Characteristics of a Cutoff Cavity Probe Applicable to Crack Detection Using the Forced Resonance Microwave Method

Ki-Chai Kim^{1,*} · Jong-Woo Kim² · Jae-Yong Kwon³ · No-Weon Kang³

Abstract

This paper presents the current characteristics inside a cutoff cavity slot probe applied to crack detection using the forced resonance microwave method (FRMM). Crack detection using FRMM has two stages: preparation and detection. In the preparation stage, the current characteristics inside the probe with a shorting plate are important for determining the crack signal and detection sensitivity. The cutoff cavity probe produces a forced resonance by adjusting a control element. There are two kinds of forced resonance: series resonance (SR) and parallel resonance (PR). Four types of current characteristics are applied to crack detection using FRMM: SR, the region around SR, the region around PR, and non-resonance. These current characteristics are discussed from the point of view of current change for crack detection. The experimental results are compared with the theoretical results to check the current state inside the cutoff cavity probe.

Key Words: Crack Detection, Cutoff Cavity, Forced Resonance, Microwave Method, Nondestructive Testing.

I. INTRODUCTION

Several nondestructive testing (NDT) techniques can be used to detect surface cracks in metal materials. These techniques include eddy current testing, AC (alternating current) field measurement, acoustic emission testing, and ultrasonic testing [1–3]. Cracks in metal that are concealed by paint, composite laminates, corrosion protection substances, and rust can be detected easily using microwave techniques compared with other techniques. Studies have shown that nondestructive surface crack detection at the microwave and mm-wave frequencies is capable of detecting and sizing surface cracks in metals [4–9]. In

[4], an open-ended waveguide operating at 20 GHz was utilized as a sensor to detect smaller surface cracks, such as fatigue cracks from changes in the reflection coefficient. However, it can easily be affected by noise, air gap, and other factors [5]. To resolve this problem, several critical parameters of the open-ended waveguide technique have been investigated [6, 7]. To obtain a higher spatial resolution, the open-ended waveguide technique needs to be used at higher frequencies [8]. Alternatively, open-ended coaxial probes have also been examined [9]. Recently, resonant probes have been reported to design near-field sensors for crack detection in metallic materials [10]. Resonant probes provide many advantages compared with other probes based on measure-

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ing changes in the reflection coefficient. Several technologies with resonant probes for crack detection have been reported, including a microstrip linear resonator, a quarter-wavelength microstrip line, a dual-behavior resonator filter, and a complementary split-ring resonator [11–14]. A more general review of state-of-the-art NDT techniques using microwave technologies is described in [15]. These techniques require a vector network analyzer (VNA), which makes the application of these types of probes difficult from a practical standpoint.

Conversely, cutoff cavity probes using forced resonance have been utilized for crack detection in metallic materials [16]. This method is called the forced resonance microwave method (FRMM). The advantage of this method is that VNA is not required, and thus the crack detection system can be established at low cost. FRMM consists of two stages: preparation and detection. It uses the current deviation from the resonance state for the cutoff cavity probe without a crack (corresponding to the preparation stage) and with a crack (corresponding to the detection stage). Therefore, knowledge of the current characteristics and the forced resonance modes of the cutoff-cavity probe in the preparation stage is needed as a reference to obtain the crack signals.

This paper presents the current states of the forced resonance of the cutoff cavity applied to crack detection using FRMM. The cutoff-cavity probe produces forced resonance by adjusting a control element. There are two kinds of forced resonance: series resonance (SR) and parallel resonance (PR). The SR causes a maximum current, and the PR and the region surrounding it produce sluggishly gradient currents. The steepest gradient currents occur around the SR. The minimum current occurs at non-resonance (NR) using the control element. Therefore, there are four types of current states in FRMM: maximum current (at the SR), minimum current (at the NR), rapidly changing current (around the SR), and slowly changing current (at the PR and around it). These current characteristics have been classified. The FRMM mainly uses SR, but PR and NR can also be used for crack detection. However, PR and NR are not as advantageous as SR. To verify the current state inside the cutoff cavity, the experimental results are compared with the theoretical results.

II. SYSTEM DESCRIPTION

The geometry of the surface crack detection system is shown in Fig. 1. The detection system consists of four parts: (1) the cutoff cavity-backed narrow slot probe with internal posts #1 and #2, (2) the external control element jX_1 for cavity resonance control, (3) the signal generator, and (4) the detector for reading the current states on post #2 and the crack signals. A voltmeter or an ammeter can be used as a detector. In Fig. 1(a),

Fig. 1. A cutoff cavity-backed slot probe for crack detection. (a) In the detection stage, the cavity probe and metal are in perfect contact and scanned on the metal surface. (b) In the preparation stage, the probe is enclosed by a shorting plate.

the probe and metal are presented separately, but in actual detection, they are in perfect contact. In the preparation stage, the slot is short, and the probe becomes a perfect cavity, as shown in Fig. 1(b).

The probe dimensions are chosen such that the cross-section $a \times b$ of the cavity corresponds to the cutoff condition for the waveguide of the same cross-section when the cavity is empty. For this reason, it is called a *cutoff cavity*. In the probe, a feed post (#1) of radius r_1 is located at $x = t_1$ and $z = s_1$. The external control element jX_1 acts as a reactance element and is connected to the top of the feed post. A detector is connected to the bottom of the parasitic post (#2) of radius r_2 at $x = t_2$ and $z = s_2$. The detector is used to check the desired forced resonance or non-resonance currents and to measure the output crack signals. Each parameter referenced in Fig. 1 is listed in Table 1.

To obtain the forced resonance and non-resonance current characteristics, Galerkin's method of moments (MoM) is used to solve the integral equations for the current distributions on the two posts inside the probe. For the evaluation of the forced resonance characteristics, a two-port network representation is used with admittance parameters to derive the deterministic equation for the length of the control element, as described in Section III-2.

Table 1. Geometric parameters

Parameter	Value (mm)
Cavity width, a	40
Cavity height, b	20
Cavity depth, c	80
x position of the feed post #1, t_1	20
x position of the parasitic post #2, t_2	20
z position of the feed post #1, S_1	30
z position of the parasitic post #2, S_2	60
Radius of the feed post #1, r_1	1
Radius of the parasitic post #2, r_2	1
Slot center position, y_s	10
Crack center position, y_c	–
Slot width, W_s	5
Slot length, L_s	40
Crack width, W	1
Crack length, L	40
Crack depth, d	1
External reactance, X_1	Variable
Detector impedance, Z_M	5 k Ω

III. THEORETICAL ANALYSIS OF FRMM

1. Integral Equations

As shown in Fig. 1(b), for the preparation stage, the probe with a metal shorting plate in the absence of a crack resonates forcefully in the cutoff cavity using the control element jX_1 connected to the top of feed post #1. The voltage V_1 is applied at $y = 0$, $x = t_1$, and $z = s_1$. The detector is also connected to the bottom of parasitic post #2 at $y = 0$, $x = t_2$, and $z = s_2$.

If the cutoff cavity is fed by a delta gap generator as a voltage source, the integral equations for the unknown electric currents $\bar{J}_1$ and $\bar{J}_2$ on feed post #1 and parasitic post #2 can be respectively written as follows:

$$\iint_{S'_1} \bar{K}_{ee11}^I \cdot \bar{J}_1 dS'_1 + \iint_{S'_2} \bar{K}_{ee12}^I \cdot \bar{J}_2 dS'_2 = -\hat{y}V_1\delta(y) + \hat{y}jX_1I_1(b)\delta(y-b) \quad (1)$$

$$\iint_{S'_1} \bar{K}_{ee21}^I \cdot \bar{J}_1 dS'_1 + \iint_{S'_2} \bar{K}_{ee22}^I \cdot \bar{J}_2 dS'_2 = -\hat{y}Z_M I_2(0)\delta(y) \quad (2)$$

where $\bar{K}_{eeij}^I$ ($i, j = 1$ or 2) is the dyadic Green function in region I (inside the cavity), which yields the electric field due to the current source. Superscript I denotes cavity region I, and subscripts 1 and 2 represent feed post #1 and parasitic post #2, respectively. $\delta(*)$ is the Dirac delta function, and $\hat{y}$ is a unit

vector in the y -direction. $I_2(0)$ is the current at the ammeter loading position, and $I_1(b)$ is the current at the loading positions of control element jX_1 . Z_M is the impedance of the detector. For convenience and simplicity, the current $I_2(0)$ at the ammeter loading position is expressed as I_{2L} .

To solve the simultaneous integral equations for the unknowns, $\bar{J}_1$ and $\bar{J}_2$ are expanded as follows:

$$\bar{J}_1(y) = \hat{y} \sum_{k=0}^K a_{1k} \cos\left(\frac{k\pi y}{b}\right) \quad (3)$$

$$\bar{J}_2(y) = \hat{y} \sum_{l=0}^L a_{2l} \cos\left(\frac{l\pi y}{b}\right) \quad (4)$$

where a_{1k} and a_{2l} are complex expansion coefficients. The integral equations are solved by applying Galerkin's MoM. Once the current distributions on the internal posts are obtained, the forced resonance characteristics can be considered for the probe by adjusting the control element.

2. Forced Resonance of Cutoff Cavity

When the probe is short-circuited with a shorting plate, we can obtain the forced resonance characteristics by treating the cutoff cavity as a two-port network, with a voltage applied at port 1 and the control element at port 2, as shown in Fig. 1. The relations between the terminal voltages and currents at each port can be expressed using admittance parameters y_{ij} ($i, j = 1, 2$):

$$\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} y_{11} & -y_{12} \\ -y_{21} & y_{22} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}. \quad (5)$$

The terminal voltage at port 2 can be expressed as $i_2 = -(1/jX_1)v_2 = -Y_1 v_2$, as a reactance element is connected to port 2. Therefore, by putting this relationship in (5), we can obtain the input impedance at the driving point in the following form:

$$Z_{in} = \frac{(y_{22} + Y_1)}{y_{11}(y_{22} + Y_1) - y_{12}^2}. \quad (6)$$

If the above impedance expression is used, the resonant condition of the cutoff cavity is

$$\text{Im}\{Z_{in}(y_{ij}, jX_1)\} = 0. \quad (7)$$

The short-circuited transmission line with the characteristic impedance Z_0 and length h_1 constitutes the control element (reactance element). Therefore, the expression for the reactance is $jX_1 = jZ_0 \tan(kh_1)$, where k is the propagation constant of the two parallel wires.

The reactance of the control element that forcibly resonates the cutoff cavity can be obtained from (7). Thus, the length of the reactance that resonates with the cutoff cavity can be expressed as:

$$kh_1 = \tan^{-1} \left\{ \frac{2y_{11}^I}{Z_0 \left(-F \pm \sqrt{E^2 - 4y_{11}^I H} \right)} \right\} \quad (8)$$

where

$$F = y_{12}^I y_{21}^I - 2y_{11}^I y_{22}^I - y_{12}^R y_{21}^R \quad (9)$$

$$H = y_{22}^I y_{11}^I y_{22}^I + y_{22}^I y_{12}^R y_{21}^R - y_{22}^I y_{12}^I y_{21}^I + y_{22}^R y_{11}^I y_{22}^I - y_{22}^R y_{12}^I y_{21}^I \quad (10)$$

y_{ij}^R and y_{ij}^I are the real and imaginary parts of y_{ij} , respectively. In (8), the positive and negative signs in the denominator produce SR and PR, respectively.

IV. THEORETICAL RESULTS AND CLASSIFICATION OF CURRENT STATES

1. Forced Resonance Characteristics

The dimensions of the cutoff cavity probe used in the numeric calculation are $a = 40$ mm, $b = 20$ mm, $c = 80$ mm, $s_1 = 30$ mm, $s_2 = 60$ mm, $t_1 = t_2 = a/2$, and $r_1 = r_2 = 1$ mm. The operating frequencies are 1 GHz and 2 GHz, and the dimension $a = 40$ mm (cutoff frequency 3.75 GHz) meets the cutoff conditions for these frequencies. An ammeter is used as a detector, but a voltmeter can also be used. The ammeter and a diode detect the crack signals rectified by the high-frequency diodes (1SS99; NEC Corp., Tokyo, Japan) connected to parasitic post #2. Their impedance is $Z_M = 5.23$ k Ω [5 k Ω (ammeter) + 230 Ω (diode)].

The probe can resonate forcefully in SR or PR by adjusting the control element according to (8), and SR is used for crack detection [16]. This paper presents the current states of the forced resonance of the cutoff cavity for crack detection using FRMM.

Fig. 2 shows the frequency characteristics of the length of the control element, $jX_1 = jZ_0 \tan(kh_1)$, which occurs with forced resonance from (8) when the cutoff cavity probe resonates forcefully from adjusting the control element for the ammeter ($Z_M = 5.23$ k Ω) connection. For the ammeter connection at 1 GHz, SR and PR occur at $kh_1 = 1.936$ ($X_1 = -130.77$ Ω) and $kh_1 = 0.971$ ($X_1 = 73.18$ Ω), respectively. At 2 GHz, SR occurs at $kh_1 = 1.411$ ($X_1 = 310.71$ Ω), and PR occurs at $kh_1 = 2.134$ ($X_1 = -79.17$ Ω). These resonance modes are summarized in Table 2.

As shown in Fig. 2, the cutoff cavity probe generates SR or PR at given frequencies by adjusting the control element jX_1 for the ammeter connection. The PR for the ammeter connection occurs at $kh_1 \approx 0$ ($X_1 \approx 0$ Ω) at around 1.60 GHz, as shown in Fig. 2. The frequency of 1.60 GHz is critical for determining the resonance. The vicinity of 1.60 GHz is sensitive when obtaining the resonance by adjusting the control element and should not be in the crack detection using FRMM. The characteristics of a voltmeter connection are almost the same as those of the ammeter connection. As mentioned previously, the forced resonances other than those at 1.60 GHz are useful for crack detection by the FRMM. It is necessary to analyze the

Fig. 2. Frequency characteristics of (a) the reactance and (b) length of the control element (kh_1) for an ammeter as a detector.

Table 2. Resonance modes of the cutoff cavity probe

Resonance frequency (GHz)	Type of resonance	External reactance (Ω)	kh_1
1	SR	-130.77	1.936
	PR	73.18	0.971
	NR	192.76	1.317
2	SR	310.71	1.411
	PR	-79.17	2.134
	NR	95.39	1.088

current states of the cutoff cavity probe at the resonance and around it. Knowledge of the input impedance characteristic of the cutoff cavity and the detector current (the ammeter connection point current) is needed to check the types of resonance.

Fig. 3 shows the detector current and input reactance versus the length of the control reactance when the operating frequency is fixed at 1 GHz and 2 GHz as an example. To determine whether SR or PR is occurring, it also shows the input reactance of the cutoff cavity probe. As shown in Fig. 3(a), for the ammeter connection at 1 GHz, SR occurs when $kh_1 = 1.936$ ($X_1 = -130.77$ Ω). The maximum current state also occurs.

Fig. 3. Load current and input reactance of the cutoff cavity probe versus control element length: (a) 1 GHz and (b) 2 GHz.

PR occurs when $kh_1 = 0.971$ ($X_1 = 73.18 \Omega$), and the current state slowly changes. The minimum current (≈ 0 mA) appears when $kh_1 = 1.317$ ($X_1 = 192.76 \Omega$), which is the NR state. For the ammeter connection at 2 GHz shown in Fig. 3(b), SR occurs when $kh_1 = 1.411$ ($X_1 = 310.71 \Omega$), and the input reactance, X_{in} , changes from capacitive to inductive. The maximum current state occurs. PR occurs when $kh_1 = 2.134$ ($X_1 = -79.17 \Omega$), and the input reactance changes from inductive to capacitive. The current state slowly changes. The detector current also appears to be minimized (≈ 0 mA) at $kh_1 = 1.088$ ($X_1 = 95.39 \Omega$), which is the NR state.

2. Classification of Current States

Based on the current states for the ammeter connection in Fig. 3, the current states of the cutoff cavity probe have a maximum current (at SR), minimum current (at NR), rapidly changing current (around SR), and slowly changing current (at PR and around it). These detector current states and resonant types are illustrated in Fig. 4. There are four kinds of current states: (1) SR with maximum current, (2) PR and the surrounding region, which has a slowly changing current, (3) NR with minimum current, and (4) region around the SR with a rapidly changing

Fig. 4. Current configuration.

current. These current states are applicable to crack detection using FRMM. One of the four current states can be used for more sensitive crack detection when setting the reference current in the preparation stage. Crack signals are detected from the deviations of the reference current.

Fig. 5 shows the classification of resonant types and directions of the detector needle movement as the crack signal appears with the four current states in the crack detection stage. Fig. 5(a) shows the three types of resonance: (1) forced resonance (SR and PR), (2) NR, and (3) region around the forced resonance. As mentioned previously, SR has the maximum current, NR has the minimum current, PR and the surrounding region have a slowly changing current, and the region around the SR has a rapidly changing current, as shown in Fig. 4. For these current states, the directions of the needle movement are shown in Fig. 5(b). The needle moves in the lower or upper direction depending on the state of crack at a given frequency. The needle movement direction should be discussed in detail at the crack detection stage. However, this paper presents only one example. The needle movement directions for the crack of $W = 1$ mm and $d = 1$ mm are shown in Fig. 5(b). In this case, when the probe scans a crack in the detection stage, the needle moves in the lower directional movement if we use SR (maximum current) and NR (minimum current). For PR (slowly changing current), the needle moves in the upper direction. Using the region around SR (rapidly changing current) and around PR (slowly changing current), the needle also moves in the upper directions when the probe scans a crack. To check the needle movement shown in Fig. 5(b), the experimental results for the crack of $W = 1$ mm and $d = 1$ mm at 1 GHz are shown in Table 3. As a future study on the detection stage, more detailed research on the movement direction of the needle for various crack dimensions is needed.

As a result, using SR and the region around SR leads to the best sensitivity for crack detection, as the current changes have the steepest gradient. PR and the region around the PR can be used for crack detection, but sensitivity is lower than that of the

Fig. 5. Classification of (a) resonant types and (b) movement directions of a needle according to the current configuration.

Table 3. Experimental results of the movement direction of the needle

Type of resonance	Reference $ I_{2L} $ (μA)	Crack signal (μA)	kh_1	Movement direction of the needle
Around SR	16.50	16.80	1.908	→
SR	17.20	16.90	1.936	←
Around SR	15.10	15.40	1.971	→
Around PR	0.69	0.84	0.923	→
PR	0.60	0.75	0.971	→
Around PR	0.45	0.60	1.020	→
NR	0.12	0.02	1.317	←

region around the SR. Using NR is also possible, but sensitivity will be even lower. Therefore, PR and NR can also be used for crack detection, but they are not as advantageous as SR.

Based on the classification of resonant types, the result of crack detection using SR is presented in [16], and the results of crack detection using the other resonant types are given in [17, 18].

V. EXPERIMENTS

To validate the forced resonance and non-resonance currents of the probe, the calculated resonant currents were compared with the measured currents. The cutoff cavity was made with copper using electroforming technology and plated with gold, and a coaxial sliding short (Model 1909C2 at 0.8–4 GHz; Maury Microwave Corp., Ontario, CA, USA) was used as a control element. The dimensions of the cutoff cavity used in the experiments are $a = 40$ mm, $b = 20$ mm, $c = 80$ mm, $s_1 = 30$ mm, $s_2 = 60$ mm, $t_1 = t_2 = a/2$, and $r_1 = r_2 = 1$ mm. An NEC 1SS99 diode and ammeter ($20 \mu A$ range) were connected to the parasitic post. The operating frequency used was 1 GHz, and the length of the control element was adjusted to obtain the forced resonance in the cutoff cavity.

Fig. 6 shows a photograph of the manufactured cutoff cavity probe with the control element and experimental setup. Fig. 7 shows the calculated and measured resonance currents for the ammeter connection. The calculated currents showed a reasonable agreement with the experimental results. The deviation could be due to the losses of the cutoff cavity and the control element and the effect of fabrication errors.

VI. CONCLUSION

This study considered the forced resonance characteristics of a cutoff cavity probe that could be applied to crack detection

Fig. 6. Photograph of the experimental setup.

Fig. 7. Measured detector currents.

using FRMM. There were four kinds of current states: maximum current (at the SR), minimum current (at the NR), rapidly changing current (around the SR), and slowly changing current (at the PR and around the PR). These current characteristics were classified. The SR (maximum current) and the region around SR were the most applicable current states. The NR, PR, and the region around PR are also available for crack detection, but their sensitivity is lower than that of SR and the surrounding region. The actual crack detection using these current states can be examined in future works.

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