

Effect of Aspect Ratio and Frequency of an Open-Ended, Coaxial Line on Admittance for Determination of Moisture in Tenera Oil Palm Fruit Using Finite Difference Method

E. M. Cheng^{1,2}, Z. Abbas³, Mohamedfareq Abdulmalek⁴, K. Y. You⁵, K. Y. Lee⁶,
N. F. Mohd Nasir¹, M. S. Abdul Majid¹, and S. F. Khor⁷

¹ School of Mechatronic Engineering, University Malaysia Perlis (UniMAP)
Pauh Putra Campus, 02600 Arau, Perlis, Malaysia
emcheng@unimap.edu.my, nashrul@unimap.edu.my, shukry@unimap.edu.my

² Bioelectromagnetic Research Group (BioEM), University Malaysia Perlis (UniMAP)
Pauh Putra Campus, 02600 Arau, Perlis, Malaysia
emcheng@unimap.edu.my

³ Physics Department, Faculty of Science, University Putra Malaysia, 43400 Serdang, Selangor, Malaysia
za@upm.edu.my

⁴ Faculty of Engineering and Information Sciences, University of Wollongong in Dubai
Dubai Knowledge Village, Dubai, United Arab Emirates
mohamedfareqmalek@uowdubai.ac.ae

⁵ School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia
Skudai, Johor 81310, Malaysia
kyyou@fke.utm.my

⁶ Lee Kong Chian Faculty of Engineering & Science, Tunku Abdul Rahman University
Sungai Long Campus, Jalan Sungai Long, Sungai Long City, Cheras, 43000 Kajang, Selangor, Malaysia
kylee@utar.edu.my

⁷ School of Electrical Systems Engineering, Universiti Malaysia Perlis (UniMAP)
Pauh Putra Campus, Arau, Perlis 02600, Malaysia
sfkhor@unimap.edu.my

Abstract — This paper intends to study the effect of variations of aspect ratio (the ratio of outer radius to inner radius of conductor) and frequency to the normalized admittance (normalized conductance and susceptance) of oil palm fruit with various moisture content (MC) on performance of RG405/U semi-rigid cable (open-ended coaxial line). Both finite difference method (FDM) and quasi-static model (admittance model) were used to compare response of normalised conductance and susceptance due to 30%, 40%, 60%, 70% and 80% of moisture content that explain all ripeness stage of oil palm fruit. Finite difference method is used to simulate complex admittance due to different MC in oil palm fruit in various ripeness. The FDM results were then compared with the quasi-static model through error analysis. The aspect ratio of 3.298 has

smaller error of normalized conductance when frequency range <3 GHz.

Index Terms — Conductance, finite difference method, moisture content, normalized admittance, oil palm fruit, open-ended coaxial sensor, susceptance.

I. INTRODUCTION

Mathematical and computational modelling have been applied in electrical and electronic research since long before to study and simulate phenomena at a wide range of applications, from the basic circuit [1] to materials [2]. Many publications about computational electromagnetic modelling in various biological systems were observed [3]. The computational electrical and electromagnetic modelling are crucial in study on

heterogeneous model for biological matter due to its complication. Experimental methods are time consuming and incur high cost expenditure. Hence, computer simulation methods play an essential role in understanding electrical behavior in the biological system, including agricultural products. Maxwell's equations in differential form are the basis in computational electromagnetic modelling. Implementation of numerical modelling in

agricultural issues is often to be conducted for engineering solution. Vagenas and Marinos-Kouris [4] implemented a finite element analysis on agricultural products to analyze diffusion of moisture during the drying process, e.g., Mung bean [5]. High voltage pulsed electric field was simulated for food preservation technology using the finite element method [6].

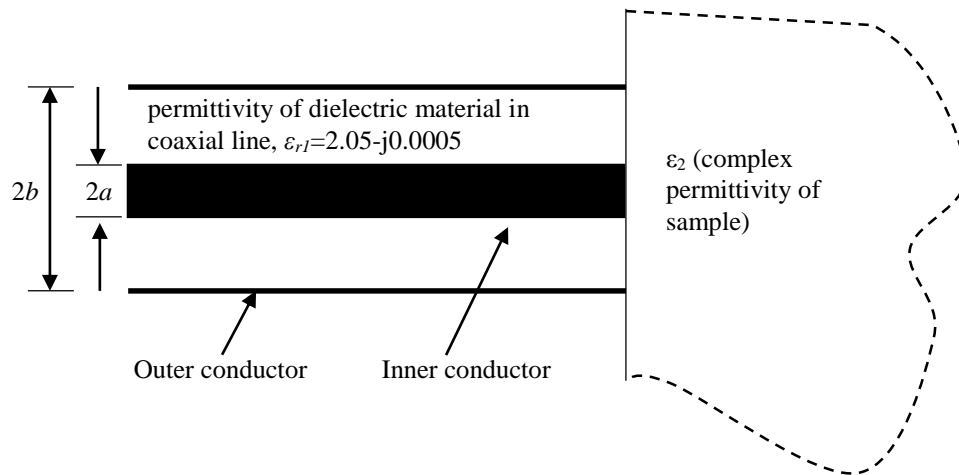


Fig. 1. An open-ended coaxial reflection sensor.

Many methods were proposed and developed to measure the quality and quality-related characteristics. They primarily employ a non-invasive methods and sensing system to determine the quality of agricultural products. Electrical properties of agricultural products become a significant concerns among the public. Electrical properties are a mean for determining moisture, the maturity of agro products, etc. [7]. In addition, electrical property describes the feasibility of microwave heating to a material subject to microwave irradiation. It is crucial in the processing of food materials because the optimum electrical parameters need to be applied. The electrical study on a material could help to analyse electrical behaviour of materials due to exposure of electric field. The studies on electrical properties of agricultural products have led to the development of various electrical based instruments.

Oil palm industry is a primary economic activity in Malaysia. Malaysia is the second largest producer of palm oil in the world. In 2011, the palm oil sector contributes USD 16.8 billion to Malaysia's Gross National Income. As a result, many efforts were done to optimise harvest of oil palm fruit to achieve a high income generation. Over the last decade, many studies were conducted on oil palm fruit using electromagnetic methods. *MC* in oil palm fruit were investigated using low cost open-ended coaxial line [8-11]. This is due to the inverse relationship between water and oil content in oil palm fruit [12]. This relationship is used to study *MC*

in oil palm fruit to determine ripeness of fruit [13] for maximum yield of palm oil. This work describes the electromagnetic behavior in oil palm fruit. It is highly important to simulate and model its behavior or response numerically for instrument development.

Many studies were conducted using a numerical method which; for example by using partial differential equations in determining the specification, dimension and requirements for optimum design of instrumentation and sensing system in oil palm harvesting. You *et al.* and Cheng *et al.* [14-16] implement numerical methods (finite element method and finite difference method) and quasi-static model on open-ended coaxial line to explore the interaction of microwave with oil palm fruit. Results that obtained can be used to determine the optimum harvesting time. However, the references [14-16] only studied a fixed aspect ratio, and meaningful comparison is hardly carried out. It is the motivation of this study to investigate an open ended coaxial line with different aspect ratio. The electromagnetic response of fruit on the coaxial line is crucial to analyse the performance of the sensing system in moisture inspection. To the best of our knowledge, there are no previous studies to model the aspect ratio of an open ended coaxial for determination of moisture in Tenera oil palm fruit. Currently, studies only use the commercially available open ended coaxial probe with fixed aspect ratio. Experimental work to study the effects of various aspect ratios are not available, as the design is limited to characteristic impedance at 50 Ω ,

75 Ω and 93 Ω . The optimization is hardly carried out for determination of moisture in Tenera oil palm fruits. As a result, quasi-static model was compared with FDM method. Various aspect ratios have been studied to investigate the response of result with moisture in fruit. On the other hand, limited studies were conducted to model and study the effect of aspect ratio of an open ended coaxial for determination of moisture in Tenera oil palm fruit. Limited model can be found for comparison. Hence, comparison between FDM and AM helps to verify reliability of FDM in designing an open-coaxial sensor for optimised specification, since AM is well-known and it has been used extensively in investigation of open-ended coaxial probe. By investigating the optimised aspect ratio and frequency range through numerical study, an experimental work can be conducted to verify the finding. Next, the streamlined design can be implemented better in the oil palm industry.

An accurate and efficient method could facilitate the design of sensing system in agricultural product. It saves time and does not cause wastage of resources. As a result, it is paramount importance to compare FDM and AM on the effect of aspects ratios for the sake of determination of suitable aspect ratio for potential sensor development.

II. MATERIALS AND METHOD

A. Normalized admittance (\tilde{Y})

An open-ended coaxial probe with radius a and b of inner and outer conductors, respectively is shown in Fig. 1. Figure 2 shows open-ended coaxial line in typical lumped-circuit model. However, the model varies according to the specification of coaxial line and frequency. $G(\epsilon_{r2})$ represent conductance in circuit model where ϵ_{r2} is permittivity of sample, C_f is the fringing capacitance on the aperture of coaxial line, and $C(\epsilon_{r2})$ is the capacitance of the sample with ϵ_{r2} . Both C and G are function of ϵ_{r1} . C_f , $C(\epsilon_{r2})$ and $G(\epsilon_{r2})$ vary based on the dimensions of the coaxial line, i.e., radius a and b as well as permittivity of the dielectric filling the line. C_0 in free space can be obtained as [17]:

$$C_0 = 2.38\epsilon_0(b - a). \quad (1)$$

The C_f and G_0 can be neglected at first approximation [18]. C_f can be obtained numerically [19] or measured merely both of capacitances [20]. On the other hand, it can be also determined approximately through quasi-static analysis [21-22]. The total capacitance, $C_T (=B_0/\omega)$ and radiation conductance, G_0 in the air can also be defined in literature [23].

When the sensor is contacted with the sample, the permittivity of the sample, ϵ_{r2} changes the end capacitance and it gives the input admittance, Y_{in} as:

$$Y_{in} = G + jB, \quad (2)$$

where G and B are the real and imaginary parts of Y_{in} , namely conductance and susceptance, respectively.

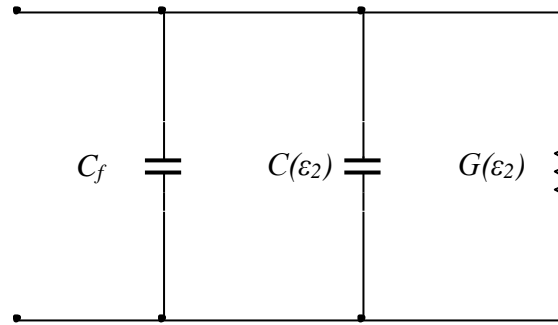


Fig. 2. Equivalent circuit for the open-ended coaxial sensor.

Admittance, Y_{in} is reciprocal of impedance, Z_{in} which can be determined through reciprocal of Z_{in} . In fact, Y_{in} is a measure of ability of a material to permit flow of electric current. On the other hand, G and B are defined as reciprocal of resistance, R and reactance, X , respectively. G (in Siemens) is ability to conduct frequency-independent electric current in a specific material. Meanwhile, B (in Siemens) is determined through reciprocal of X . Likewise, B play a similar role like G but it is subjected to frequency-dependent electric current. R is opposition of frequency-independent current due to chemical composition in a material.

In general, the input impedance can be expressed as:

$$Z_{in} = R + jX. \quad (3)$$

The input impedance model for lumped-circuit as shown in Fig. 2 can be expressed as:

$$Z_{in} = \frac{1}{j\omega C_f + j\omega C(\epsilon_2) + G(\epsilon_2)}. \quad (4)$$

In this work, input admittance of open-ended coaxial line, Y_{in} was studied due to the variation of MC and aspect ratio of the coaxial line using FDM. Results of FDM were compared with the admittance model for verification.

B. FDM for admittance

i) Calculation of admittance

Heavy calculation of simultaneous equations in the matrix is needed to implement FDM in admittance calculation. In this work, an iterative method was used to conduct calculation for electric potentials in scalar wave equation at every node to form a matrix [15-16]. The potential at a particular node is calculated based on potential values at adjacent nodes using Equation (5):

$$V_{m,n} = \frac{1}{4}(V_{m+1,n} + V_{m-1,n} + V_{m,n+1} + V_{m,n-1}), \quad (5)$$

where m and n are the row and column number,

respectively. Perfect electric conductor (PEC) and Perfect Matched Layer (PML) were used to define and restrict computational regions, respectively. The reflection occurs on the boundary between Polytetrafluoroethylene (PTFE) in the coaxial line and the sample. The electric flux density can be expressed in Equation (6) at the dielectric boundary:

$$D_{1n} = D_{2n}, \quad (6)$$

where D_{1n} and D_{2n} are the normal components of the electric flux density in region PTFE in coaxial line and the sample under test (oil palm fruit), respectively. According to Gauss' Law,

$$\oint D \cdot dl = \oint \epsilon E \cdot dl = Q_{enc} = 0, \quad (7)$$

due to absence of free charge on the dielectric boundary. $E = -\nabla V$ is substituted in Equation (6) to be Equation (7):

$$0 = \oint \epsilon \nabla V \cdot dl = \oint \epsilon \frac{\partial V}{\partial n} \cdot dl, \quad (8)$$

where $\frac{\partial V}{\partial n}$ is the derivative of V normal to the contour l .

Equation (7) on the boundary as shown in Fig. 1 can be expressed as:

$$V_0 = \frac{\epsilon_1}{2(\epsilon_1 + \epsilon_2)} V_1 + \frac{\epsilon_2}{2(\epsilon_1 + \epsilon_2)} V_3 + \frac{1}{4} V_2 + \frac{1}{4} V_4. \quad (9)$$

The potentials on boundary, V_{ring} were obtained through Equation (8) using finite difference method. The total potential, V_{area} , and the total charge, Q_{area} , on the aperture of the probe can be determined using Equations (10) and Equation (11), respectively [24]:

$$V_{area} = \int_a^b V_{ring} d\rho, \quad (10)$$

$$Q_{area} = \epsilon \int_a^b \int_0^{2\pi} \frac{V_{ring}}{\rho} \rho d\phi d\rho, \quad (11)$$

where ρ is the radius at aperture of the coaxial probe, and ϕ is the azimuthal angle on aperture. The normalized and characteristic admittance are given in Equations (12) and (13):

$$\frac{Y}{Y_0} = \tilde{Y} = \frac{j\omega C_T}{Y_0}, \quad (12)$$

$$Y_0 = \frac{2\pi}{\sqrt{\frac{\mu_0}{\epsilon_1}} \cdot \ln\left(\frac{b}{a}\right)}, \quad (13)$$

where μ_0 is the free space of permeability, since PTFE is a non-magnetic material.

ii) Truncation of infinite computation region

In FDM computation, the extent of the sample to be simulated is only part of the actual sample because the fringing field of the open-ended coaxial sensor could only be reached around 2mm depths. The actual dimension of the sample (oil palm fruit) is much greater

than 1 cm. Therefore, the PML condition must be applied to reduce the mesh size. A PML is an artificial absorbing layer for a computational electromagnetic solution. It commonly used to restrict computational regions in numerical method to simulate problems with open boundaries. For practical reasons, the infinite space is usually truncated due to the limitation of computing machine used. PML is helpful to avoid the undesired reflection in computation [25]. Thus, the computation solution is achievable. To produce a reflectionless boundary, computation/truncated region (region 1/ region 2) interface for the normally impinging wave should theoretically abide by:

$$\Gamma = \frac{\eta_1 - \eta_2}{\eta_1 + \eta_2} = 0, \quad (14)$$

and

$$\eta = \sqrt{\frac{\mu(1 + \sigma/j\omega\mu)}{\epsilon(1 + \sigma/j\omega\epsilon)}}. \quad (15)$$

It can be achieved by equating $\epsilon_1 = \epsilon_2$ and $\mu_1 = \mu_2$ where ϵ_1 , ϵ_2 , μ_1 , μ_2 , k_1 , k_2 , η_1 and η_2 are the permittivity of region 1, permittivity of region 2, permeability of region 1, permeability of region 2, wave number of field at region 2, intrinsic impedance of media in region 1 and intrinsic impedance of media in region 2, respectively. The voltage at truncated nodes, V_2 was solved using:

$$V_2 = V_1 e^{-jk_2 x - \sigma \eta_2 x}, \quad (16)$$

where V_1 is the voltage of the node at boundary of computation region.

iii) Numerical modeling error

The modeling errors are due to several assumptions made in arriving at the mathematical model. To simplify the computation work, a nonlinear system may be represented by a multiple linear PDE unit. For instance, the truncation error and round-off error are common numerical error.

The truncation error was advent due to the elimination of terms in infinite series. High-order terms in the Taylor series expansion were neglected in derivation finite difference schemes and causes truncation error. Finer meshes can reduce the truncation errors by reducing the mesh size [26]. Besides, truncation errors can be reduced using a large number of terms as well in the series expansion of derivatives. In other words, higher-order approximations should be implemented in computation.

Round-off errors restrict precision when used for computation. The size limitation of registers in the arithmetic unit of the computer causes round-off errors. Using double-precision arithmetic can help to minimize round-off errors. If all operations implemented using integer arithmetic, the round-off errors can be avoided.

C. AM (Quasi-static model)

The work by [27] described the homogeneous case, in which an air-filled coaxial line is radiated into the free space. At the same time, the aperture admittance has been formulated as Equation (17):

$$\tilde{Y} = \frac{jk_2}{k_1 \ln(b/a)} \times \int_0^\infty \frac{d\zeta}{\zeta(\zeta^2 - k_2^2)^{1/2}} |J_0(\zeta a) - J_0(\zeta b)|^2, \quad (17)$$

where k_1 and k_2 are wave number at internal media and external media, respectively. ζ is a parametric equation which was defined in [27].

The open-ended coaxial probe began to be applied as a sensor in biological sensing during the early 1980s. The literatures [28]-[31] formulated the electrical property such as aperture admittance or impedance in capacitance terms. The open-ended coaxial sensor can be implemented up to 1 GHz using [31]:

$$\tilde{Y} = \frac{j\omega(\varepsilon_r C_0 + C_f) + G(\varepsilon_r)^{2.5}}{Y_0}. \quad (18)$$

Since excitation of the coaxial probe is a TEM mode, neither the electric field nor magnetic field oscillates along the direction of propagation. Equation (17) express dominate wave (TEM) at the coaxial aperture probe. In other words, AM depict reflection occur at aperture of the probe.

It was extended to oil palm fruit moisture sensing recently [11]. The assumption which the sample under test can be represented more accurate with the presence of conductive element was made by Brady and Stuchly [32-33]. The capacitance formulation became inapplicable at higher operating frequency because the actual theoretical value is not satisfied with capacitance formulation at a higher frequency, especially for lossy materials with one single value of capacitance, C_T [34]. Misra [22] simplified the model in approximated series expansion. The aperture admittance which is presented in rational function model as expressed in Equation (19) was used to determine the complex permittivity of materials, ε_r .

$$\tilde{Y} = \frac{\sum_{n=1}^4 \sum_{p=1}^8 \alpha_{np} (\sqrt{\varepsilon_r})^p (j\omega a)^n}{1 + \sum_{m=1}^4 \sum_{q=0}^8 \beta_{mq} (\sqrt{\varepsilon_r})^q (j\omega a)^m}, \quad (19)$$

where α_{np} and β_{mq} are the coefficients of the Equation (19). These two coefficients are determined by the size and the type of coaxial sensor. This model was developed in the early 1990s [35-37].

The normalized admittance, \tilde{Y} has real and imaginary parts, namely normalized conductance, G/Y_0

and susceptance B/Y_0 , in which can be written as [38-39]:

$$\tilde{Y} = \frac{G}{Y_0} + j \frac{B}{Y_0}, \quad (20)$$

where

$$\frac{G(0)}{Y_0} = \frac{\sqrt{\varepsilon_r}}{\ln(b/a)\sqrt{\varepsilon_c}} \int_0^{2\pi} \frac{1}{\sin \theta} \times \quad (21)$$

$$\left[J_0(k_o \sqrt{\varepsilon} b \sin \theta) - J_0(k_o \sqrt{\varepsilon} a \sin \theta) \right]^2 d\theta$$

$$\frac{B(0)}{Y_0} = \frac{\sqrt{\varepsilon_r}}{\pi \ln(b/a)\sqrt{\varepsilon_c}} \times$$

$$\int_0^\pi \left[\begin{array}{l} 2 Si \left(k_o \sqrt{\varepsilon} (a^2 + b^2 - 2ab \cos \theta) \right) \\ - Si \left(2k_o \sqrt{\varepsilon} a \sin \left(\frac{\theta}{2} \right) \right) \\ - Si \left(2k_o \sqrt{\varepsilon} b \sin \left(\frac{\theta}{2} \right) \right) \end{array} \right] d\theta, \quad (22)$$

where ε_c is the dielectric constant of the material that fills the coaxial line and ε_r is the dielectric constant in the sample, k_o is the free space propagation constant, J_0 is the zero-order Bessel function, and Si is the sine integral. Equations (21) and (22) can be approximated by the first terms of the Taylor series expansion [39].

III. RESULTS AND DISCUSSION

From Fig. 3 to Fig. 7, it can be observed that the theoretical normalized conductance and susceptance varies with frequency, aspect ratio (b/a) and moisture content (MC) in oil palm fruit. There are five MC values reported in this section, namely 30%, 40%, 60%, 70% and 80% that depict all the ripeness stage of oil palm fruit. 30% and 40% MC represent the minimum amount of water content in oil palm fruit or maximum accumulation of oil content (ripe stage). The 60% MC is located in the transition region where the MC decreases drastically. Meanwhile, 70% and 80% MC indicates the maximum amount of MC in oil palm fruit or minimum accumulation of oil content (immature stage). On the other hand, the aspect ratio, b/a which were studied in this work are 1.57, 2, 3.298, 4 and 5, respectively.

The normalized conductance, G/Y_0 increases with frequency. This can be explained by the conductance, $G = \frac{\sigma}{\varepsilon} \cdot C$ where $\frac{\sigma}{\varepsilon}$ increases with frequency [15].

Hence, G and G/Y_0 increases with frequency as shown in Fig. 3 to Fig. 7. However, the G/Y_0 increases with MC as well for all b/a . It is because dielectric constant and loss factor of oil palm fruit increases with MC [15]. In all aspect ratios, G/Y_0 at high MC is higher than low MC . It

might be due to the increment of conductivity as MC increase. The presence of high MC facilitate the activities of ionic substance in fruit, e.g., fatty acids, since water is good ionic solvent. The formation of ionic substance in fruit due to water heightened conductivity of fruit. On the other hand, it can be observed that the discrepancy of G/Y_0 between FDM and AM increase progressively when frequency increases. It might be due to the assumption made by AM where the sample has infinite extent. This assumption is inapplicable in this work as the coverage of electric field from the aperture of the coaxial line is limited within 2 mm of thickness [40]. Nevertheless, PML was applied to define the extent of coverage of field in fruit using FDM. Same percentage of MC at infinite and finite extent exhibit different effect to wave propagation. At high frequencies, the applied field has poorer ability to penetrate into fruit. Moreover, high frequencies of applied field in infinite extent of fruit is invalid as the coverage of fringing field from the coaxial line is merely 2 mm. It does not consistent with assumption made by AM where the propagation medium is considered infinite in size. However, FDM defined the computed region within 2 mm thickness. The assumption above of AM lead to inaccurate computation. It does not confirm to the limitation of open-ended coaxial line. Hence, it was believed that FDM is more practical to be used to simulate behaviour of electrical admittance.

It can be noticed that low b/a exhibit low level of G/Y_0 for all level of MC . It can be deduced through Equation (13). High b/a lead to low Y_0 and in turn, it causes high G/Y_0 . It can be seen through variation of G/Y_0 where the variation for $b/a = 5$ is the widest compared with other lower b/a , i.e., 1.57, 2, 3.298 and 4. The aspect ratio, $b/a = 3.298$ presents considerably smaller error compared with $b/a = 1.57, 2,$ and 4 when frequency < 3 GHz. This aspect ratio indicates the smallest average error, i.e. 0.03 Siemen. Commercial RG405/U coaxial cable has $b/a = 3.298$. It indicates RG405/U coaxial cable is appropriate for application in moisture sensing for frequency < 3 GHz [15-16]. For frequency > 3 GHz, the smallest average error is shown by the smallest b/a ($=1.57$) coaxial line, i.e., 0.30 Siemen. It suggests that lower b/a lead to a better agreement between FDM and AM in term of G/Y_0 for frequency > 3 GHz. The average error of low b/a for frequency range > 3 GHz is significantly lower than high b/a . It can be seen through drastic increment of G/Y_0 from AM when b/a increases. The increment of b/a also indicates that the capacitance between the inner and outer conductor as well as fringing capacitance decrease. Subsequently, it causes an increment of G . AM does not take fringing effect into account. As a result, AM is discrepant from FDM, especially at high frequencies. In addition, increment of b/a lead to the decrement of capacitive effect in coaxial line. Subsequently, inductive effect becomes significant in coaxial line. The inductive effect could charge the

ionic substance inductively and cause the vigorous activity of ionic substance in fruit. It enhances G due to increment of conductivity. AM is more sensitive to b/a than FDM. It might be due to the aforementioned assumption. The assumption presumes homogeneous structure of the infinite region in the sample. The resistance of sample on the flow of electric current due to the movement of ionic substance in fruit is degraded. It could clarify that higher MC lead to a severe discrepancy between AM and FDM.

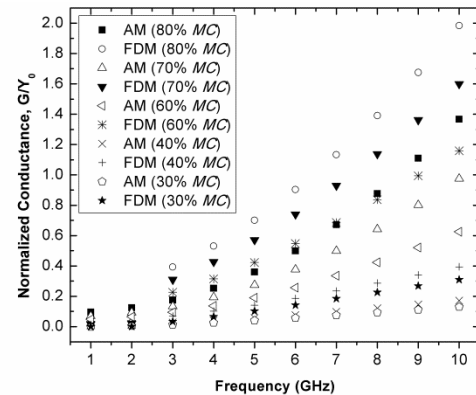


Fig. 3. The variation of G/Y_0 which $b/a = 1.57$ over frequency using FDM and AM.

Likewise, the normalized susceptance, B/Y_0 increases with frequency. The lumped-circuit in the coaxial sensor is equivalent to a RLC circuit. Therefore, susceptance, B vary with resistance, capacitance and inductance. Generally, it can be seen that increment of frequency causes capacitive reactance, X_c decreases and hence yield to the increment of B/Y_0 . However, B/Y_0 from AM decreases when frequency > 7 GHz for $b/a > 3.298$. When $b/a > 3.298$, the capacitance decline due to the increment of distance between inner and outer conductor of the coaxial line. The assumption of AM increases the effect of G/Y_0 when b/a increases. When $b/a > 3.298$, it turns coaxial line to be inductive. Hence, the increment of frequency leads to decrement of B/Y_0 . The decrement is even drastic when MC is high. This is due to the presence of a substantial ionic substance which can increase the conductivity of fruit. These ionic substances act as charge carrier to conduct current between inner and outer conductor. It was justified through higher b/a , i.e., 4 and 5 (Fig. 11 and Fig. 12) where these b/a values exhibit the greatest error range, especially $b/a = 5$ where its error is up to 35 Siemens. Meanwhile, the errors of B/Y_0 between FDM and AM that presented in Fig. 8 to Fig. 12 increases with frequency. It is similar to G/Y_0 . For $b/a \leq 2$ (Fig. 8 to Fig. 9), the error range that presented is similar which is within 1.8 Siemens. However, the error range that shown by $b/a = 3.298$ (Fig. 10) is less than 1 Siemen. FDM exhibit consistent

trendline as B/Y_0 of all MC increases. Specification of finite computation region within 2 mm range sustain the domination of capacitive effect in coaxial line. It might be due to consistency between coverage of open-ended coaxial line and the finite computation region in FDM. Consideration of the fringing effect in FDM also play a vital role. Also, the increment of MC results in the increase of B/Y_0 . Substantial MC enhance the effect of capacitive as MC has high dielectric constant. It is due to the the high polar moment tht presented in water molecule, H_2O .

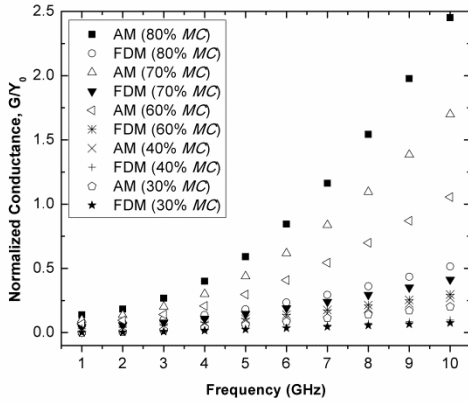


Fig. 4. The variation of G/Y_0 which $b/a=2$ over frequency using FDM and AM.

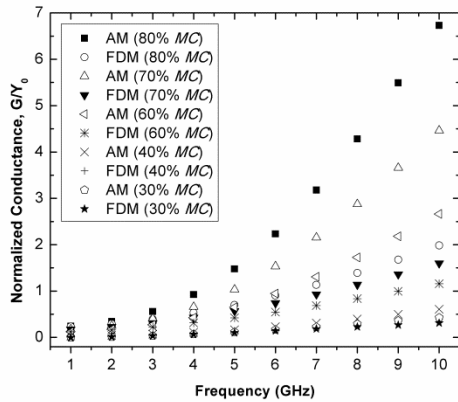


Fig. 5. The variation of G/Y_0 which $b/a = 3.298$ over frequency using FDM and AM.

It can be noticed that B/Y_0 of FDM has better agreement with AM when frequency ≤ 2 GHz. It can be seen through the lowest error that presents between AM and FDM as shown from Fig. 8 to Fig. 12. However, the frequency that < 2 GHz is highly sensitive with the presence of an ionic substance in fruit. It may lead to the discrepancy between computation and real case because the moisture is the paramount importance, instead of presented ionic substance in fruit. Ionic conductivity, σ has significant effect in 1 GHz, since dielectric properties

in agriculture are primarily dependent on water activity and ionic conductivity, σ of fluids contained in their cellular structure [41-42]. This implies that variation of \tilde{Y} can be due to polar moment of water molecule and ionic conductivity of fluids as well.

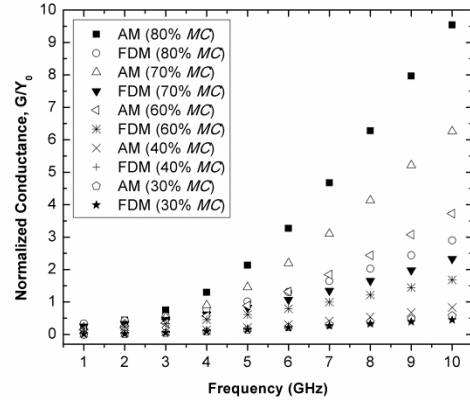


Fig. 6. The variation of G/Y_0 which $b/a = 4$ over frequency using FDM and AM.

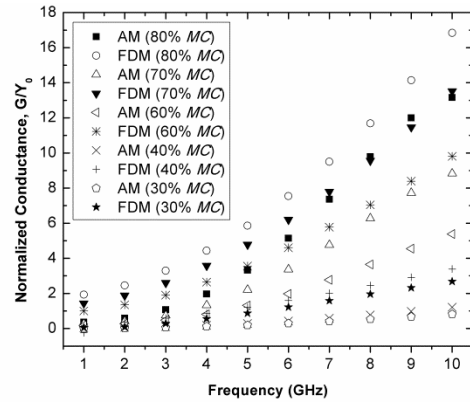


Fig. 7. The variation of G/Y_0 which $b/a = 5$ over frequency using FDM and AM.

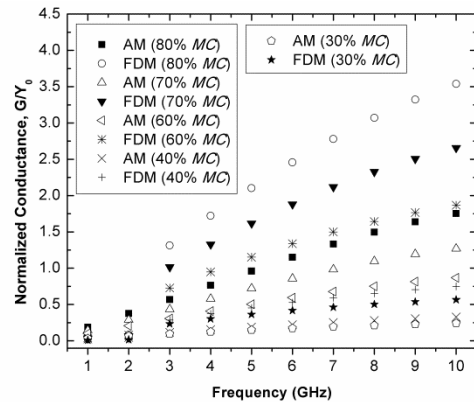


Fig. 8. The variation of B/Y_0 which $b/a = 1.57$ over frequency using FDM and AM.

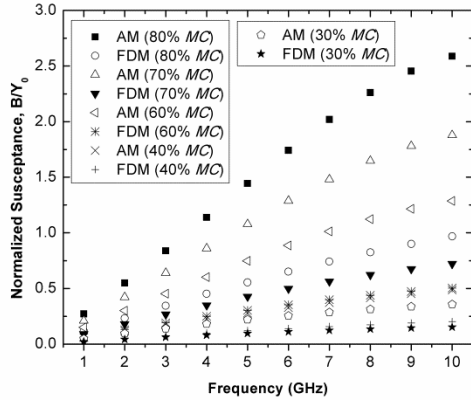


Fig. 9. The variation of B/Y_0 which $b/a = 2$ over frequency using FDM and AM.

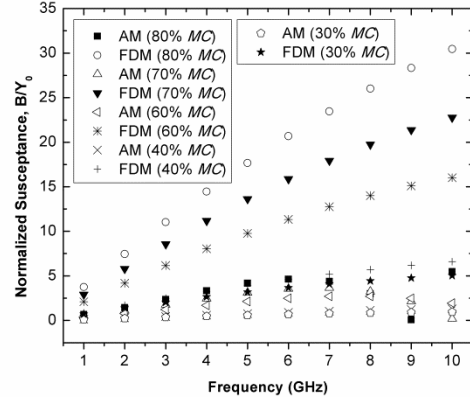


Fig. 12. The variation of B/Y_0 which $b/a = 5$ over frequency using FDM and AM.

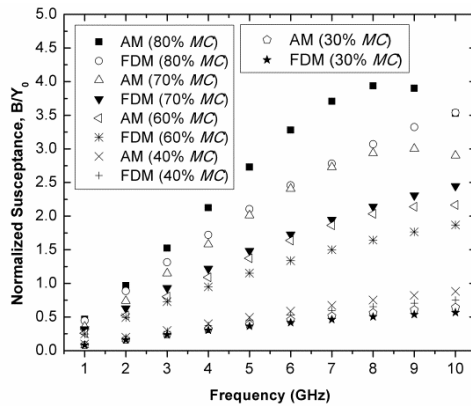


Fig. 10. The variation of B/Y_0 which $b/a = 3.298$ over frequency using FDM and AM.

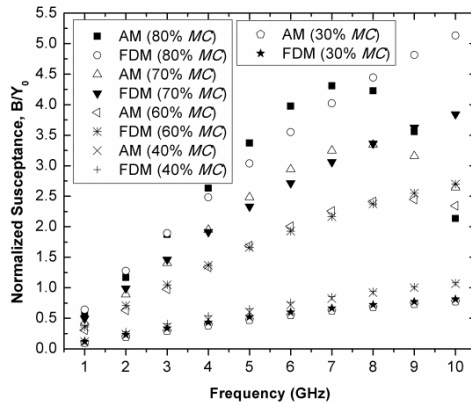


Fig. 11. The variation of B/Y_0 which $b/a = 4$ over frequency using FDM and AM.

IV. CONCLUSIONS

In this work, the admittance was simulated using FDM and AM on an aperture of open-ended coaxial line. The comparison was conducted between FDM and AM. It can be observed that finite difference method shows better agreement with AM in term of G/Y_0 . G/Y_0 of FDM and AM increases with frequency and MC for all b/a . The error of G/Y_0 between FDM and AM increase with frequency. The assumed infinite computation region by AM is the main cause to these error. Ratio $b/a = 3.298$ exhibit the least error of G/Y_0 when frequency < 3 GHz. When $b/a > 3.298$, coaxial line turn to be inductive. It becomes major reason to the increment of error. Generally, B/Y_0 increases with frequency MC and b/a . However, AM exhibit anomaly behavior where B/Y_0 decreases when $b/a > 3.298$ due to the transition from capacitive to inductive. Suffice to say, FDM and AM have the best agreement in terms of G/Y_0 and B/Y_0 at $b/a = 3.298$ when frequency ≤ 2 GHz. It implies that aspect ratio of $b/a = 3.298$ is suggested to be used for study.

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Ee Meng Cheng was born in 1980. He obtained his B.Sc (Honours)-Instrumentation Science in Universiti Putra Malaysia in 2004. He pursued his M.Sc. in Wave Propagation at the Institute for Mathematical Research on 2005 in Universiti Putra Malaysia and his Ph.D in Microwave at the Faculty of Science in 2007 in Universiti Putra Malaysia. Recently, he is a Senior Lecturer in School of Mechatronic Engineering, Universiti Malaysia Perlis. On the other hand, he is also Chartered Engineer from Institution of Engineering and Technology as well as Engineering Council, United Kingdom. His main personnel research interest is in the computational electromagnetic modeling, microwave dielectric spectroscopy, wave propagation in RF & microwave and microwave sensors development for food and agricultural applications.



Zulkifly Abbas was born in Alor Setar, Malaysia, in 1962. He received the B.Sc. degree with honors in Physics from the University of Malaya, Kuala Lumpur, in 1986, the M.Sc. degree in Microwave Instrumentation from the Universiti Putra Malaysia (UPM), Serdang, in 1994, and the Ph.D. degree in Electronic and Electrical Engineering from the University of Leeds, Leeds, U.K., in 2000. He is currently an Associate Professor with the Department of Physics, UPM, where he has been a faculty member since 1987. His main personnel research interest is in the theory, simulation, and instrumentation of electromagnetic wave propagation at microwave frequencies focusing on the development of microwave sensors for agricultural applications.



Mohd Fareq bin Abdul Malek obtained his B.Eng (Honours)-Electronic and Communication Engineering in The University of Birmingham, United Kingdom in 1994. He pursued his M.Sc. (Eng) in Microelectronic Systems and Telecommunications at The University of Liverpool, United Kingdom in 2003 and Ph.D. in

Electrical Engineering (Radio Frequency and Microwave) in 2005 at The University of Liverpool, United Kingdom. Currently, he is Associate Professor in Faculty of Engineering and Information Sciences, University of Wollongong in Dubai. His main personnel research interest is in electron maser, antenna design, embedded computing and microwave absorber development.



Kok Yeow You was born in 1977. He obtained his B.Sc. Physics (Honours) degree in Universiti Kebangsaan Malaysia in 2001. He pursued his M.Sc. in Microwave at the Faculty of Science in 2003 and his Ph.D. in Wave Propagation at the Institute for Mathematical

Research in 2006 in Universiti Putra Malaysia. Recently, he is a Senior Lecturer at Radio Communication Engineering Department, Universiti Teknologi Malaysia. His main personnel research interest is in the theory, simulation, and instrumentation of electromagnetic wave propagation at microwave frequencies focusing on the development of microwave sensors for agricultural applications.



Kim Yee Lee was born in Muar, Johor, Malaysia. He received his B.Sc. Physics, M.Sc. Microwaves, and Ph.D. Microwaves all from the Universiti Putra Malaysia in year 2002, 2004, and 2008 respectively. In December 2007, He joined Universiti Tunku Abdul Rahman as

a Lecturer in Department of Electronics and Electrical Engineering. His areas of research include microwave measurement technique, microwave circuit and instrumentation, control and automation, material properties measurement, and instrumentation calibration.



Nashrul Fazli Mohd Nasir received his Bachelor Degree in Biomedical Engineering from Universiti Malaya and later pursued his M.Sc. in Biomedical Engineering at Keele University (UK). He later received his Ph.D. in Electrical Engineering and Computer Engineering from

Royal Melbourne Institution of Technology (RMIT) University, Australia. His research interests are in Biomaterials, Biosensors and Material Characterization in Biomedical Engineering. Currently, he is the Deputy Dean of Students Affair and Alumni for the School of Mechatronic Engineering, Universiti Malaysia Perlis.



Mohd Shukry Abdul Majid has more than 15 years of experience in teaching, research, and industries. He received his B.Eng. in Mechanical Engineering from University Manchester Institute of Science and Technology (UMIST) in 2001. Straight after, he worked as a

Research and Development (R&D) Engineer at a semiconductor industry before joining Universiti Malaysia Perlis (UniMAP) as a Lecturer. He completed his M.Sc. in Mechanical Systems Engineering from the University of Liverpool in 2004 and his Ph.D. in Composite Engineering from Newcastle University, UK in 2011. Currently, he is serving Universiti Malaysia Perlis as an Associate Professor at School of Mechatronic Engineering. His current research interests lie in the strength of material's area with emphasis on the composite piping, looking at the performance of composite structures, NDE's of composites and natural fibre/green composites, hybrid reinforced/filled polymer composites, fire retardant, lignocellulosic reinforced/filled polymer and biodegradable composites. On the other hand, he received his professional engineer qualification (Ir.) from Board of Engineer Malaysia (BEM) in Mac 2016 and has been a Chartered Engineer (CEng) from the Engineering Council, United Kingdom since 2014.



Shing Phan Khor was born in 1982. She obtained her B.Sc. with Edu. (Honours)-Physics in Universiti Putra Malaysia in 2007. She pursued her Ph.D. in Materials Science at the Faculty of Science in 2011 in Universiti Putra Malaysia. Recently, she is a Senior Lecturer at School of

Electrical Systems Engineering, Universiti Malaysia Perlis (UniMAP). Her main personnel research interest is in the glass science and focusing on dielectric, optical, mechanical and thermal properties.