INDUSTRIAL MICROWAVE SENSORS

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ABSTRACT

Microwave sensors are used for a variety of applications in the industry, in medicine, and for research purposes. This paper gives a survey of the different types of sensors and rewieves the latest developements reported by European institutes and companies.

INTRODUCTION

The demand for sensors for the measurement of most diverse quantities has grately increased with the automatisation of industrial processes. In many cases microwave techniques provide competitive solutions. A large number of important applications are found in the field of moisture measurement, but many other material quantities as well as dimensions and movement are also measured using microwaves. The major advantages with microwave sensors are the capabilities to measure nondestructively, without contact from a short distance, using penetrating waves, without helth hazards to the personnel. Disadvantages are the usually high degree of specialization and the simultaneous existence of several variables effecting the microwave measurement (temperature, density, moisture, structure, etc.) in material measurements. There are, however, some sensor types, like for example the free-space transmission sensors that are used for the measurement of many different materials. The basic calibration against the quantity to be measured is done for each material separately. The problem with many variables can be mastered by using the multiparameter technique (resonant frequency & quality factor, phase & attenuation, several frequencies, or combination with other techniques) [1, pp.80-87].

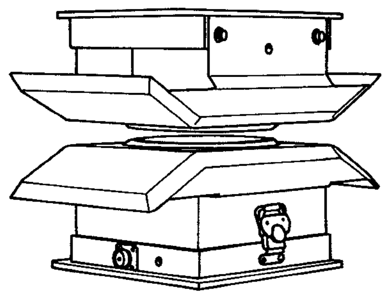
Microwave sensors first appeared in the 60's, but the development was slow because of the difficulties mentioned above. During the last fifteen years the realization of microwave sensors has been facilitated by the microwave components becoming smaller, better and cheaper and by the development of data processing technology.

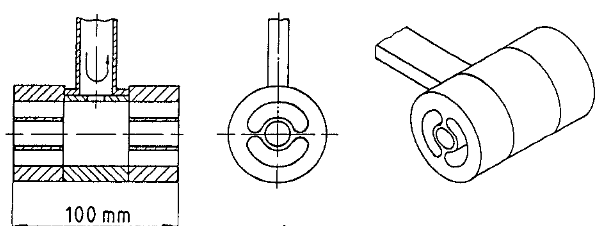
RESONATOR SENSORS

A microwave resonator is made of a section of transmission line with open or shorted ends. Depending on the type of transmission line, the resonators are called for example coaxial, microstrip, stripline, slotline, or cavity resonators. When the resonator is used as a sensor, the object to be measured is brought into contact with at least some part of the electromag- netic field in the resonator. As a consequence, the resonant frequency and the quality factor will change in relation to the permittivity of the object. Because of the large variety of possible structures, sensors can be designed for measurement of almost any kind of object. Resonators can for example measure thin films, slabs, threads, surfaces, gases, liquids, powders, or granular materials. Resonator probes can be pushed into soft materials and for example an array of stripline resonators can measure the real-time moisture profile of a paper web in a paper machine, without touching the paper.

The Swedish company, Skandinaviska Processinstrument Ab (Scanpro), has developed a range of both hand-held and mechanically scanning (Fig. 1a) cavity resonator sensors for the measurement of moisture in paper, pulp, felt, and cellulose. The first model came on market in 1968. The development of the sensors has continued since then and today their share of the market is substantial. The sensors for the on-line measurement of paper are usually used in the dry end of the paper machine. They are split cavities employing two resonant modes. One mode is less affected by the paper than the other mode, thus providing compensation for thermal expansion and humidity variations.The

a)





b)

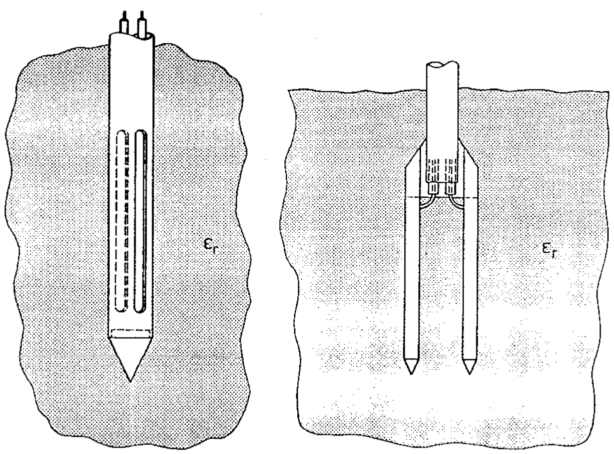
Figure 1. Split-cavity sensor (a) made by Scanpro (Sweden) for the measurement of moisture in paper, and a TE_{011}-cavity (b) developed at the Radio Laboratory of HUT for the measurement of humidity in harsh environmental conditions.

dry weight of the paper must be known for the calculation of the moisture because of the one-parameter nature of the paper measurement.

In Finland the Radio Laboratory of the Helsinki University of Technology (HUT) has developed stripline resonator sensors since 1983. The applications range from measurement of the mass per area of a layer of wood particles in a chipboard factory to measurement of moisture in veneer sheets and paper [2,3]. The stripline structure is simple and therefore cheap. In the Radio Laboratory large arrays of sensors with a common box of electronics have been developed for the real-time mapping of the properties of materials on wide production lines The latest developed application was an array for measurement of moisture in the wet end of a paper machine. This was a cooperation with Ivoinfra Inc. Current developments concern stripline resonators that are a quarter of a wavelength long. With that technique, the size of the sensors can in many cases be reduced by 50

At Radio Laboratory of HUT a humidity sensor for harsh environmental conditions has been developed [4] (Fig. 1b). It is a cylindrical cavity resonator for the mode TE_{011} . The electric field of the mode vanishes on all walls, thus allowing some accumulation of dirt. This may be for example condensed resin in a veneer dryer or dust. The sensor can also withstand high temperatures inside dryers or ovens.

Based no the research of Radio Laboratory of HUT, Toikka Engineering in Finland has developed hand-held resonator probes. The devices are battery powered and intended for field use. They are computer controlled and equipped with semiconductor memory for the storage of typically one day's measurements. One is a slot-resonator (an axial slot machined in the surface of a steel tube, Fig. 2a) that is pushed down through the peat layers in marshlands to examine the quality of the peat [5]. The measured permittivity closely correlates with the energy content. The other is the so-called snow fork [6] (Fig 2b). It is a two-conductor line resonator. It can be pushed into snow without causing almost any change in the density. From the resonant frequency and the quality factor the density and the wetness (liquid water) are calculated.



a) b)

Figure 2. Hand-held resonant probes (Toikka Engineering, Finland) for the measurement of the energy content in peat (a) and the density and wetness of snow (b).

TRANSMISSION SENSORS

The basic transmission sensor consists of two horn antennas, a transmitter and a receiver. The object to be measured is put between the antennas in such a way that the microwaves pass through the object. The attenuation or the phase shift are measured. Such a free-space transmission sensor is suitable for measurements on conveyor belts or in large pipes (Fig. 3). This type of sensor is the most often encountered microwave sensor in the industry. The major problem with free-space transmission sensors is caused by the multiple reflections inside the object and in the space between the antennas and the object. The difficulties are usually avoided by ensuring that the attenuation in the object is high enough ($\geq$10 dB), by using oblique transmission, large distance between the object and the antennas (limited by diffraction), or frequency sweep.

In some sensors the microwaves are guided from the transmitter to the receiver by a transmission line. Such guided wave transmission sensors are used for example for the measurement of liquids (e.g. microstrip structure) or films (e.g. split waveguide). They resemble resonator sensors, but are better suited for measurement of high-loss materials.

In Germany Laboratorium Prof. Dr. Berthold has developed a free-space transmission sensor for use on conveyors. Both the attenuation and the phase shift are measured, and a radioactive sensor is used for the compensation of variations in the thickness of the material layer. The instrument is versatile, but an important application is the measurement of moisture in coal [7].

In Poland the Wiltech company has developed a versatile instrument [8]. The control unit can be used with both

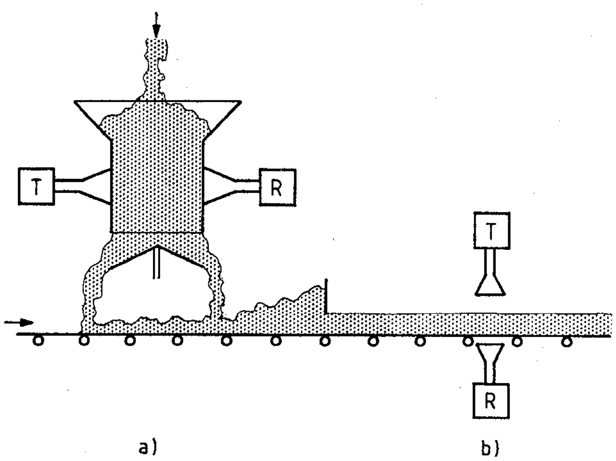


Figure 3. Free-space transmission sensors mounted for measurement (a) in a pipe or (b) on a conveyor belt.

guided wave and free-space transmission sensors. Sophisticated modulation techniques are used to compensate for reflections and other sources of error.

In Finland Kajaani Automation Inc. is currently developing microwave sensors for the pulp and paper industry.

REFLECTION SENSORS

The reflection sensors are based on the measurement of the reflection coefficient, for example from the open end of a transmission line. A widely used sensor is the open-ended coaxial sensor. The open end is held against the surface of the object or is immersed or pushed into it. The sensor is well suited for research purposes, in which case the advantages are the broad bandwidth (typically two decades), the small measurement area, and the ease of sample preparation.

In Cambridge University (UK) a practical laboratory measurement system has been developed [9]. The sensor head is made of 6.4 mm diameter semirigid coaxial cable. The control unit is an automatic network analyzer and the calibration is based on the measurement of three known liquids. Their particular interest was to study cryopreserved tissue during the rewarming process.

Reflection measurements can also be accomplished in free space. For example at the Belorussian Academy of Sciences in Minsk, millimeter wave ellipsometric methods for the investigation of dielectric coating materials have been developed [10]. In ellipsometry the ratio of the reflection coefficients for vertical and horizontal polarization at oblique incidence is measured. A hand-held instrument for the measurement of for example paint and ceramic coatings on tools and turbine blades has been developed. The thickness range is 4-200 μm and the measurement area is in the order of 2×3 cm.

RADAR SENSORS

Sensors that measure the flight of time or the frequency of the echo from an object are called radar sensors. More specifically, the sensor may be a pulse, impulse, FM, or doppler radar, or an interferometer or a combination of those. Radar sensors are used for example for the measurement of surface level in vessels, vibration, movement (burglar alarm, door openers), shape, and for the detection of subsurface reflecting interfaces or objects. An important future application is the anti-collision for cars that is developed in a joint European project.

Autronica AS in Norway and Saab Marine Electronics Ab in Sweden have developed radar sensors for the measurement of surface level in tankers. The sensors can be installed behind a dielectric window to reduce the explosion risk. Because of the target being a single, clearly defined surface, the measurement accuracy is a few millimeters, much better than the theoretical resolution.

Ylinen Electronics in Finland has developed a range of Doppler sensors, for example speedometers for icebreakers and traffic counters (34 GHz). The traffic counters are easily moved from one location to the next and they can be used on small gravel roads also, where the use of inductive loops is impossible.

Keltronics Ab in Sweden has developed a doppler radar for vibration measurement of large machines in the industry. The control unit contains a software package for analysis of the results for diagnostic purposes.

The applications of impulse radar (short-pulse radar) have been studied in many places. In UK radars have been developed for example by the British Gas Engineering Research Station for the detection of pipes and cables using a rotating antenna and deconvolution techniques [11]. At the Sheffield University aperture synthesis techniques have been developed [12]. At Radio Laboratory of HUT (Finland) a portable, battery-powered radar for field use has been developed [13]. The shortest impulse that can be transmitted is 200 ps. The radar has proven useful for detection of structures or moisture damages in floors and walls of buildings. It is also successful in detecting rot in living trees.

SPECIAL SENSORS

In many cases some specific feature of an object can be utilized in the sensor. For example knots in timber are detected because of their ability to act like dielectric waveguides. The angle of grain in timber is detected from the anisotropy of the permittivity.

At the Belorussian Academy of Sciences in Minsk (USSR) a hand-held sensor for the inspection of dielectric coatings has been developed [14]. The measurement principle is besed on the propagation of surface waves in the coating layer. The sensing element is a dielectric waveguide at a small distance (¡1 mm) from the object. For certain frequencies the propagation constant in the dielectric waveguide equals that of the surface waves in the coating, causing strong coupling to occur.

RADIOMETER SENSORS

Microwave rediometers receive the blackbody radiation emitted from an object. Because the black-body radiation depends on the temperature, radiometers can be used for the measurement of temperature from a distance through for example smoke or fog, where the infrared radiometer will fail. The microwave radiometer can also measure the internal temperature of an object. If several frequencies are used, the temperature as a function of depth can be derived.

Medical aplications of microwave radiometry have been studied in many institutes in Europe. The research at the University of Lille [15] in France has led to commercial equipment marketed by O.D.A.M. The product is equipment for treatment of cancer by microwave hyperthermia and simultaneous temperature monitoring by microwave radiometry.

In Italy several institutes have cooperated in tests with multi-frequency radiometry for the detection of subsurface temperature as a function of depth in biological tissues [16].

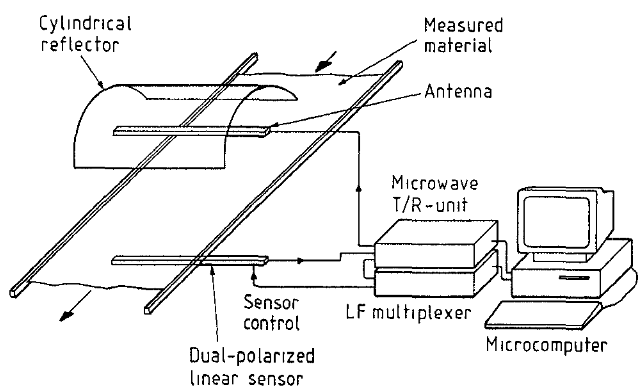


Figure 4. Linear tomographic system made by Satimo (France) for the measurement of sheetlike materials in the industry.

ACTIVE IMAGING

By measuring both the phase and the amplitude of the field reflected from (holography), or transmitted through (tomography), an object, the three-dimensinal distribution of the permittivity can be calculated. These methods are being studied in several institutes at the moment, e.g. Belorussian State University in Minsk (USSR), Laboratoire des Signaux et Systemes (France) [17], Departamento de Electrofisica, E.T.S.I.Telecommunicación, Barcelona (Spain) [18]. The future applications will probably be found in the field of medicine, and in detecting hidden objects in for example security checks.

The research in France has led to some commercial products of Satimo. One is designed for the three-dimensinal inspection of biological tissues. Another consists of a linear source and a linear array of sensors (Fig. 4). It can measure the permittivity distribution with a resolution of 1 cm of a sheetlike material moving through the sensor.

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