Isolation of the Zenneck Surface Wave: Update

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***Abstract*:** This paper focuses on the methodology and results regarding the isolation of the Zenneck surface wave using finite element simulation techniques. An optimal surface for Zenneck surface wave propagation is used. By comparing the unique theoretical properties of the Zenneck surface wave to the results of these simulations and preliminary measurements it was found that a Zenneck surface wave was present.

1 Introduction

This paper focuses specifically on isolating the Zenneck surface wave in simulation software with the aim of propagating it experimentally.

There are several variants of surface waves, however only the Zenneck surface wave is considered in this paper and therefore all future references to surface waves herein will relate to the Zenneck type which can be defined as “a wave that propagates along an interface between two media without radiation” [1].

2 Surface Wave Propagation

2.1 Boundary Conditions

To obtain a solution to Maxwell’s equations for a plane Zenneck surface wave, the following assumptions can be made (see Figure 3):

- no field variation in the *y*-direction (plane wave condition). Therefore, $\partial/\partial y=0$;
- field variations in the *x*-direction can be represented by $exp(-\gamma_o x)$ in the dielectric and by $exp(-\gamma_1 x)$ in the medium;
- field variations in the *z*-direction are as yet unknown and must be solved for.

where *x* is the direction of propagation and *z* is in a direction vertically away from the boundary.

In order to satisfy Maxwell’s Equations all the field components should be equal at the boundary, $z=0$. This solution, known as the “resonance condition” [2], is a valid solution to Maxwell’s Equations with E_x, E_z and H_y field components supported by a flat surface. It is characterised by an exponential decay of the field on both sides of the boundary.

Using the equations that describe the radial form of Zenneck surface wave, one can obtain the expected decay rate in the direction of propagation as $\frac{1}{\sqrt{r}}$. This factor can be found by examining the Hankel functions of the radial form of solutions at large radii [1] outside the medium:

$$H_0(-j\gamma r) \approx \sqrt{\frac{2}{j\pi\gamma r}}\exp(-\gamma r)\exp(j\tfrac{1}{4}\pi) \tag{1}$$

$$H_1(-j\gamma r) \approx \sqrt{\frac{2j}{\pi\gamma r}}\exp(-\gamma r)\exp(j\tfrac{3}{4}\pi) \tag{2}$$

2.2 Idealised Surface

[1] states that the optimal surface for the propagation of a surface wave is purely reactive. A suitably designed corrugated metallic surface meets this requirement as it has a purely reactive surface impedance. Consider the corrugated surface shown in Figure 1. The surface impedance is given by:

$$Z_S = jZ_W\left(\frac{d}{D}\right)\tan\left(\frac{2\pi h}{\lambda}\right) \tag{3}$$

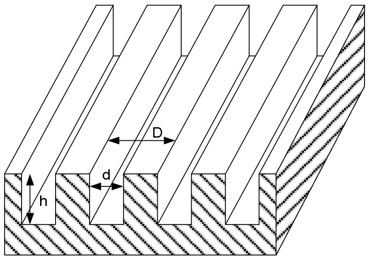

Figure 1 Corrugated Surface

where d, D and h are defined in Figure 1, λ is the wavelength and Z_W is the impedance of the material in the grooves, e.g. Z_0 for air (377 Ohms).

A continuous metallic corrugated surface has close to zero loss, thus it can be assumed that any losses seen will be due to spreading. This knowledge enables the properties of a Zenneck surface wave to be demonstrated in simulation software and on the bench. From Equation 3, it can be shown that an inductive surface reactance can be produced if the corrugation depth is less than a quarter wavelength and not less than its width. [1] suggests that for the surface impedance to appear uniform, at least three complete corrugations within a wavelength are required.

2.3 Simulation Methodology

The image shown in Figure 2 was produced using Ansoft's High Frequency Structure Simulator (HFSS) finite element electromagnetic simulation tool. This simulation had a total length greater than 10 wavelengths and an electrically short RF source. Using the unique properties of a surface wave and an idealised surface, the simulation results can be analysed to show that a surface wave is present. The following properties were analysed:

1. Field structure;
2. Decay rate away from boundary and from source;
3. Interface acts as waveguide.

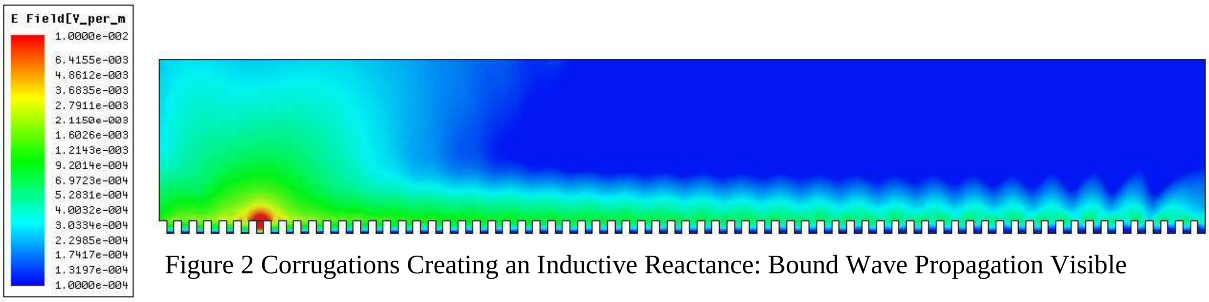

Figure 2 Corrugations Creating an Inductive Reactance: Bound Wave Propagation Visible

3 Simulation Results

3.1 Field Structure

The expected field structure of a surface wave is the E-field turning over on itself and terminating back on the surface. When the vectors are displayed, one can see in Figure 3 that this field structure is visible and thus indicates that a Zenneck surface wave is present.

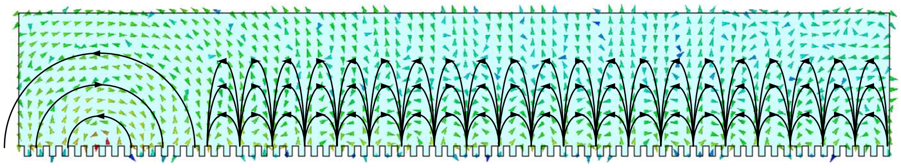

Figure 3 Theoretical & Simulated E-Field of a Zenneck Surface Wave

3.2 Field Decay

E-field cuts were taken to examine how the field decays horizontally from the source along the boundary and vertically away from the boundary (

Figure **4**). If a surface wave is present, the E-field decay rate from the source horizontally along the boundary should be approximately $\frac{1}{\sqrt{r}}$ (where r is distance from the source) and exponential vertically away from the boundary. The results from the simulation can be plotted and compared to theory. It was assumed that the unbound field is the space wave. Some space wave will be present as the source used was not a perfect surface wave launcher. In order to excite a perfect, fully bound surface wave, [1] states that a launcher with infinite aperture perpendicular to the boundary is required in addition to an ideal surface.

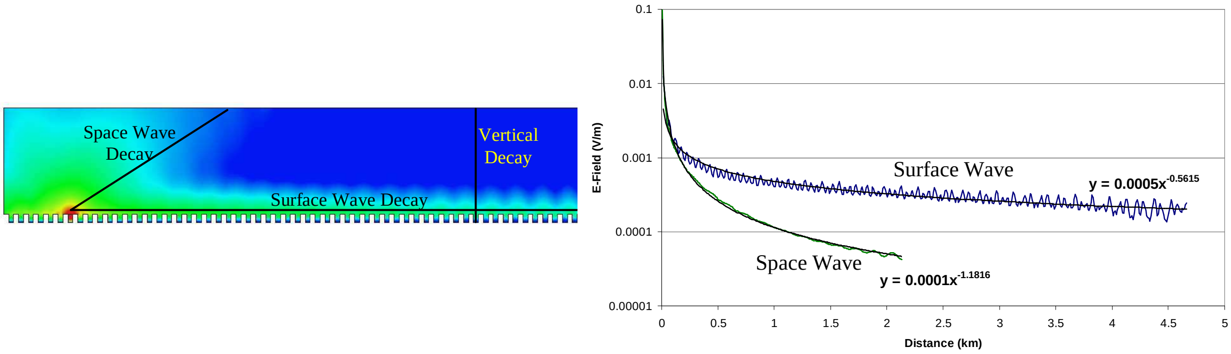

Figure 4 Field Cuts to Examine E-field Decay Rate

In Figure 4, the E-field along the line marked ‘Space Wave’ decays away at $r^{-1.18} \approx \frac{1}{r}$ based on the line of best fit. It is not exactly $\frac{1}{r}$ due to limitations in the simulation software. However, this decay rate contrasts dramatically with the E-field along the line marked ‘Surface Wave’ where the E-field decays at $r^{-0.56} \approx \frac{1}{\sqrt{r}}$. The ripple in the raw data from the simulation is due to slight variations in the field caused by the corrugated surface and reflections from the boundaries/end of the corrugations due to limitations in the simulation software.

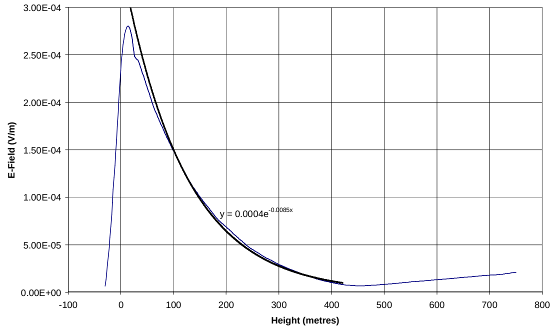

Figure 5 Decay Rate Away from Boundary

In Figure 5 the E-field increases from the bottom of the trough and reaches a peak just above the surface of the corrugations. The field then decreases exponentially with respect to distance. This exponential decay rate (blue) shows excellent agreement with surface wave theory for the chosen frequency and surface configuration (black) and is further evidence that a surface wave is being simulated. The space wave becomes dominant where the field starts to increase again.

This experiment was repeated on the bench at much higher frequencies, using aluminium corrugations as defined above. A transmitter and receiver were set up with approximately 30 wavelengths between them. The receiver was then incrementally moved vertically away from the boundary and the S21 captured. The preliminary results (assumes transmit power of 1W), are shown below, where the transmit frequency corresponds to an approximate surface impedance of j180 Ohms.

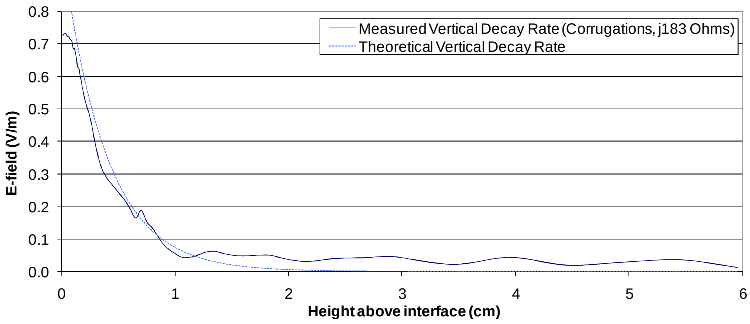

Figure 6 E-Field Measured Vertical Away from the Boundary

Figure 6 shows that the decay rate expected in the first wavelength (~1cm) is approximately the same as theoretically predicted. The variation at greater heights is most likely due to all the energy not being coupled into the Zenneck surface wave and some of the field reaching the receiver via a free space path.

3.3 Bound Wave

To show that the interface is acting as a waveguide and that the wave is therefore bound to the surface a gradient was introduced in the simulation and the surface impedance defined as a boundary condition. It can be seen in Figure 7 that if a suitably reactive surface (10+j500 Ohms surface impedance) is chosen the wave will remain bound even if a 45 degree gradient is introduced. Once again, a space wave is present as the source is not perfect. Additionally, due to limitations in the simulation software, a resistance must be included (loss mechanism) for convergence.

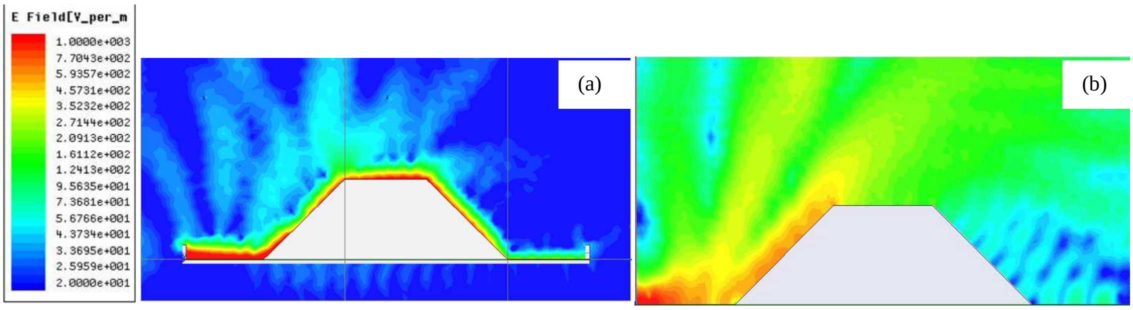

Figure 7 E-Field for (a) High Reactive Impedance Surface & (b) PEC surface

To confirm that this is due to the wave being bound, it can be compared to a PEC surface where no surface wave should be present (b). It can easily be seen when comparing the above two simulation results that the wave is being guided by the reactive surface. Some field is still present after the gradient in the PEC simulations; however this is due to diffraction.

Once again, this setup was recreated on the bench, and the author can confirm that preliminary measurements indicate that the S21 was significantly greater when launched over corrugations than when a flat metal sheet was used.

4 Conclusions

By using an idealised surface, it has been possible to demonstrate the Zenneck surface wave in HFSS. This has been verified by comparing some of the unique properties of the Zenneck surface wave with simulation results. This paper has shown there is a good correlation with theory and thus it is indicative that a surface wave is present in these simulations. Preliminary measurements also indicate that by setting up an appropriate environment, it is possible to extend these techniques into the lab and deliberately propagate the Zenneck surface wave.

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