A Quick Approximation Method for Estimating the Dimensions of Patch Antennas using CMA

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Abstract—**In this paper, a quick method for estimating the patch width is presented using CMA. The proposed method can be completed in four steps, based on the relationship between the patch width as the variable and different resonant frequencies, and has been validated using four substrates. This method is advantageous as it facilitates antenna designers in estimating the width of the radiator patch using only CMA without the effects of substrate and excitation. Basically, the generated formula enables the calculation of the actual patch width by simply substituting the width of the patch produced based on one of the CMA's characteristic angle. This parameter which is originally used to find the natural resonant frequency of the structure makes the proposed method time- and resource-efficient. The set of obtained results have been validated to be realistic with satisfactory accuracy.**

Keywords—**CMA, estimate the width, wearable antenna, MoM.**

I. Introduction

Characteristic mode analysis (CMA) been applied to understand the operating principles and use them to optimize the antenna's geometrical structure and performance [1]. The insight provided on the antenna radiating phenomenon makes it an efficient tool for designing antenna [2-3]. On the other hand, flexible textile antennas are gaining increasing attention due to their application in wearable systems [4-6]. Textile antennas are low-profile, thus is considered the best candidate to be integrated within clothing for wireless body area networks (WBANs) [7-8]. Due to the need for a planar configuration for wearable on-body antennas, patch antennas have been one of the most popular choices. For such antennas, their dimensions are critical in determining its operating frequency and final performance. Different methods based on classical formulas (and calculators derived from them) are available to estimate a set of initial dimensions. They can be summarized as follows:

- the transmission-line model (TL) formula which can be used to design conventional patch antennas is explained in [9-10]. This method assumes that the patch antenna is designed with known operating frequency, dielectric constant, and substrate thickness.
- the concept of equivalent design [11-12]. In this method, the dimensions of a rectangular patch antenna is estimated repetitively when designs are made for the same frequency but for different dielectric constants.
- the artificial neural network model (ANN) method is used to estimate the dimensions (length, width) of a rectangular patch antenna. Input parameters include substrate thickness and dielectric constant, resulting in a minimum level of percentage of error was reported in [13].
- the particle swarm optimization technique is used for the precise calculation of the parameters of a rectangular patch antenna. This resulted in resonant frequency and feed point of the antenna with any dimensions and any substrate thickness [14].

This work proposes a method to introduce specific formula for each substrate in sequential steps, based on the simulation results from CMA and method of moment (MoM). These formulas are then used to quickly estimate the patch dimensions when operating at different frequencies based only on the CMA. The proposed relations between the two methods bridges the changes of the natural resonant frequencies contributed by the properties of any substrate materials, and by extension, on its dimensions. Due to this, designers are able to use the end 'calibrated' results to generate specific formulas for each antenna to simply calculate the width of the patch at different operating frequencies. The next section presents the data collection, followed by the generation of formula. Finally, section 3 concludes the proposed work.

II. The Approximate Mathematical Formula

A. Data Collection

The first step in the proposed method is to calculate the patch's width and length based on CMA without including the substrate and excitation. This is followed by the calculation of the patch width and length using MoM, including the substrate and excitation. The collected CMA data can be either the modal significance (MS), characteristic angles (CA), or eigenvalues. MS represents the normalized amplitude of the current modes. A mode is considered at resonance when its modal significance is closer to unity or at least 0.7. Also, CA gives an understanding of the mode behavior near resonance. In this study, CA is chosen as the CMA parameter, as shown in Fig. 1. It is easier to use the CA to investigate the resonance of a structure than the MS parameter. Mode 1 can be observed as a dominant mode, and it becomes more efficient at a specific operating frequency as

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the CA moves closer to 180°. The patch dimension at CA = 180° is then recorded in Tables I to VIII. The previous process is repeated next using MoM, aimed at achieving a minimum reflection coefficient at the operating frequency. The patches dimensions obtained at this step are also recorded. All steps are performed for consecutive frequencies using FEKO software, where simulation is performed for each dimension. Four substrates are used to validate the suggested method, as follows:

1. Felt (with a relative permittivity of ε_r = 1.3, loss tangent ($tan\delta$) =0.044, and thickness = 3 mm).
2. RO4003C substrate (ε_r =3.4, $tan\delta$ = 0.002, and thickness = 0.085 mm).
3. Jeans fabric (ε_r =1.7, $tan\delta$ = 0.085, and thickness = 1 mm).
4. Rogers RT/Duroid 5880 substrate (ε_r = 2.2, $tan\delta$ = 0.0009, and thickness = 0.508 mm).

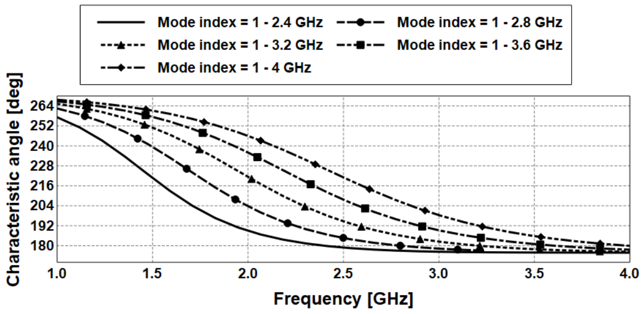

Fig. 1. Characteristic angle of a square patch at different operating frequencies.

The formula proposed for each substrate facilitates the estimation of the patch dimensions without the effects of the substrate, ground, and excitation. In turn, this process makes the overall design process more time efficient. Besides being not limited to traditional patches, this method can also be used to estimate the dimensions for the patch with multiple slots if the dominant modes are correctly excited. The patch dimensions from each substrate type are presented in Tables I to IV. A systematic procedure of the proposed method is summarized in Fig. 2.

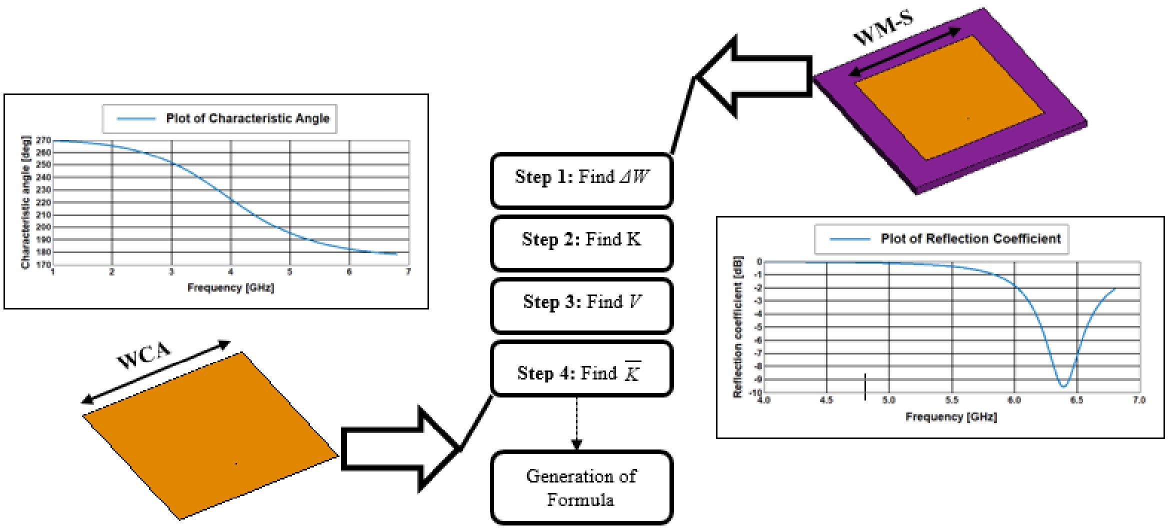

Fig. 2. Summarized the process of generation formula.

TABLE I
PATCH WIDTH ESTIMATION ON FELT SUBSTRATE USING CMA

f (GHz)	*WCA* (mm)	*WM-S* (mm)	ΔW = *WCA* – *WM-S* (mm)	K = *WM-S* / ΔW	*WM-F* (mm)	D = |*WM-S* – *WM-F*| (mm)
2.4	70	**48.7**	21.3	2.28	**48.4**	0.3
2.6	64.7	**44.71**	19.99	2.23	**44.69**	0.02
2.8	60	**41.5**	18.5	2.24	**41.4**	0.1
3.0	56	**38.62**	17.38	2.22	**38.6**	0.02
3.2	52.3	**36.04**	16.26	2.21	**36.01**	0.03
3.4	49.3	**33.91**	15.39	2.2	**33.91**	0
3.6	46.5	**31.96**	14.54	2.19	**31.95**	0.01
3.8	44.1	**30.26**	13.84	2.18	**30.27**	0.01
4.0	42	**28.8**	13.2	2.18	**28.8**	0

TABLE II
PATCH WIDTH ESTIMATION ON A RO4003C SUBSTRTAE USING CMA

f (GHz)	WCA (mm)	$WM\text{-}S$ (mm)	$\Delta W = WCA - WM\text{-}S$ (mm)	$K = WM\text{-}S / \Delta W$	$WM\text{-}F$ (mm)	$D = \lvert WM\text{-}S - WM\text{-}F \rvert$ (mm)
2.4	70	**34.5**	35.5	0.97	**34.7**	0.2
2.6	64.7	**31.89**	32.81	0.97	**31.94**	0.05
2.8	60	**29.3**	30.7	0.95	**29.5**	0.2
3.0	56	**27.4**	28.6	0.95	**27.42**	0.02
3.2	52.3	**25.47**	26.83	0.94	**25.49**	0.02
3.4	49.3	**23.88**	25.42	0.93	**23.93**	0.05
3.6	46.5	**22.4**	24.1	0.92	**22.48**	0.08
3.8	44.1	**21.1**	23	0.91	**21.23**	0.13
4.0	42	**20.03**	21.97	0.91	**20.14**	0.11

TABLE III
PATCH WIDTH ESTIMATION ON JEANS FABRIC USING CMA

f (GHz)	WCA (mm)	$WM\text{-}S$ (mm)	$\Delta W = WCA - WM\text{-}S$ (mm)	$K = WM\text{-}S / \Delta W$	$WM\text{-}F$ (mm)	$D = \lvert WM\text{-}S - WM\text{-}F \rvert$ (mm)
2.4	70	**44.75**	25.25	1.77	**44.65**	0.1
2.6	64.7	**41.3**	23.4	1.76	**41.205**	0.095
2.8	60	**38.2**	21.8	1.75	**38.15**	0.05
3.0	56	**35.57**	20.43	1.74	**35.55**	0.02
3.2	52.3	**33.2**	19.1	1.73	**33.143**	0.055
3.4	49.3	**31.22**	18.08	1.72	**31.195**	0.025
3.6	46.5	**29.4**	17.1	1.71	**29.375**	0.025
3.8	44.1	**27.82**	16.28	1.7	**27.815**	0.005
4.0	42	**26.5**	15.5	1.7	**26.45**	0.05

TABLE IV
PATCH WIDTH ESTIMATION ON ROGERS RT/Duroid 5880 SUBSTRATE USING CMA

f (GHz)	WCA (mm)	$WM\text{-}S$ (mm)	$\Delta W = WCA - WM\text{-}S$ (mm)	$K = WM\text{-}S / \Delta W$	$WM\text{-}F$ (mm)	$D = \lvert WM\text{-}S - WM\text{-}F \rvert$ (mm)
2.4	70	**41.6**	28.4	1.46	**41.6**	0
2.6	64.7	**38.35**	26.35	1.45	**38.367**	0.017
2.8	60	**35.48**	24.52	1.44	**35.5**	0.02
3.0	56	**33**	23	1.43	**33.06**	0.06
3.2	52.3	**30.8**	21.5	1.43	**30.803**	0.003
3.4	49.3	**28.97**	20.33	1.42	**28.973**	0.003
3.6	46.5	**27.265**	19.235	1.41	**27.265**	0
3.8	44.1	**25.8**	18.3	1.4	**25.801**	0.001
4.0	42	**24.51**	17.49	1.4	**24.52**	0.01

B. *Generation of Formula*

The formulas to perform these estimations are derived as follows.

$$\Delta W = W_{CA} - W_{M\text{-}S} \tag{1}$$

where W_{CA} is the width of the patch calculated using the CMA method without substrate and excitation, and $W_{M\text{-}S}$ is the width of the patch calculated using MoM (with substrate and excitation). Then, the ratio between the patch width produced by a full-wave analysis to the difference between the width values produced by CMA and full-wave analysis, K can be calculated as:

$$K \approx Average\ [W_{M\text{-}S} / \Delta W] \tag{2}$$

Next, the general form of the proposed formula, $W_{M\text{-}F}$ is calculated as:

$$W_{M\text{-}F} = [KW_{CA} / \overline{K}\ ]\text{-}V \tag{3}$$

where $V = \varepsilon_r / 2$ represents the value of substrate permittivity divided by 2, and $\overline{K}$ represents the value of k with an estimated correction factor (R) which varies between (0.8 to 0.9) for all substrates, calculated as:

$$\overline{K} = K + R \tag{4}$$

Finally, the deviation between the patch width value in simulation and the proposed formula, D, is used to determine the accuracy of the proposed method, as follows:

$$D = W_{M\text{-}S} - W_{M\text{-}F} \tag{5}$$

The final step is to collect all data and use them to estimate a set of customized formula for each substrate, as presented in Table V. These simple closed-form formulas provide satisfactory accuracy in estimating the patch dimensions. As shown in Fig. 3, the rate of the deviations in dimension between the values obtained from the formula and the actual value varies depending on the operating frequencies. It can be seen that the value of the deviation is relatively higher at some of the operating frequencies due to the effect of dielectric constant, thicknesses, and dimensions of the substrate used. However, their variations are less than 0.5 mm, which indicates the accuracy of the proposed formula in estimating the patch dimensions.

TABLE V
PROPOSED FORMULAS FOR DIFFERENT SUBSTRATE MATERIALS

Substrate	Dielectric constant (ε_r)	Loss tangent ($tan\delta$)	Thickness (mm)	Proposed formula
Felt	1.3	0.044	3	WM-F = (0.7WCA)-0.6
RO4003C	3.4	0.002	0.085	WM-F = (0.52WCA)-1.7
Fabric Jeans	1.7	0.085	1	WM-F = (0.65WCA)-0.85
Rogers RT/Duroid 5880	2.2	0.0009	0.508	WM-F = (0.61WCA)-1.1

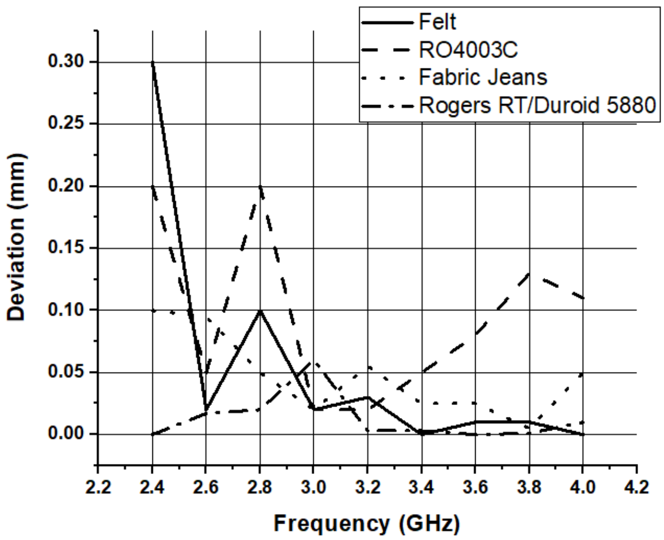

Fig. 3. Deviation results at different substrates

III. CONCLUSIONS

In this paper, a new procedure based on the CMA technique to quickly estimate the dimensions of the patch on different substrate materials is presented. Four steps are proposed to create the formula by finding a relationship between the variable data obtained at different resonant frequencies. This enables the quick estimation of the dimensions of the patch using CMA without including the substrate and excitation.

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