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Microwave testing with the pitch-catch method

Johann H HINKEN [1], Aschwin GOPALAN [2]

[1] fitm Hinken Consult, Magdeburg, Germany, Phone: +49 171 2053208, e-mail: johann.hinken@fitm.de
[2] Rohmann GmbH, Frankenthal, Germany, Phone: +49 6233-3789-0, e-mail: gopalan@rohmann.de

Abstract
Polyethylene (PE) pipes in practice often are joined by butt welding. Here the pitch-catch method with microwaves is proposed for the inspection of the weldseam of such butt weldings. An example is presented which shows the application of this method. -The design of the microwave coupler is based on the eigenmode analysis in the pipe wall and in the coupler. These eigenmodes are similar to ultrasonic Lamb waves. – A test of a butt-welded PE pipe using the microwave pitch-catch method showed that artificial defects down to millimeter dimensions could clearly be found.

Keywords: microwave testing, butt welding, PE pipes, non-destructive testing

1. Introduction

Sections of polyethylene (PE) pipes in practice often are joined by butt welding to give a continuous pipe. The weldseams have to be non-destructively inspected immediately after welding and before burying. This report shows, that the pitch-catch method, which is used in ultrasonic testing, can be transferred to microwave testing and that this method is useful for butt-weld inspections.

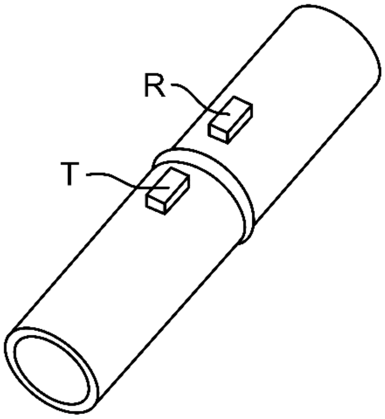


Figure 1: PE pipe with weldseam and positions of microwave couplers for transmitting (T) and receiving (R)

Fig. 1 shows the principal positioning of the welded pipe and the two microwave couplers. These are used to couple the microwave from the transmitter into the pipe wall (T) and to couple the microwave out of the pipe wall to the receiver (R). The microwave is propagating within the pipe wall and through the weldseam. There it is affected by inhomogeneities. In this way the receiver can detect irregularities in the weldseam.

In [1] first test with such arrangement were performed. However, in these tests couplers were used, which radiated in radial direction into the pipe. Thus only weak stray fields passed the weldseam. The results were not satisfying and had to be improved.

It seems to be more efficient to excite a microwave such, that it propagates in longitudinal direction within the pipe wall, propagating directly through the weldseam. For the design of an adequate exciter (coupler) at first the electromagnetic wave propagation longitudinally in the pipe wall is to be theoretically investigated, then the coupler can be designed properly. This is shown in the following section. After that, tests are described.

2. Wave propagation in the pipe wall

For simplification, the pipe wall is approximated by a dielectric plate extending to infinity in the propagation direction (z), see fig. 2.

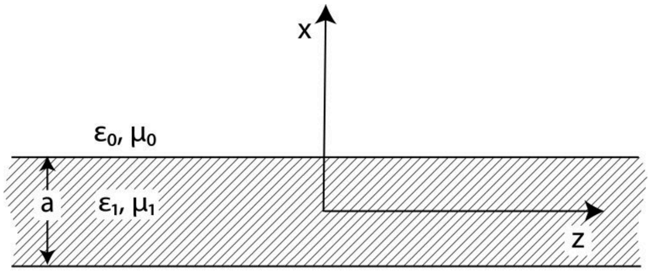


Figure 2: Dielectric plate with infinite extension in y direction, i.e. perpendicular to the drawing plane. a: plate thickness. $\varepsilon_0, \varepsilon_1, \mu_0, \mu_1$: permittivity and permeability constants of plate and exterior space. After [2].

In [2] the propagation of electromagnetic waves in such plate is described theoretically. Starting from vector potentials the eigenwaves and partially the field distributions are calculated. The eigenvalues are classified as even and odd waves according to the ansatz of the vector potential in x direction. Furthermore there are TM waves with only an electrical field component in propagation direction z, i.e. with magnetic field components only in transversal direction. And there are TE waves with only a magnetic field component in propagation direction z, i.e. with electrical field components only in transversal direction. All field components are shown in table 1.

Table 1: Field components of the eigenwaves

Type of eigenwave	Field components
odd TM wave	Ex, Ez, Hy
even TM wave	Ex, Ez, Hy
odd TE wave	Ey, Hx, Hz
even TE wave	Ey, Hx, Hz

The waves have different cutoff frequencies. Inside the plate they have sine or cosine dependences in x direction with a normalized wavenumber u. They have exponentially decaying fields in +x direction above the plate and in –x direction below the plate, both with the normalized decay constant v. And there is a parameter V proportional to the frequency f and the plate thickness a:

$$\mathrm{V} = \pi * f * a * \sqrt{\mu_1 * \varepsilon_1 - \mu_0 * \varepsilon_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

The characteristic equations of the four types of eigenwaves are

odd TM waves: $u * tan(u) = \frac{\varepsilon_1}{\varepsilon_0} * v$ ……………………………….(2)

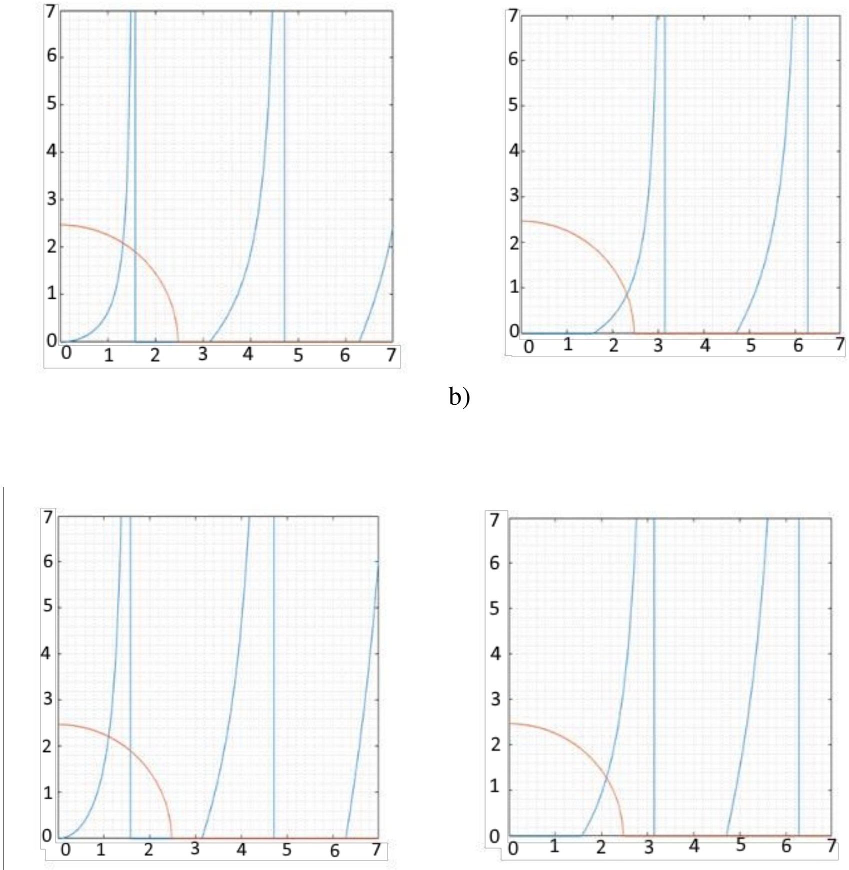
even TM waves: $-u * cot(u) = \frac{\varepsilon_1}{\varepsilon_0} * v$ ……………………………….(3)

odd TE waves: $u * tan(u) = \frac{\mu_1}{\mu_0} * v = v$ ………………………….(4)

even TE waves: $-u * tan(u) = \frac{\mu_1}{\mu_0} * v = v$ ………………………..(5)

In equations (4) and (5) there is considered that the plate material is nonmagnetic, i.e. that its permeability is $\mu_1 = \mu_0$.

The intended test frequency is f = 24.125 GHz and the material is polyethylene with $\varepsilon_{r1} = 2.5$. From this the characteristic equations follow as shown in fig. 3 where also the parameter V is plotted.



a) b)

c) d)

Figure 3: Graphic presentation of the characteristic equations. a) odd TM waves, b) even TM waves, c) odd TE waves, d) even TE waves. Horizontal: u. Vertical: blue: v(u), red: V(u).

With the current parameters in each case of a) to d) there is only one point of intersection of the red arc V(u) with the blue v(u) curves. That means, at f = 24.125 GHz, $\varepsilon_{r1} = 2.5$, and a = 8 mm only one eigenwave of each type of eigenwaves is beyond cutoff and can propagate. The wavenumbers k_{z1} and wavelengths λ_{z1} in z direction of these four eigenwaves are shown in table 2.

Table 2. Wavenumbers and wavelengths of waves beyond cutoff

	k_{z1}/1/mm	λ_{z1} in mm
odd TM waves	0,7265	8,649
even TM waves	0,5494	11,436
odd TE waves	0,7463	8,419
even TE waves	0,6021	10,435

For further investigation the odd TM wave is chosen as the useful wave. Its field distribution is shown in fig. 4.

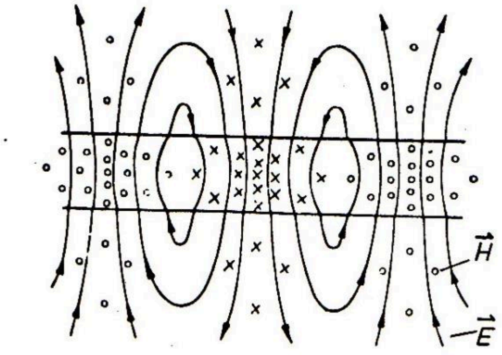


Fig. 4: Field distribution of the odd TM wave in cross sectional view [2].

Within the plate and at its boundaries there are predominantly electrical field components in x direction. This is important for the development of a good exciter (coupler).

3. Coupler

3.1 Development of the coupler

It is planned to use an open rectangular waveguide as the primary radiator. And in the plate a wave is to be excited that travels only in +z-direction and not in –z-direction. This is not possible with an excitation at a single point but only with a properly distributed pattern. For this the coupler has to generate an electrical field, which has a projection onto the z-axis with a wavelength equal to the wavelength of the useful wave. Then due to constructive interference an excitation of the useful wave is to be expected. An oblique irradiation out of an open waveguide would not be helpful, because the projection of the incident wave in z-direction onto the boundary always has a wavelength, which is larger that $\lambda_0 = c_0/f = 12.435$ mm (c_0 = speed of light) and that is larger than λ_{z1} = 8.649 mm, which is the wavelength of the useful wave in the plate.

The situation is physically similar to the excitation of slab waves (Lamb waves) in ultrasonic testing where prisms are used for coupling. A similar method is used here.

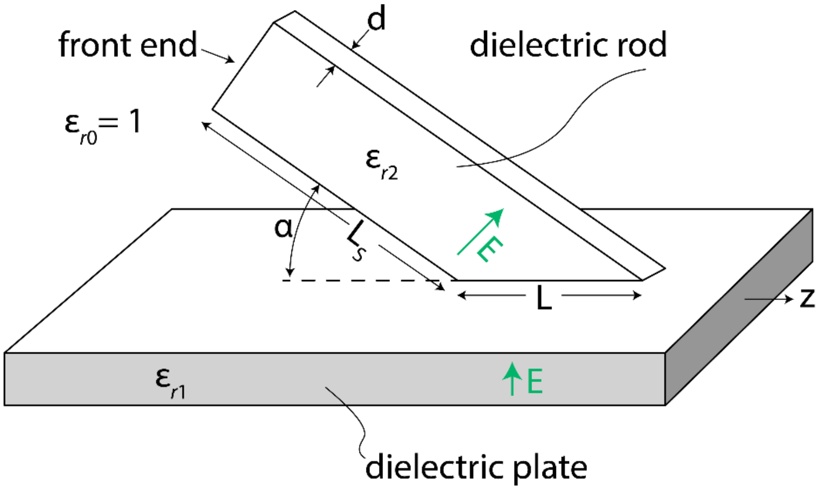


Figure 5: Dielectric rod as basic coupling element. E: electrical field strength

Fig. 5 shows the coupling structure. Not shown in fig. 5 is the open waveguide which in proper orientation at the front end irradiates the wave with proper polarisation into the dielectric rod. The wave propagates along the dielectric rod. The angle α is adjusted such that the projection of the rod wave onto the plate surface along the coupling length L is equal to the plate wave which is to be excited. Details are described in the following.

A precondition is for this type of coupling is $\varepsilon_{r2} > \ \varepsilon_{r1} = 2.5$. So PMMA with ε_r = 3.4 is chosen as material of the dielectric rod.

To calculate the field in the rod, again it is approximated as an infinitely extended dielectric plate. To ensure that the electrical fields of the exciting and the excited wave on the coupling surface substantially have the same direction, the odd TE-wave is chosen as the useful wave in the dielectric rod. According to table 1 its electrical field is in the plane of the assumed plate or dielectric rod, respectively. The directions of the electrical fields E in the coupling area are shown in fig. 5. For the excitation of the odd TE-wave the feeding waveguide is oriented such that its narrow side is parallel to the broad side of the rod.

The thickness of the rod is determined from the condition that no higher order eigenwaves but only the lowest odd TE-wave are beyond cutoff in the rod. For this, equ. (4) is evaluated according to the present situation and shown in fig. 6:

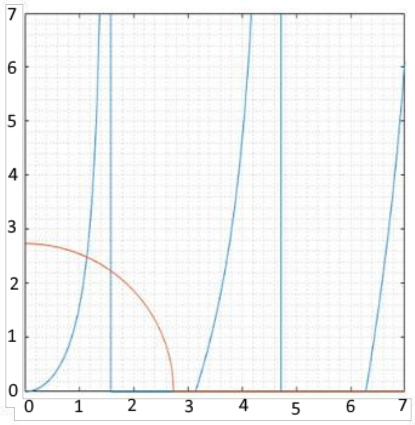


Figure 6: Graph of the characteristic equation of the odd TE-wave. Blue: v versus u, red: V versus u. Parameters: $\varepsilon_{r2} = 3.4$, f = 24.125 GHz, d = 7 mm

Fig. 6 shows the result with a thickness of d = 7 mm, because with this thickness the red curve intersects the blue quasi-tangent braches only once. From this the wavelength of the rod wave in axial direction of the slab follows as $\lambda_2 = 7.20$ mm. It is smaller than the wavelength $\lambda_{z1} = 8.649$ mm of the useful wave in the plate. Both are matched with the projection of the rod wave at an angle α which follows from

$$\cos(\alpha) = \frac{\lambda_{z1}}{\lambda_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

as

$$\alpha = 34^{o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

In this way a constructive interference between exciting wave and useful wave in the plate is achieved. Furthermore the excitation of the useful wave is determined by the coupling length L and by the extent to which the two waves overlap in the cross section. The last one can experimentally be optimised by changing the distance between plate and rod. From practical reasons the coupling length is chosen as L = 26 mm.

The length L_S of the rod has to be large enough so that local field distortions near to the exciting waveguide are decayed and only the useful wave in the rod is left at the coupling surface. On the other side the coupler should be easy to handle. A length of three times the width, i.e. $L_S = 60$ mm seems appropriate.

3.2 Realisation of the coupler

To do first tests according to the calculation in section 3.1 a coupler was designed, see Fig. 7. Two specimens have been manufactured.

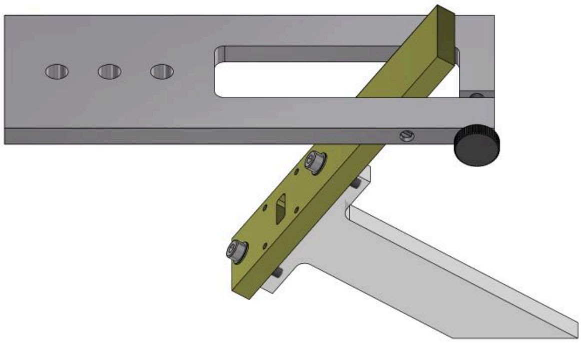


Figure 7: Designed coupler

The dielectric rod is milled by CNC according to the calculations. A brass plate serving as a holder has a drill pattern and a cutout to contact a waveguide flange of type WR42/R220. On the upper side of the brass plate a coaxial-to-waveguide adapter is to be mounted. Opposite, on the bottom side the dielectric rod is screwed to it. The brass plate is rotatably attached to a mounting plate. So the coupler can be fastened to a support in such a way that the angled end of the dielectric rod lays flat on the pipe's surface.

3.3 Example: Inspection of a PE-pipe weld with the microwave pitch-catch method

A section of a butt-welded PE pipe was available for testing. The outer diameter and the wall thickness were 125 mm and 8 mm, respectively. At the weldseam, which extended inwards and outwards, the wall thickness was approximately 12 mm. Four artificial defects had been machined into the weld bead. These defects were two through holes of diameter 3 mm and 5 mm as well as two blind holes of diameter 3 mm and depths of 2 mm and 4 mm, drilled from inside.

Fig. 8 shows the key part of the laboratory test setup with the orange pipe. The two couplers for transmitting and receiving are opposing each other. They are connected to a network analyser (not shown in fig. 8), which is operated at 24.125 GHz and works as transmitter and receiver. The output is the transmitted signal given as the scattering parameter $|S_{21}|$. A computer is connected, which processes and displays the data.

The clear width between the sharp corners of the dielectric rods were varied. Their least possible distance with the weldseam in between, i.e. about 15 mm, showed to give the highest signal-to-noise ratio. This was also the case at the least possible distance between pipe and dielectric rods, i.e. when touching. It was made sure that the lower ends of the rods were well aligned to the pipe.

The pipe was pivoted by wheels and turned around manually.

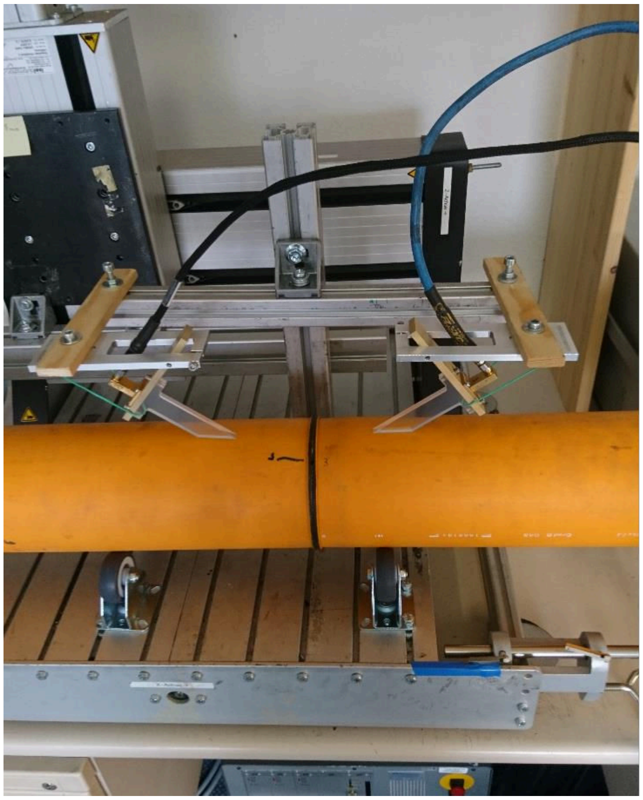


Figure 8: Partial view of the laboratory test setup for microwave testing using the pitch-catch method. Device under test: butt-welded PE pipe

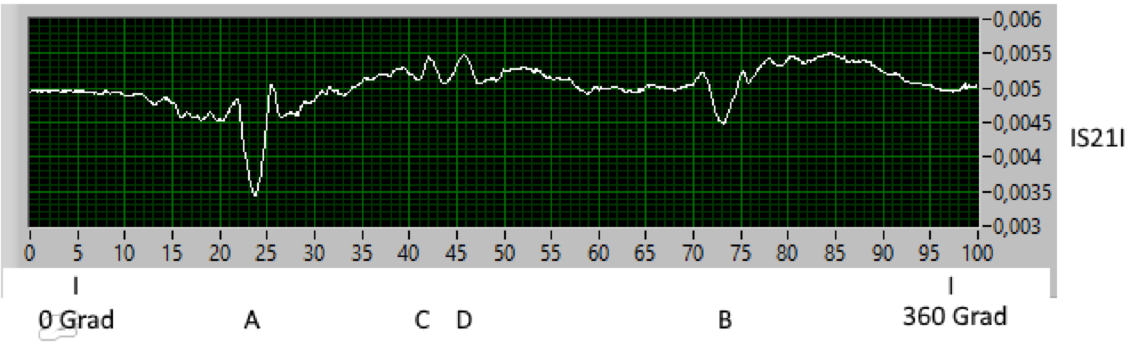


Figure 9: Circumferential scan through the weldseam. Uncalibrated transmission parameter $|S_{21}|$ versus the rotating angle. A, B: Through holes with diameters of 5 mm and 3 mm, respectively. C, D: blind holes from the inner side with diameters 3 mm and depths about 2 mm and 4 mm, respectively.

Fig. 9 shows a typical result. The through holes A and B with diameters 5 mm and 3 mm can well be recognized. And also the blind holes C and D with diameters 3 mm and depths of about 2 mm and 4 mm give clear indications. This shows, that the wave which propagates in the pipe wall completely penetrates the cross section of the wall. This furthermore shows, that the weldseam with the microwave pitch-catch method can be inspected in its whole depth.

4. Conclusions

At the chosen microwave frequency of 24.125 GHz the developed coupler, from outside the pipe can excite a wave in the wall of a butt-welded PE pipe. The wave is propagating within the wall and in axial direction. An identical coupler beyond the weldseam is used to couple out the microwave and lead it to a receiver. So the microwave is directly penetrating the weldseam and is affected by its inhomogeneities. In this way artificial defects in the weldseam were detected. These defects were through holes and blind holes from the inner side.

Butt welds between PE pipe sections have to be non-destructively tested in-situ on the building site after welding and before burying the long pipe. The presented microwave test method can be integrated into a compact and robust equipment, which can be used by trained personal for testing the weldseam and documentation directly on the building site. No couplant is necessary. It should be emphasized that microwave energies are very low and not ionizing. Thus the microwaves are harmless. So for the environment or operators no harmful exposure arises, as could be expected by testing with chemicals or high-energetic radiation.

The method is not limited to the topology of pipes. Also weldseams in plastic plates and bonding in foam panels can be tested. For this an adjustment of the coupler to the electromagnetic properties of the material under test is necessary. This can easily be done according to the method described in section 3.1

Acknowledgement

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