruction Approach for the Assessment of Magnetic Diagnostic Systems in Nuclear Fusion Devices

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Abstract – The information coming from the diagnostic system is of vital importance for the correct functioning of many electromagnetic devices. In particular, for nuclear fusion devices, the magnetic measurements are used for a number of fundamental identification tasks such as equilibrium and plasma boundary reconstruction. The quality and the reliability of the measurements strongly impact on the final results; therefore, proper techniques able to detect faulty probes and to assess their effectiveness are very beneficial. When calibration and other self-consistence tools fail to detect loss of reliability, numerical approaches can help in detecting and eventually correcting information from the malfunctioning channels. The paper proposes a general approach for the fast identification of broken probes based on suitable reconstruction procedures. The approach is tested in Tokamak reactors, but it is quite general and it can be easily extended to other application fields.

***Index Terms*— Identification Problems, Probes Fault Detection, Nuclear Fusion.**

I. INTRODUCTION

THE DETECTION of faults and malfunctioning in diagnostic systems is a fundamental task in electromagnetic devices characterized by the presence of processes to be identified by means of external measurements.

Particularly, the operations in complex nuclear fusion devices such as tokamaks [1] require a number of identification tasks (e.g.: the plasma equilibrium or position and boundary reconstruction [2]) for both off-line analysis and real-time control of the device [3]. Such tasks are performed by using sophisticated numerical tools, but their reliability relies strongly on the accuracy of the information provided by the diagnostic system [4].

In such context, the presence of faulty or strongly inaccurate probes can have detrimental effects in the reconstruction processes leading to a performance degradation of the whole device.

In general, the detection of malfunctioning probes can occur in two different stages: during the off-line phase or the operating phase of the device.

In the first case, the value measured by the probe can be tested against a set of nominal values. For nuclear fusion devices, for example, it is possible to compare the values of the measured and nominal data for dry-run shots and discard the information given by the most incoherent probes.

Malfunctioning detection is much more complex in real-time during plasma shots, since the probes measure also the contribution given by the unknown effects of the plasma and therefore there is no direct knowledge on the values to be expected.

Although the problem is quite relevant, only a few methods for the identification of faulty magnetic probes in nuclear fusion devices are currently present in the literature [5]-[7].

In this paper, a model based on numerical analysis of the global coherency between measured and reconstructed data in a general identification process is proposed as an aid to detect malfunctioning probes for both off-line and operating phases. As a test bed, the magnetic diagnostics in a tokamak, used for real-time plasma contour identification and for off-line plasma equilibrium reconstruction, are considered.

The paper is organized as follow: Sect. II provides the mathematical model whereas Sect. III describes an example of an application for an ITER-like geometry.

II. MATHEMATICAL MODEL

A set of probes S in complex devices is typically designed to favor redundancy as the device maintenance can be very difficult in case of malfunctioning.

The proposed procedure takes advantage of such redundancy to test the correct behavior of each of the probes. It is articulated in the following two steps to be repeated for each probe P_i ($i = 1, 2, \ldots, N_P$, where N_P is the number of probes):

1. use the information of all the probes except the P_i to reconstruct the magnetic field distribution by solving a suitable inverse problem;
2. assess the reliability of P_i by comparing the discrepancy between the measured value $m^{(i)}$ and reconstructed value $m_r^{(i)}$ with the probe accuracy and error bar of the reconstruction.

However, it should be noticed that, in case of high redundancy on the diagnostic system, the results do not change significantly if no probe is excluded in step 1.

In order to perform the step 2, suitable discrepancy norms should be introduced as an absolute and a relative error.

$$\varepsilon_{abs}^{(i)} = \left|m^{(i)} - m_r^{(i)}\right| \tag{1}$$

$$\varepsilon_{rel}^{(i)} = \frac{\left|m^{(i)} - m_r^{(i)}\right|}{\left|m^{(i)}\right|} \tag{2}$$

However, (2) can be not particularly suited when vanishing or almost vanishing values of $m^{(i)}$ are measured. As an effective alternative choice the absolute error value can be normalized with respect to the probe range.

When the promptness is a priority, the procedure operates following a modified strategy. The full set of probes S is subdivided in a number of subsets S_k with $k = 1, \dots, N_S$ so that $S = \bigcup_{k=1,\dots,N_S} S_k$. For $k = 1, \dots, N_S$ the following steps are repeated:

1'. similarly to the step 1, but in this case the magnetic field is reconstructed by using the information coming from all the probes except those in S_k;
2'. assess the performance of all the probes in S_k as suggested in 2.

The number N_S of subsets and their composition have to be calibrated taking into account the conflicting needs of accuracy and promptness.

On the basis of the reliability assessment of each probe, suitable measures can be taken such as:

- the exclusion from S of the unreliable probes;
- a suitable preconditioning of the reconstruction model by weighting each equation on the basis of the accuracy of the related probe.

III. EXAMPLE OF APPLICATION

In order to assess the methodology, a simple application to an ITER-like [4] Tokamak is analyzed. The device is supposed to include a diagnostic system based on (i) a set of 208 tangential/normal pick-up coils for the magnetic field measurement, (ii) a set of 14 poloidal and toroidal flux loops for the magnetic flux detection and, finally, (iii) a set of 22 saddle loops for the measurement of field normal to the vessel. In Fig. 1 the poloidal section is reported.

By means of the CREATE-NL simulation code [8], a consistent, axisymmetric plasma equilibrium has been numerically generated; the plasma, characterized by a current of 15 MA, is confined by a suitable set of poloidal currents.

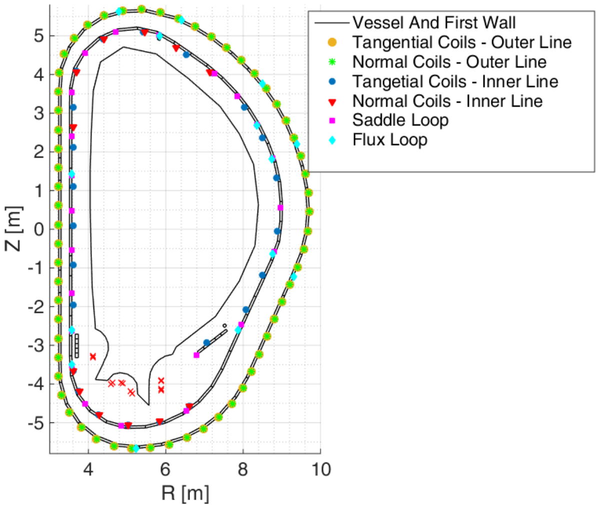

Fig. 1. Sketch of the magnetic measurement system.

Then, a standard reconstruction 2D procedure [2], [9] has been used for the electromagnetic reconstruction of the field map. In this case, only pick-up measurements have been used for the reconstruction.

In order to simulate a malfunctioning probe, its measured value is randomly generated in the interval given in the range of measurement of the specific diagnostic.

According to the procedure described in the Section II, all the probes are supposed to properly operate (providing the actual data numerically generated) except the #196 falling in a serious malfunctioning ($\varepsilon_{rel}^{(i)} = 204\%$, corresponding to an absolute error of $\varepsilon_{rel}^{(i)} = 0.98\,T$). The difference between measured and reconstructed values are shown in Fig. 2, where each probe is identified by an index between 1 and 208.

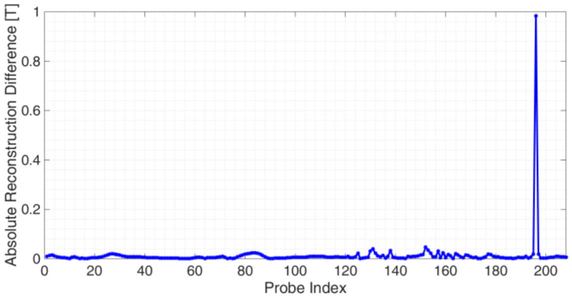

Fig. 2. Comparison between measured and reconstructed data.

Additional tests, carried out but not reported for the space limitation, show that, thanks to the redundancy of the system, similar results are achieved if no probe is excluded in step 1 (see Section II).

In the full paper the assessment will be completed, by discussing the impact of the measurement uncertainties on the detection of malfunctioning probes and, in addition, evaluating the effectiveness of the measures described in Section II to treat the presence of faulty probes.

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