# Detection of Surface Defects in Metallic Materials Using Evanescent Microwaves

J. KEROUEDAN, P. QUEFFELEC, P. TALBOT, S. DE BLASI,
Université de Bretagne Occidentale, Brest, France,
A. LE BRUN, J. KEROUEDAN, Chatou, France

**Abstract** - In this paper, we describe how microwaves can be used to detect surface micro-cracks on metallic surface. We propose a resonant probe based on the excitation of evanescent waves. We investigate the electromagnetic analysis of the probe when interacting with cracks and demonstrate its sensitivity to cracks. This theoretical demonstration is confirmed by experiment.
*Keywords* – Microwave techniques, resolution and sensitivity of the sensor, near field microscopy method, Evanescent Microwave Probe, resonator

## 1. Introduction

The fatigue ageing of metallic materials while on operation is one of the recurrent concerns in energy production plants. The early non-destructive diagnostic of surface defects would allow pertinent preventive maintenance without having to dismount and prematurely change healthy components.
Most of the present automated non-destructive testing (NDT) solutions to detect these surface cracks are based on ultrasound or eddy current techniques. The advantages of ultrasound and eddy current methods are their high sensitivity and resolution. However, eddy currents are sensitive to many parameters what makes the interpretation of the signals sometimes delicate and the ultrasonic techniques cannot be operated everywhere (e.g. need for a liquid coupling media).
EDF R&D, attentive to the availability of new control methods that could complete the acoustic and electromagnetic NDT toolkit presently available on the market, works with the LEST team to evaluate the potential of emergent techniques using microwaves.

In this paper, we demonstrate the feasibility of micro-cracks surface detection by an evanescent (near field) microwave technique based on the shift of the resonance frequency "$f_r$" and the quality factor "Q" of a resonant circuit. First, we will present a brief state of the art of crack detection microwaves methods. In this part, by highlighting the limitations of currently used microwave techniques, we will justify the use of a near field resonant cavity to detect micro-cracks. Secondly, we will describe the probe. Then, we will deal with the electromagnetic modelling of the sensor and of the interactions between the evanescent waves and the cracks. Finally, theoretical and experimental results will be compared and the envisaged prospects will be stated.

## 2. State Of The Art of Micro-Cracks Detection by Microwave Techniques

During the last years, studies about the detection of surface cracks on metallic structures using microwaves have been performed [1], [2], [3], [4]. The principle of these existing microwave techniques is well established. It measures the electromagnetic variation created

by the presence of an obstacle on the reflection coefficient (VSWR) at the end of an open coaxial line [1] or waveguide [2]. The cracks width and depth are deduced from the reflection coefficient magnitude and phase variations introduced by the cracks.
Due to the use of well-known open structures of propagation, these methods are easily implemented but allow until now to reach only resolutions of the order of a millimetre in study conditions still too conventional (straight and even crack). The resolution of these detection devices is of the order of a half-guided wavelength ($\lambda_g/2$). To fill the previously mentioned conditions (detection of micro-cracks), the low resolution of this technique requires the increase of the working frequency resulting in a cost increase of the measurement devices and a size reduction of the sensors. To detect surface cracks of several microns (µm) width, a Japanese team [3] worked with a coaxial probe operating at 110GHz! At such high frequencies Signal to Noise Ratio (SNR) problems appear and the measurement using a network analyser is delicate. The measured signal must be amplified and filtered to be detected outside the noise of the network analyser and of the external environment that disrupts the measurement system. Moreover, the micro-crack detection using a coaxial probe or a waveguide requires the measurement of magnitude variations about the hundredth of dB and the measurement of phase variations of a few degrees. As a result, these measurements are very difficult with a network analyzer. On the other hand, the network analyzer appears perfectly adapted to the measurement of a resonance (resonance frequency and quality factor). In addition, methods of material characterization resting on the use of resonators make it possible to obtain resolution lower than the micron [5].

Consequently to get over the limits of existing crack detection microwave techniques, we suggest a resonant probe based on the excitation of evanescent waves.

## 3. Description of the Technique

As mentioned before, in order to detect micro-cracks, we have selected a near field microscopy method [5], [6], [7], [8] based on the variations of the resonance frequency "$f_r$" and the quality factor "Q" of a resonant cavity due to disruptions caused by the crack in the vicinity of the cavity. This technique makes it possible to increase significantly the resolution ($\lambda/1000$) and consequently to work at lower frequencies and to avoid low SNR problems.

The first resonator we have developed consists of a $\lambda_g/4$ long micro-strip line drawn on alumina substrate and ended by a radiating electrical dipole [7].

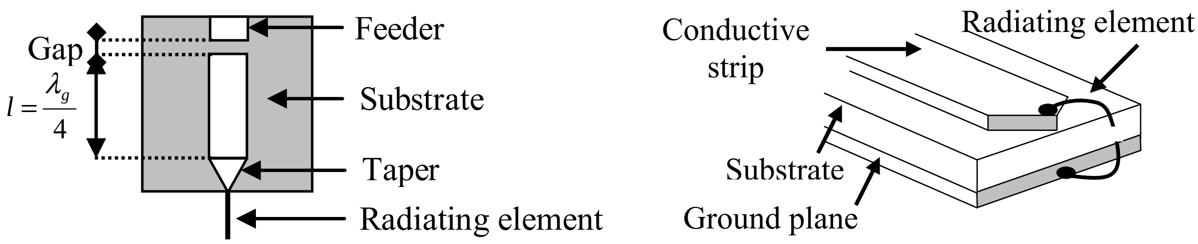


Fig.1: Micro-strip resonator design: complete structure (left) and zoom on the electrical dipole (right)

The micro-strip resonator (Fig.1) is made up of six main elements: a substrate, a feeder, a gap (zone of coupling), a $\lambda_g/4$ long transmission line, a taper and a radiating element.

The substrate is principally characterized by its dimensions and its electromagnetic characteristics (permittivity $\varepsilon_r$ and loss tangent tg$\delta$). Its width, length and height are respectively 25.4mm (1 inch), 25.4mm and 508µm. The choice of the substrate type is very important. Indeed, the evanescent waves are mainly located at the end of the substrate. Moreover, their magnitudes decrease exponentially. In the case of a high permittivity substrate, the exponential decrease is steeper than for a low permittivity substrate because the energy has a tendency to be more confined in the material than for a low permittivity substrate. Consequently, the distance between the probe and the metal under test can be more important in the case of a low permittivity substrate, however, the radiating intensity will be lower. The probe will be then less sensitive. For the probe simulation and realization, alumina 96% with permittivity $\varepsilon_r$=9.4 and loss tangent of tg$\delta$=$6.10^{-3}$ was chosen. The transmission lines drawn on the alumina substrate are in gold (conductivity $\sigma$=$4.1.10^7$ S/m) and the metallization thickness is t=5µm.

The feeder is used to feed the $\lambda_g/4$ long line. To ensure a good adaptation with the microwave source (network analyser), its characteristic impedance is 50Ω. The effective permittivity $\varepsilon_{reff}$ of this structure of propagation is $\varepsilon_{reff}$=6.5.

The gap [9], [10] defines a capacitive coupling zone between the feeder and the $\lambda_g/4$ resonant line. It is an essential element of the probe permitting to transmit the energy transported by the feeder towards the resonator. The length of the gap influences the value of the quality factor Q of the resonator.

The $\lambda_g/4$ line constitutes the radiating element of the circuit. Its length depends on the wavelength and consequently according to the relation (1), it depends on the operating frequency.

$$\lambda_g = \frac{c}{f \cdot \sqrt{\varepsilon_{reff}}} \qquad (1)$$

Where $\lambda_g$ is the guided wavelength, c=$3.10^8$m/s the velocity of the light in vacuum, f is the operating frequency and $\varepsilon_{reff}$ the effective relative permittivity of the propagation structure ($\varepsilon_{reff}$=6.5 in our case). A high operating frequency permits to work with shorter lines but the decrease of electromagnetic field at the end of the substrate becomes steeper (the decrease of fields is inversely proportional to the operating frequency) so it is necessary to move the probe closer to the metallic surface under test. At the opposite, a low operating frequency allows to move away from the metal but cause an increase of the circuit dimensions. In fact, the minimum resonance frequency is fixed by the length of the substrate i.e. 25.4mm.

The taper allows a transformation of impedance between the resonant line of characteristic impedance Zc=50Ω and the radiating element [7].

Finally, the last element of the evanescent microwave probe is the radiating electrical dipole. It is a golden wire of small diameter (17µm) welded to the end of the taper (Fig.2) in order to channel the weak radiation that comes from the resonator towards the sample to characterize.

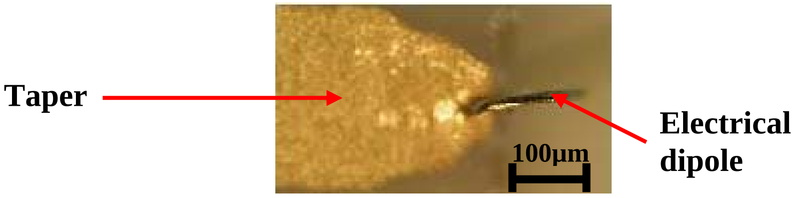


Fig. 2: View of the top of the electrical dipole welded to the end of the taper

The more the diameter of the wire will be fine, the more the resolution of the probe will be high providing that the probe is very close to the sample. The electrical dipole is composed of two wires. The first one is connected to the taper and the second one is connected to the ground plane. The capacity formed by the space between the upper wire (connected to the line) and the lower wire (connected to the ground plane) generates a radiating electromagnetic field.

The different components of the evanescent resonant device must be optimized in order to obtain a probe with high levels of sensitivity and resolution. In our case, the sensitivity is expressed by the importance of the variations of “$f_r$” and “Q” when the probe crosses a crack with fixed dimensions.

## 4. Simulations

Simulations were realized with ADS (Agilent) and HFSS (Ansoft) softwares. The theoretical approach is used to reach two main goals:

- To optimize the probe dimensions and its electromagnetic characteristics (the factors $f_r$ and Q).
- To increase the probe sensitivity when crossing the cracks and its resolution for micro-cracks detection.

The resonator in situation of metallic surface scan can be considered as the set: feeder, gap, resonant line, taper, radiating dipole and metallic plate. Nevertheless, it has been shown [11] that the radiation induced by the radiating dipole at the end of the substrate represents only a tiny part in the total characteristic of the resonator. So, initially, it seems interesting to make an approximate calculation of the resonator characteristics in taking into account only the set: feeder, gap, resonant line, taper and then to refine calculation by reinstating the other elements of the whole evanescent probe.

The first step of our process consists in optimizing the parameters “$f_r$” and “Q” of the resonant cavity. We study the probe without the dipole and without the metallic plate. Our aim is to dimension a resonator with a quality factor as high as possible. As mentioned during the description of the probe, the quality factor depends mainly on the gap size. For a gap length of 200µm, the obtained results are depicted in Fig.3.

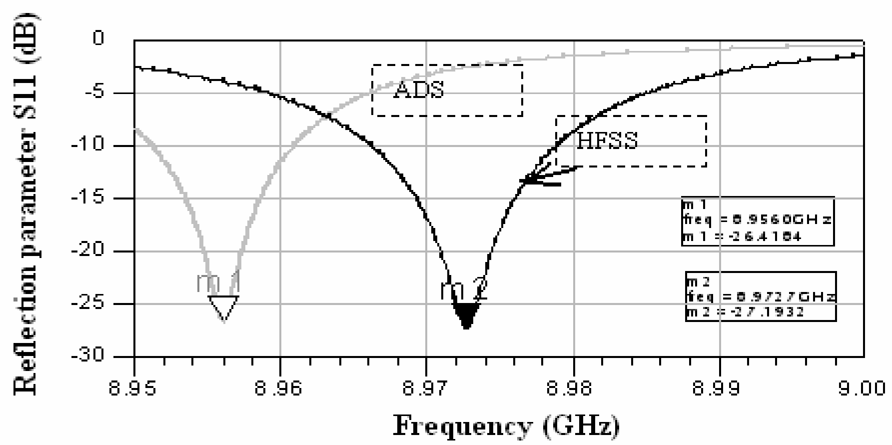


Fig. 3: Simulation of the resonator with ADS and with HFSS softwares, for a gap of 200µm

A good agreement between the results obtained with ADS and HFSS is noticed. The small difference between the values of the resonance frequencies can be explained by the different calculation methods used by the two simulators. ADS uses a formalism based on the transmission-line theory whereas HFSS uses a more rigorous method. HFSS relies on the resolution of Maxwell equations in a Finite Element Method (FEM) environment. HFSS takes into account numerous phenomena appearing in the electromagnetic structure.

From the reflection parameter magnitude, we can also deduce the quality factor of the resonator Q:

$$Q = \frac{f_0}{f_2 - f_1} \quad (2) \quad \begin{cases} f_0 : \text{frequency (resonance frequency) associated to S11min} \\ f_1 : \text{frequency on the left of } f_0\ (f_0 > f_1) \text{ associated to S11min+3dB} \\ f_2 : \text{frequency on the right of } f_0\ (f_0 < f_2) \text{ associated to S11min+3dB} \end{cases}$$

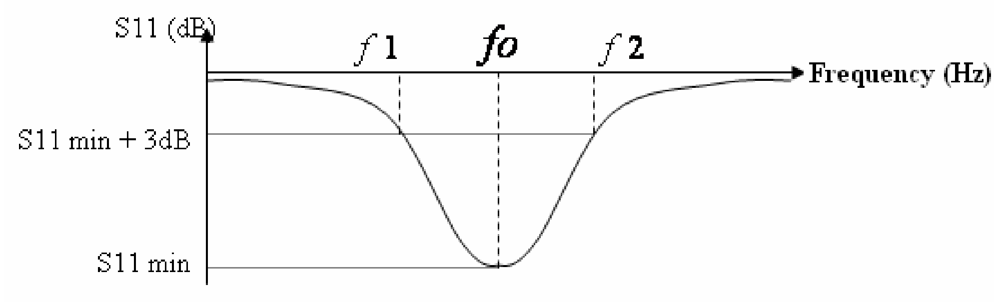


Fig. 4: Determination of the quality factor Q of the resonator

From the curves presented in Fig.3, we deduce the quality factors of the circuit simulated with ADS and HFSS: $Q_{ADS}$ = 6400 and $Q_{HFSS}$ = 5400.

Secondly, we study the sensor with the dipole and with the metallic plate in order to understand how the probe interacts with the metallic surface and with the cracks. Because of the three-dimensional aspect (due to the electrical dipole) of the complete sensor, a 3D analysis with HFSS is necessary. The resonator to optimize is now composed of the evanescent probe in the presence of a steel plate located at a fixed distance *d* above the end of the sensor. These simulations permit to evaluate the sensitivity and the resolution of the sensor. For a given crack (width and depth fixed), the sensitivity is the capability to achieve the strongest shift of $f_r$ and Q. For a given configuration of the probe (sensor dimensions and distance *d* between the sensor and the metallic plate fixed) and a minimum value for the resonance frequency $f_r$ and quality factor Q shifts, the resolution is the minimum size of the cracks that can be seen (and consequently detected) by the probe. Fig.5 presents the reflection coefficient curves obtained for a 200µm wide crack and a distance probe-steel plate *d* of 50µm.

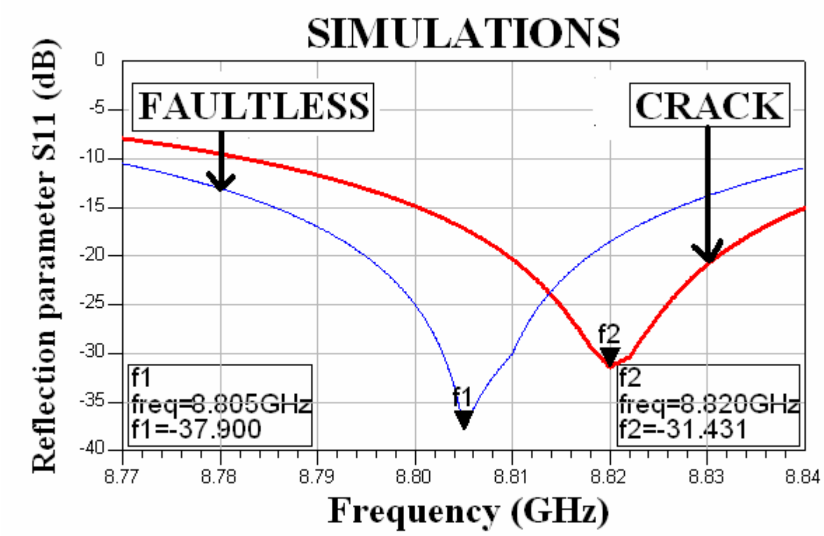


Fig. 5: Reflection parameter S11 above faultless metallic plate and above a crack obtained with HFSS

This study theoretically confirms the existence of a variation of the two parameters of the resonator "$f_r$" and "Q" during the crossing of the probe above the crack. The calculated shift of «$f_r$» and «Q» are $\Delta f_r$=15MHz and $\Delta Q$=555. The SNR problems are avoided because the operating frequencies are relatively low. This method of detection is original compared to the techniques proposed in the literature on the state of the art. It is not a question any more of measuring a variation of the dynamics of a reflection coefficient (which poses the problem of the SNR) but to be able to distinguish two different values of frequencies what is less problematic.

## 5. Experimental Validation

Measurements were performed on steel plate containing 200µm wide EDM notches. The extremity of the probe is located 50µm above the plate. The measurement system is made up of an Agilent PNA E8364A (45MHz - 50GHz) network analyzer and a motorized 3 axes displacement device (Fig.6) on which the probe is fixed (Fig.7).

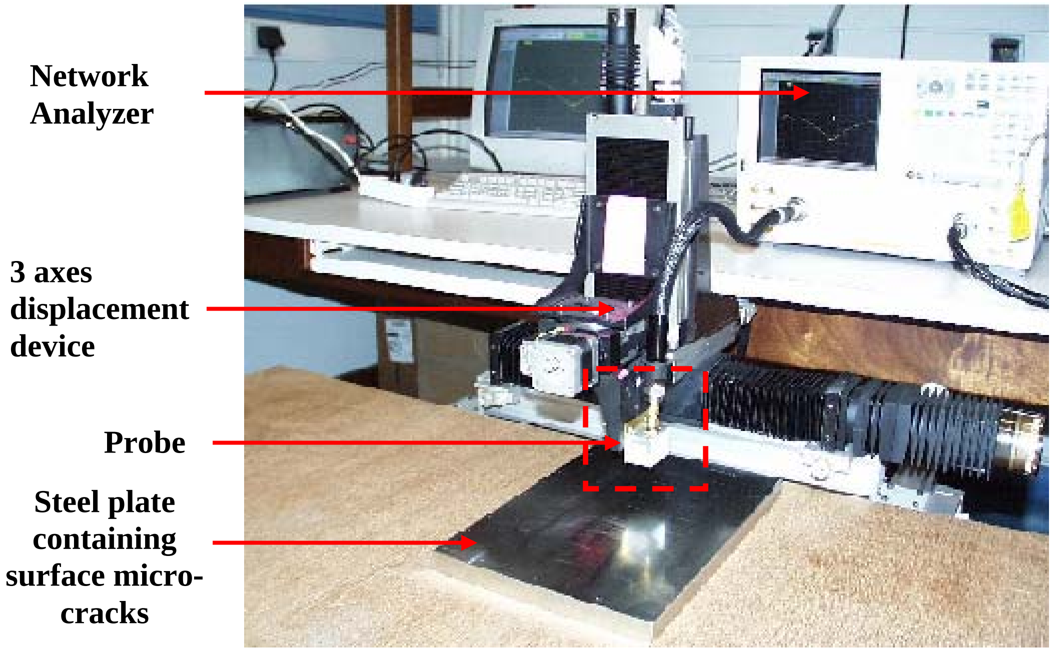


Fig. 6: Overall view of the measurement device

Fig. 7: Zoom on the probe with its fastening system

Fig.8 shows the reflection coefficient curves above faultless metallic plate and above an artificial flaw obtained in experiment.

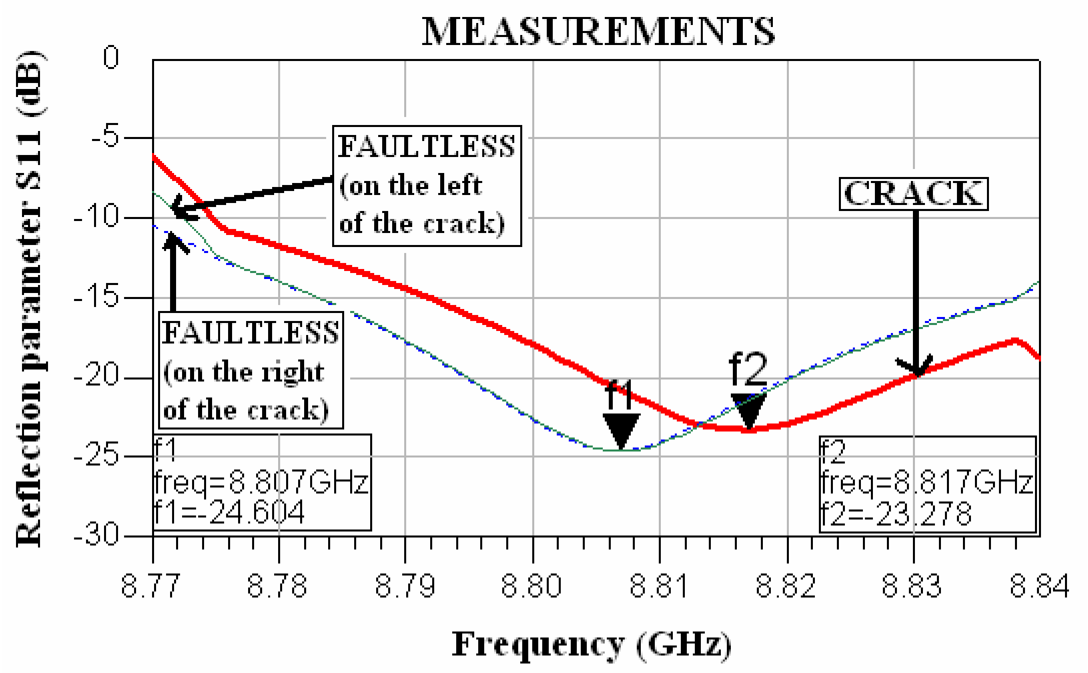


Fig. 8: Measured reflection parameter S11 as a function of the frequency above faultless metallic plate and above an artificial flaw (crack)

The existence of a shift of «$f_r$» and «Q» ($\Delta f_r$=10MHz and $\Delta Q$=80) is confirmed by experiment. These variations are easily detected with a good accuracy using a network analyser. It should be noted that on the two sides of the EDM notch (on the left and on the right of the EDM notch (crack)) the same resonance frequency $f_r$ and the same factor Q are found. So the reproducibility of measurement is well checked and the principle of the detection is demonstrated (because the shift of $f_r$ and Q could have been due to a defect of planarity of the metallic plate). Inaccuracies inherent in the technological realization of the probe and uncertainty concerning the positioning of the sensor 50µm above the steel plate can explain the difference observed between theory and experiment. These results underline in particular the need to use an accurate method of control of the distance between the sensor and the metallic plate under test.

## 6. Conclusion and Ongoing Research

We have shown theoretically and experimentally the possibility to detect surface cracks by an evanescent microwave probe. This technique allows to increase significantly the resolution ($\lambda$/1000) and consequently to work at lower frequencies and to avoid Signal to Noise Ratio (SNR) problems with the testing device.

Nevertheless further theoretical studies are necessary to improve the resolution and the sensitivity of the sensor. For example, we want to evaluate the potential of coplanar structure and antennas arrays to detect metallic surface micro-cracks. In addition, the modelling of the physical phenomena in the vicinity of the resonant should be useful to account for the operation of the evanescent microwave sensor.

Moreover, to approach as well as possible the simulation conditions with HFSS during the measurement, the development of a precise device of control of the distance probe-steel plate is necessary.

Finally, after having designed an optimal probe (in term of sensitivity and resolution), we will try to link the variations of the factors $f_r$ and Q to the geometrical parameters (width and depth) of the crack.

## 7. References


[1] C.-Y. YEH, "Detection and sizing of surface cracks in metals using open-ended rectangular waveguide", Ph.D. Dissertation, Electrical Engineering Department, Colorado State University, 1994.

[2] Y. WANG, R. ZOUGHI, "Interaction of Surface Cracks in Metals with Open-Ended Coaxial Probes at Microwave Frequencies", Materials Evaluation, vol. 58, n° 10, pp. 1228-1234, Oct. 2000.

[3] Y. JU, M. SAKA, Y. JU, D. LUO, H. ABE, "NDE of closed fatigue crack on metal surface", 10th International Conference on Non-Destructive Testing, Brisbane, Australia, Sept. 2001.

[4] S. GUILLOU, P. QUEFFELEC, P. TALBOT, "Détection de Micro-Fissures à l'aide de Techniques Micro-Ondes", Rapport de stage de Maîtrise de Sciences des Matériaux LEST/Université Paris-Sud 11, Jul. 2003.

[5] M. TABIB-AZAR, D.P. SU, A. POHAR, S. LECLAIR, G. PONCHAK, "0.4µm spatial resolution with 1 GHz (λ=30cm) evanescent microwave probe", Review of Scientific Instruments, vol. 70, n° 3, pp. 1725-1729, Mar. 1999.

[6] M. TABIB-AZAR, M. KATZ, J.L. LECLAIR, "Evanescent Microwaves: a novel super-resolution, non-contact and non destructive imaging technique for biological applications", IEEE Transactions on Instrumentation and Measurement, vol. 48, n° 6, pp. 1111-1116, Dec. 1999.

[7] M. TABIB-AZAR, D. AKINWANDE, G. PONCHAK, S. LECLAIR, "Novel physical sensors using microwave probes", Review of Scientific Instruments, vol. 70, n° 8, pp. 3381-3386, Aug. 1999.

[8] S. DE BLASI, P. QUEFFELEC, P. TALBOT, "Mise en évidence de la faisabilité de la détection de fissures de fatigue dans les métaux en champs proches", Rapport de stage de DEA Dispositifs Hyperfréquences et Technologies associées, LEST/UBO, July 2004.

[9] P. BENEDEK, P. SILVESTER, "Equivalent Capacitances for Microstrip Gaps and Steps", IEEE Transactions on Microwaves Theory and Techniques, vol. MTT-20, n° 11, pp. 729-733, Nov. 1972.

[10] B. EASTER, "The Equivalent Circuit of Some Microstrip Discontinuities", IEEE Transactions on Microwaves Theory and Techniques, vol. MTT-23, n° 8, pp. 655-660, Nov. 1972.

[11] J.F. ZURCHER, "Imagerie micro-onde de matériaux utilisant une technique de perturbation de résonateur", 16ème Colloque International Optique Hertzienne et Diélectrique Groupement Ampère, Université du Maine, LE MANS, Sept. 2001.