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Two-dimensional boundary shape reconstructions in rectangular and coaxial waveguides

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HIGHLIGHTS

- Shape reconstruction method for two-dimensional boundary deformations in waveguides.
- First-order perturbation approach is used to calculate the scattering parameters.
- Scattering parameters given as linear functions of continuous deformation functions.
- Reconstructions of two-dimensional deformations of rectangular waveguide boundaries.
- Reconstructions of two-dimensional deformations of coaxial waveguide boundaries.

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ABSTRACT

We present a method for shape reconstruction of deformed metallic boundaries in rectangular and coaxial waveguides using microwave scattering. Our developed reconstruction method is a theoretical basis for a future on-line microwave-based monitoring system for power grid components. The bundle of winding conductors in the active part of a typical power grid component is modeled as a continuous metallic surface. Then, electromagnetic field perturbation theory in conjunction with inverse problem theory is used to reconstruct the shape parameters of this surface. We assume small perturbations of the boundaries, such that the scattering parameters of the waveguide in the first-order perturbation have linear dependencies of the continuous deformation function. Thus, the corresponding inverse problem can be linearized and we can employ direct inversion, without the need for optimization which requires a higher computational effort. Tikhonov regularization is used to regularize the arising ill-conditioned linear system. The reconstructions, performed with noisy synthetic measurement data, show a good agreement with the actual shapes of the studied two-dimensional localized shape deformations for both rectangular and coaxial waveguide boundaries.

1. Introduction

This work aims to study the theoretical foundations for on-line microwave-based monitoring systems that can be used to monitor adverse material and structural changes inside power grid components. The electric power grid consists of components like power generators, power transformers, switchyards, cables and transmission lines. Most of the existing diagnostic methods for these components are off-line methods, such as frequency response analysis [1] and dielectric

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spectroscopy [2], which involve a non-service stress of the component and financial loss of revenue during the tests. One widely used on-line method—Dissolved Gas in oil Analysis [3], is an integral method, where the measured gas concentrations can be either the result of a recent fault, or a result of running the component over a long time period. In summary, there are currently no on-line diagnostic methods that give a reliable real-time diagnosis of the internal structure of critical power grid components. This has led to our research group proposing microwave diagnostics for power grid components [4–8]. Apart from the possibility of accurate and real-time imaging, microwave diagnostics also have other advantages such as non-ionizing nature of the microwave radiation, low hardware costs, compact measurement equipment and the possibility to differentiate between different types of materials.

In our previous works [4,5], reconstruction from synthetic measurement data of the positions of up to ten individual conductors loaded in a waveguide, was performed by means of an optimization method. In [5], elliptic and wave-shaped (as defined in [5]) mechanical deformations were studied, and it was found that these types of deformations, to the first order of approximation, could be reduced to radial displacements such as those described in [4], showing that essentially the same mathematical tools can be used to cover a broad range of conductor deformations. It should however be noted that the analysis in [4,5] used a discrete conductor model with a number of individual conductors being treated as obstacles in the waveguide and where the mode matching technique was used to handle a limited number of such discrete obstacles.

The first steps towards a continuous model were taken in [6,7], where the bundle of winding conductors was not considered in detail but instead modeled as equivalent outer boundary surfaces, which shape was to be reconstructed. These studies were extended and improved in [8]. A similar representation of the electric field with Taylor series for shape reconstruction, as in [8], was also investigated in [9] for the reconstruction of the shape of a perfectly conducting object illuminated by a single plane wave at a fixed frequency. However, the reconstructions in [8] are done using a perturbation approach, which linearizes the inverse problem with no need for iterative solving like in [9]. Furthermore, the shape reconstructions in [8] are performed in a waveguide environment, and not in the free space.

The present paper uses the same basic mathematical formalism as in [8], but there are two major differences. Firstly, the paper [8] considered deformation functions with variation only in one dimension (longitudinal), but in the present study, we for the first time treat localized two-dimensional deformations in both the transverse and longitudinal directions of the waveguide. Secondly, the paper [8] used only scattering parameters from the fundamental mode of the waveguide, measured over a range of frequencies. In the present study on the other hand, we investigate the effect of adding scattering data from the higher order modes in the waveguide, over a constant frequency band, on the accuracy of the reconstructions of two-dimensional boundary deformations. Hence, although the present paper can be seen as an extended version of [8], the abovementioned improvements provide an essentially novel approach to the problem of reconstruction of two-dimensional deformations in a waveguide boundary.

2. Methods

In practical diagnostic situations, we need to characterize objects without the possibility to remove them from environments in which they operate. Such environments are often not optimal regarding the conditions for solving inverse problems. However, for many diagnostic purposes it is justified to neglect some properties of the actual structure and model it as an environment that can be controlled and optimized. One such model is when an object is inserted in a waveguide, where we have a well-defined electromagnetic field pattern. Electromagnetic field theory with inverse problem theory can then be used to reconstruct material and shape parameters. In a waveguide, there may be several different kinds of objects and properties to reconstruct e.g.

1. local deformations in the wall geometry, like indentations and extrusions
2. dielectric and/or magnetic properties of bulk obstacles inside the structure
3. local changes of surface impedances, e.g. boundary walls material properties
4. cracks and appearance/disappearance of ducts in the waveguide walls.

The reconstruction of some of the abovementioned properties have been studied in the literature. For example, a reconstruction method for inhomogeneous surface impedance and shape of a two-dimensional (2D) cylindrical object located over a perfectly electric conducting (PEC) plane, which has a mirror effect on the measured data that corresponds to a full view configuration, was presented in [10]. The method in [10] may be seen as the first step to a guided wave environment, where the guided modes are due to reflections between the boundary walls. In [11], the inverse problem of retrieving the shape of an inaccessible, perfectly electric conducting target from a set of far field measurements was considered, and a reconstruction method in which the unknown scatterer is modeled by means of a surface impedance was used. Reconstruction of properties of metallic pipelines, where the undeformed structure is a periodic arrangement of pipe sections welded together, and the inverse problem is to detect changes in the circular radius in one or several sections is another example [12]. The study in [12] resembles our earlier study of periodically loaded waveguides [7]. As a final example, the properties of a 3D object located inside a rectangular waveguide were reconstructed using several waveguide modes in [13].

The necessity to use several waveguide modes for accurate resolution results can be understood intuitively, considering that for resolving a given length scale, we need wavelengths of the corresponding order. For objects inside a waveguide, such wavelengths will be smaller than the cross-sectional dimensions of the waveguide, whereby higher order modes will propagate.