

Theoretical Analysis of the Rectangular Defect Orientation using Magnetic Flux Leakage

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This paper presents an approach to estimate the orientation of the rectangular defect in the ferromagnetic specimen using the magnetic flux leakage technique. Three components of the magnetic flux leakage profile, such as radial, axial, and tangential component are considered to estimate the orientation of the rectangular defect. The orientation of the rectangular defect is estimated by the proposed analytical model using MATLAB software. The results calculated by the analytical model are validated by the three-dimensional finite element analysis using COMSOL Multiphysics software. Tangential component provides better performance to estimate the orientation of the rectangular defect compared with radial and axial component of the magnetic flux leakage profile.

Keywords: Magnetic flux leakage, orientation of the defect, radial component, axial component, tangential component, finite element analysis.

1. INTRODUCTION

Magnetic Flux Leakage (MFL) technique is a well-established Non-Destructive Testing (NDT) method to detect the surface and subsurface defects in the ferromagnetic material. The basic principle of the MFL is that a specimen under inspection is magnetized near saturation under the applied magnetic field. If there is no defect on the specimen, the majority of the magnetic flux lines pass through the specimen material itself, in contrast, the leakage field is created due to the smaller permeability in the defect region [1]-[4]. Three major vector components of the leakage profile are radial, axial, and tangential. The geometry of the defect and its dimension may change the pattern of the three components [5], [6]. Forward and Inverse approach are referred to in the MFL inspection technique. Dipole based analytical model and finite element based numerical model provide the solution for a forward approach. In this work, forward approach is considered to detect the orientation of the rectangular shaped defect. In forward approach, the MFL testing is performed in the calibrated sample with a known defect and the pattern of the leakage profile is recorded. The data obtained through the in-situ inspection of the specimen in literature are compared with the MFL profile generated by the calibrated samples. Recording the pattern of the leakage profile for the known defect in forward approach is not necessary when the dipole model is considered [2], [7]. Zatspein et al. (1966)

introduced an analytical model using the point or strip of dipole for rectangular shape defect [8]. The magnitude of the leakage profile and the externally applied field are not considered. Later on, Shcherbinin et al. (1972) extended the Zatspein model by considering the 3-D rectangular shape defect with finite size. The maximum amplitude of the radial and axial components of leakage profile in the symmetry axis was considered and the size of the defect was not discussed. [9]. Forster et al. (1986) improved the model of Shcherbinin for the same type of defect by considering the magnitude of the applied field and magnetic property of the specimen [10]. Minkov et al. (2002) applied the dipolar model to 3-D rectangular defect and reported that the strength of the radial component leakage profile is directly proportional to the depth of the defect [11]. Sushant.

Dutta et al. (2009) proposed a 3-D analytical model for surface breaking in ferromagnetic specimen which has a maximum magnitude for radial component rather than for axial and tangential. Leakage signal prediction and defect characterization were also performed using the analytical model [12]. Maryam Ravan et al. (2010) developed an analytical model for the arbitrary defect sizing. The main drawback of that method is longer computation time [13]. Wenhua Han et al. (2014) developed an algorithm to estimate the two-dimensional defect in fast manner and the length of the defect is not considered [14]. Dipole model was developed to measure the alternating magnetic field

created for circular type defect in the titanium alloy pipe. The eddy current principle is used in this study. Distorted eddy current in the defect region generates the alternating magnetic field in the radial direction of the pipeline. Volumetric studies are performed to validate the analytical model along with the finite element method and experimental method [4]. Analytical model for the radial component of the leakage profile is proposed and lift-off study is also performed. Estimation of the defect from analytical model is correlated with the actual defect parameter. Performance of the analytical model is validated through experimental results [5]. The performance of the radial and axial component of non-orientated rectangular defect is analyzed and we conclude that the radial component provides excellent performance to estimate the length and depth of the defect [15]. COMSOL Multiphysics software is employed to estimate the crack depth using alternating current potential drop technique [16]. The effect of defect orientation of the steel plates was studied and the influence of the orientation was estimated in terms of crack propagation [17].

In general, the rectangular defect was presented with orientation on the specimen. In this research work analytical model is proposed to estimate the orientation of the rectangular defect using the three components of the leakage profile. Among the three components, tangential component provides the good performance to estimate the orientation of the defect. For validation, the finite element studies are performed by using COMSOL Multiphysics software.

2. ANALYTICAL MODEL FOR THREE COMPONENTS OF MFL

Fig.1. shows the rectangular shape defect on the steel slab with the notation of length '2l', width '2w', and depth 'd'. The angle between the discontinuity orientation and magnetization direction is represented by 'β'.

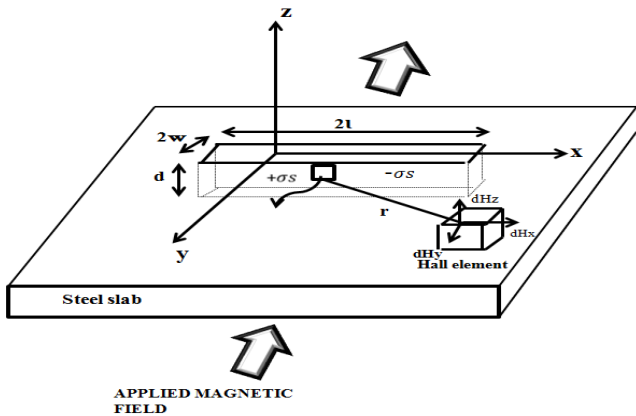


Fig.1. Dipolar representation of rectangular defect.

Three components of the leakage profile are represented as axial component 'B_x', tangential component 'B_y', and radial component 'B_z'. The orientation of the defect may affect the three components of the leakage profile. The Axial (x'),

tangential (y'), and radial (z') component of the magnetic field at a point with coordinates x', y', and z' is given by

$$B_x(\beta) = \frac{\sin^2 \beta \sigma_{ms}}{2\pi\mu_0}$$

$$\left[\arctan \frac{d(x'\sin\beta + b)}{(x'\sin\beta + b)^2 + z'(z' + d)} \right. \\ \left. - \arctan \frac{(x'\sin\beta - b)}{(x'\sin\beta - b)^2 + z'(z' + d)} \right] \quad (1)$$

$$B_y(\beta) = \frac{\sin\beta \cos\beta \sigma_{ms}}{2\pi\mu_0}$$

$$\left[\arctan \frac{d(x'\sin\beta + b)}{(x'\sin\beta + b)^2 + z'(z' + d)} \right. \\ \left. - \arctan \frac{(x'\sin\beta - b)}{(x'\sin\beta - b)^2 + z'(z' + d)} \right] \quad (2)$$

$$B_z(\beta) = \frac{\sin\beta \sigma_{ms}}{4\pi\mu_0}$$

$$\left[\ln \frac{(x'\sin\beta + b)^2 + (z' + d)^2}{(x'\sin\beta - b)^2 + (z' + d)^2} \right. \\ \left. + \ln \frac{(x'\sin\beta - b)^2 + z'^2}{(x'\sin\beta + b)^2 + z'^2} \right] \quad (3)$$

To analyze the MFL signal characteristics of the discontinuity in a different orientation, the length 2l, the width 2w, depth d, lift-off z', and $\sigma_{ms}/4\pi\mu$ were assumed to be 2 cm, 1.5 cm, 0.50 cm, 1 mm and 1, respectively. The B_x(β), B_y(β), and B_z(β) are calculated for the orientation angle β from 0 to 90 degrees.

From Fig.2. it is observed that the magnitude of the three components of the MFL signal varied for the different orientations of the defect. The defect orientation angle β is increased from 0 to 90 degrees and the analytical model output is observed. The amplitude of the axial and radial component is increased and very minor magnitude changes in the 75, 80 and 90-degree orientation are observed. The amplitude of the tangential component is first increased from 0 to 45-degree orientation and then decreased from 45 to 90 degrees. Polynomial expression for axial, radial, and tangential component of the leakage profile is derived using the magnitude of the leakage profile. Tangential component has two polynomial expressions, the expression (6a) is used to estimate the orientation from 0 to 45 degrees and the expression (6b) is used to estimate the orientation from 46 to 90 degrees.

$$axial \ angle = 33B_x^3 - 69B_x^2 + 107B_x + 3 \quad (4)$$

$$radial \ angle = 2B_z^3 - 6B_z^2 + 21B_z + 1 \quad (5)$$

$$tangential \ angle = -242B_y^3 + 286B_y - 74 \quad (6a)$$

$$tangential \ angle = 222B_y^3 + 286B_y^2 - 28B_y + 90 \quad (6b)$$

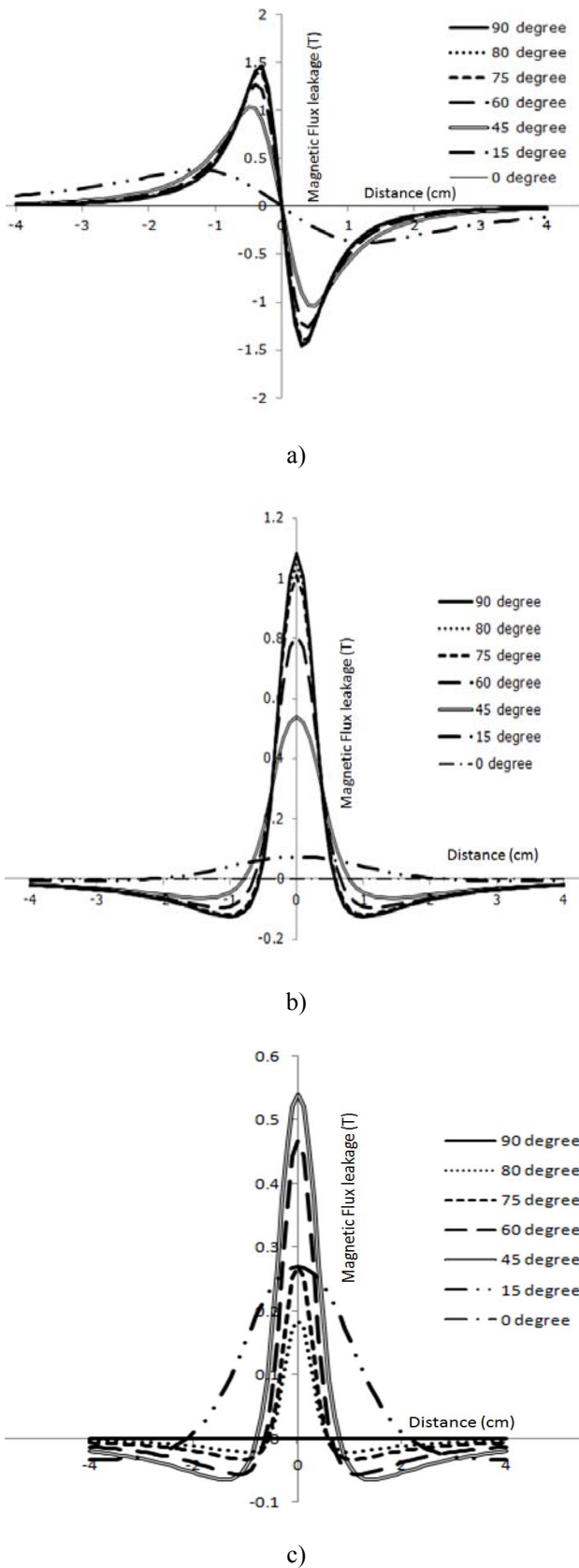


Fig.2. MFL profile of analytical model output for the different orientation of discontinuity
a) Axial profile, b) radial profile, c) tangential profile.

Error percentage of the three components of the MFL profile during the estimation of the angle is shown in Table 1. The average error percentage of the radial and axial leakage profile component is '13' and '7'. When comparing axial and radial component, the axial component has less average error percentage. It is observed that the radial component failed to estimate the orientation of the defect. Among the three components, tangential leakage profile provides better estimation. Axial and tangential components are considered to estimate the defect orientation in numerical studies.

Table 1. Estimated error % for orientation of three profiles.

Actual angle (degree)	Estimated angle for Axial (degree)	Estimated angle for Radial (degree)	Estimated angle for Tangential (degree)	Error (%) for Axial profile	Error (%) for Radial profile	Error (%) for tangential profile
15	10	17	15	33	46	0
45	47	39	45	4	13	0
60	60	67	60	0	11	0
75	71	78	75	5	4	0
80	81	79	80	1	1	0
90	89	82	90	1	8	0

3. NUMERICAL MODEL FOR TANGENTIAL AND AXIAL COMPONENT OF MFL

The finite element approach is an efficient method to identify the defect on the inspected specimen. Three-dimensional finite element studies are performed to validate the proposed analytical model. COMSOL Mutiphysics 4.3a modeling software is utilized to implement the finite element analysis. AC/DC module of the software is facilitated to compute the electric and magnetic field analysis on the inspected specimen. Fig.3. shows the three-dimensional geometry of 15-degree oriented rectangular defect on the rectangular ferromagnetic steel slab with permanent magnet. The length, width and thickness of the ferromagnetic steel slab are 100 cm x 100 cm x 15cm. The rectangular defect is of length 50 cm, width 5 cm and depth 7.5 cm with 15, 45 and 80-degree orientations. Two permanent magnets are used to magnetize the inspected specimen. The entire arrangement is surrounded by the air bounded domain.

Table 2. shows the domain specification of ferromagnetic plate and the permanent magnet in COMSOL Multiphysics 4.3a.

In the preprocessing of the geometry, tetrahedral element is considered for meshing operation. Fig.4. shows the tetrahedral meshed geometry of the specimen with the help of 131,338 elements and 838,650 numbers of degrees of freedom. Computation time taken for this preprocessing is 72 seconds.

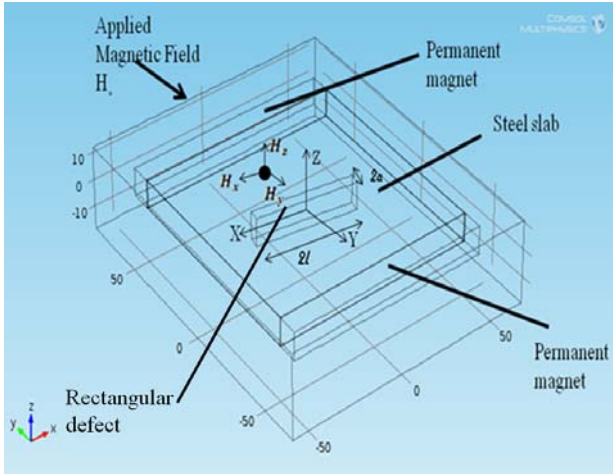


Fig.3. Geometry of the specimen with defect.

Table 2. Domain specification of the model.

Specification	Ferromagnetic Plate	Permanent Magnet
Material	ASTM A213-76a, Grade T9 (9Cr-1Mo)	Neodymium
Relative permittivity	1	1
Electrical conductivity [S/m]	4.032e6	sigma_solid_1 (T[1/k])
Relative permeability	100	4000

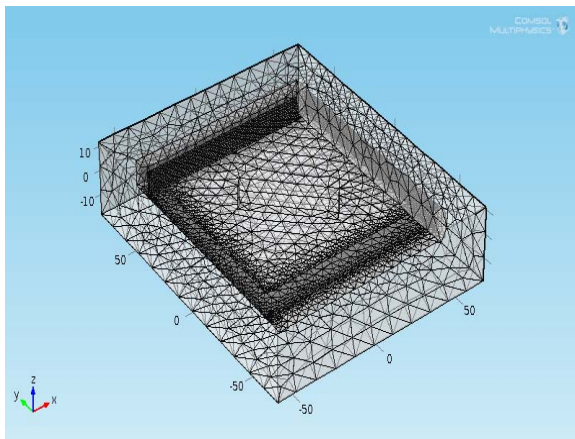
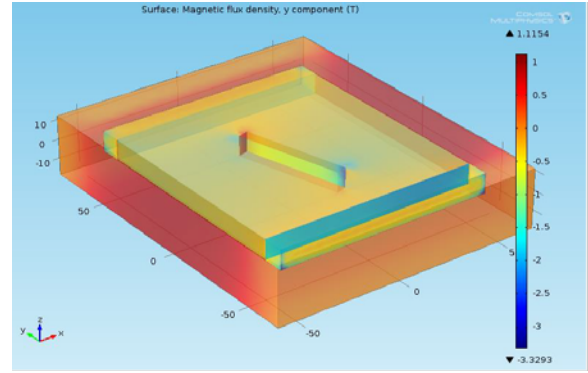


Fig.4. Meshed geometry of the specimen with defect.

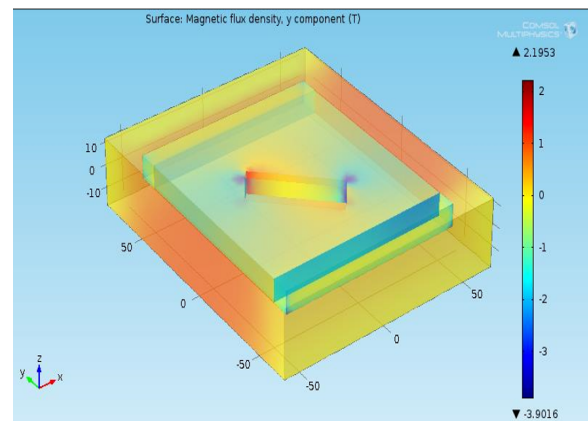
The property of the mesh considered for this finite element analysis is shown in Table 3.

Table 3. Properties of mesh.

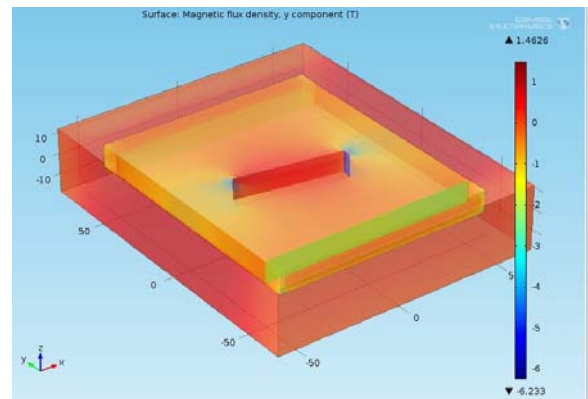
Element size parameter	Value
Max element size	12
Min element size	1.5
Max element growth rate	1.45
Resolution of curvature	0.5
Resolution of narrow regions	0.6



a) 15-degree orientation



b) 45-degree orientation



c) 80-degree orientation

Fig.5. Surface plots of the tangential component for different orientations of the defect.

In the AC/DC module of COMSOL Multiphysics software, the stationary solver study is performed on the developed geometry. In post processing of the solved geometry the surface plot is constructed. Fig.5. shows the surface plot of 15, 45 and 80-degree orientation of the defect. The uniform distribution of the magnetic field in the entire region of the specimen and the variation of the leakage profile in the defect region shows the effective arrangement of permanent magnet along with the inspected specimen. The stepwise single point line scan is performed for 100 cm length of the specimen and the magnitude of the axial and tangential component of the leakage profile is observed.

4. RESULTS AND DISCUSSION

To validate the proposed analytical model a comparison study is performed between the outputs of analytical model with numerical model. The dimension of the defect in the comparison study is considered to be of length 50 cm, width 5 cm, and depth 7.5 cm. The orientation of the defect with respect to the applied magnetic field is 15 degrees, 45 degrees, and 80 degrees. Fig.6. shows the normalized output of the axial and tangential component of the analytical model. Normalization of the magnetic leakage profile output does not affect the defect information [2]. The magnitude of the axial component decreases while the orientation of the defect increases. In the case of tangential component, the magnitude is increased from 0 to 45 degrees of orientation and then the magnitude of the profile is decreased up to 90 degrees of orientation.

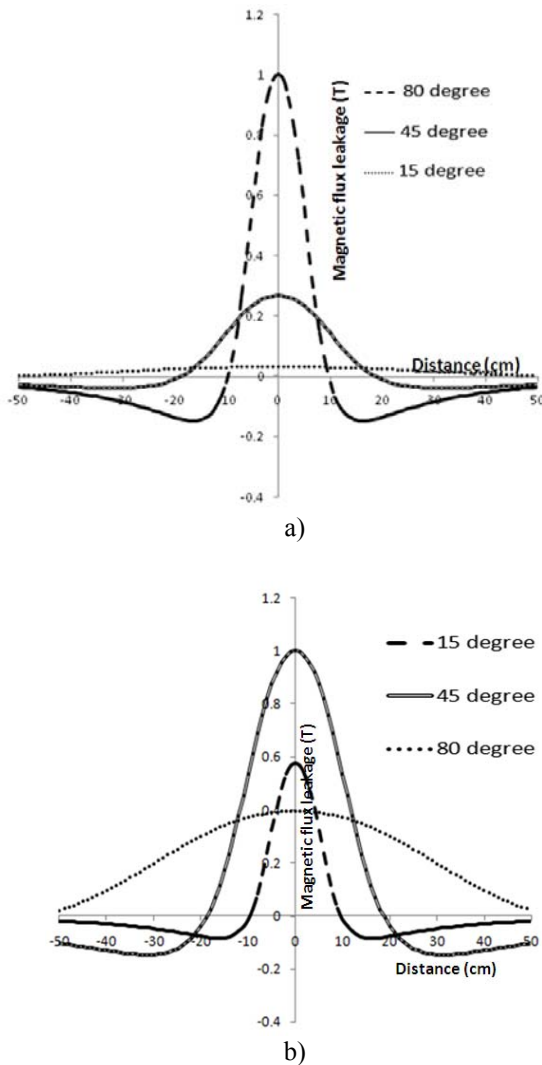


Fig.6. Analytical output for different orientation
a) axial component, b) tangential component.

The polynomial expression is derived using the actual angle with the corresponding analytical output magnitude of the leakage field. The equation (7) is derived with the help of axial profile magnitude and the equation (8) is derived

with the help of tangential profile magnitude. Error percentage of the angle estimation for the axial and tangential component of the analytical model output is shown in Table 4.

$$\text{axial angle} = -145B_x^3 + 208B_x^2 + 24B_x - 1 \quad (7)$$

$$\text{tangential angle} = B_y^3 + 29B_y^2 - 8B_y + 1 \quad (8a)$$

$$\text{tangential angle} = -238B_y^3 + 182B_y^2 - 74B_y + 90 \quad (8b)$$

Table 4. Estimated error % for analytical model.

Actual angle (degree)	Estimated angle for Axial (degree)	Estimated angle for Tangential (degree)	Error (%) for Axial component	Error (%) for Tangential component
15	21	15	28	0
45	41	45	8	0
80	82	80	2	0

Fig.7. shows the normalized output of the axial and tangential component of numerical model. The magnitude of the leakage profile of both components in numerical model is varied as discussed in the analytical model output. The polynomial expression is derived using the actual angle with the corresponding numerical output magnitude of the leakage field.

$$\text{axial angle} = 9B_x^3 - 46B_x^2 + 79B_x - 2 \quad (9)$$

$$\text{tangential angle} = 67B_y^3 - 88B_y^2 + 67B_y + 0 \quad (10a)$$

$$\text{tangential angle} = -39B_y^3 - 12B_y^2 - 53B_y + 90 \quad (10b)$$

Error percentage of the angle estimation for the axial and tangential component of the numerical model output is shown in Table 5.

Table 5. Estimated error % for numerical model.

Actual angle (degree)	Estimated angle for Axial (degree)	Estimated angle for Tangential (degree)	Error (%) for Axial component	Error (%) for Tangential component
15	18	15	20	0
45	42	45	5	0
80	83	80	3	0

The tangential component provides the minimum error percentage when compared to the axial component in analytical and numerical model output. The orientation of the defect on the ferromagnetic specimen is estimated accurately using the tangential component of the MFL profile.

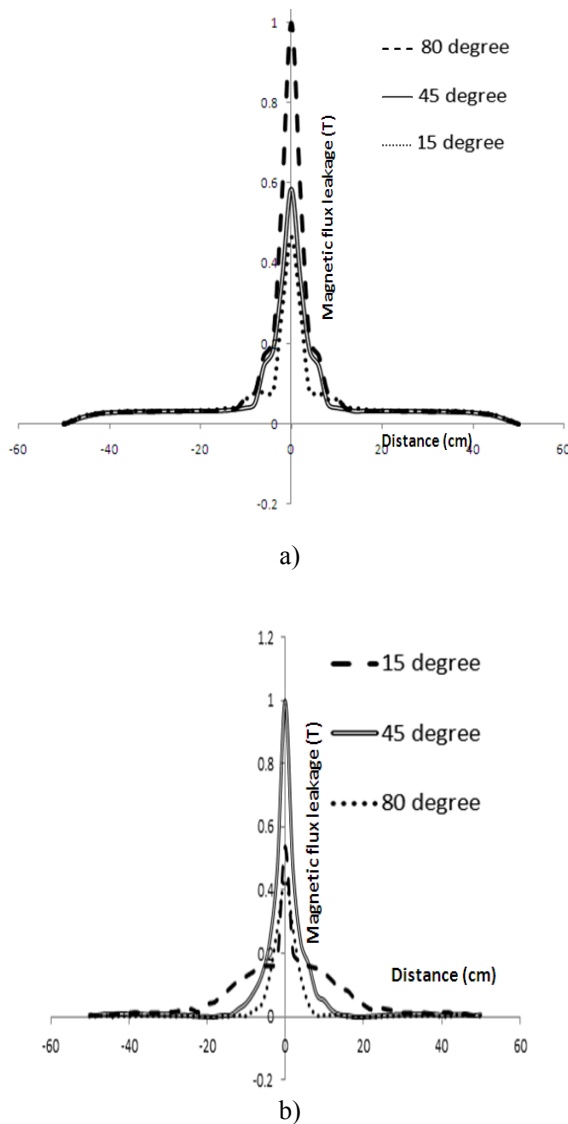


Fig.7. Numerical output for different orientation
a) axial component, b) tangential component.

5. CONCLUSION

We have developed an analytical model to estimate the orientation of the defect in ferromagnetic specimen. The result of the analytical model analysis showed that the radial component has large error to estimate the angle of the defect, and hence, the axial and tangential components are considered in the numerical study. The tangential component measured the defect orientation in precise manner when compared to the axial component. For validation purpose the numerical studies are performed using COMSOL Multiphysics software. Good correlation among the analytical and numerical studies revealed the good performance of the proposed method. The most important step of the forward approach, such as recording the pattern of the leakage profile for the known defect, is eliminated by using the proposed analytical model and also the proposed model provides support to reconstruct the defect in the inverse MFL problem.

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