FINITE ELEMENT ANALYSIS OF I-BEAM POWER EFFICIENCIES OF GROUNDED SHIELDS

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Abstract

Power efficiencies of grounded shields for structural I-beams in the steel industry are studied. Shielding is necessary in such environment due to the high consumption of stray power losses originating from the induction of eddy currents in I-beams. The objectives of eddy current shielding is to minimize stray power losses and improve power efficiencies. In this study, grounded shields are considered. The finite element method is used in this study in conjunction with the asymptotic boundary conditions for rectangular boundaries which are efficient and effective for problems with large aspect ratios.

Keywords: shielding, grounding, finite element and asymptotic boundary conditions.

1. Introduction

In the steel industry, power losses due to eddy currents are very significant. This is because huge currents flow through the furnace electrodes and busbars. The currents can be as high as tens of thousands of Amperes. The magnetic fields generated by such currents induce eddy currents in the surrounding metallic structures such as the structural steels (I-beams). The subsequent high power losses in these metallic structures increase the production costs due to the power losses and the adoption of possible cooling measures to prevent overheating. In this era of greater environmental awareness of the effects of power generations and higher requirements of products competitiveness, it is important to reduce power consumptions and improve process efficiencies. Consequently, reduction of stray power losses is imperative to achieve these goals.

One way to reduce these undesirable losses is to shield the structural components from the source magnetic fields. The goal is to achieve optimal power efficiency by using the least amount of shielding material or by employing appropriate grounding connections. Power efficiency is defined as the ratio of total power loss in the component and shield to that of the unshielded component. For shielding to be effective, power efficiency should be smaller than 1. The smaller the power efficiency, the more efficient the shielding.

The study on eddy current shielding for the improvement of power efficiencies has been reported by a number of researchers. The experimental study [1] used a frequency scale model to gain insight into the eddy current distributions in steel I-beams and the role of shielding in reducing the stray power losses. The scale models are related to real structures according to modeling techniques presented in [2]. The modeling technique used scaling ratios to obtain field quantities of complex electromagnetic problems through the measurement of scaled models. The circuit approach in [3] is based on the transformer circuit model to estimate power losses in metallic structures surrounding a high current carrying conductor. Analytic solutions were presented in [4] to investigate shielding effectiveness in structures under transverse magnetic field excitation. Shielding of metallic structures in the vicinity of a current carrying conductor perpendicular to the structures was studied using analytic solutions [5]. Shielding efficiencies were obtained for steel bars close to a high current carrying conductor [6]. In the steel industry, steel I-beams are used as structural components. Shielding of such structures were presented in [7]. In both studies [6], [7], the method used is the hybrid integro-differential finite element – Green's function approach.

There are two possible grounding connections in shieldings. One is the floated or ungrounded. We have addressed these in previous studies [6], [7]. The other connection is the grounded shields. In [8], design optimization of grounded and ungrounded shields was presented. In this paper, we will focus on the effects of shield grounding on the power efficiency of I-beams.

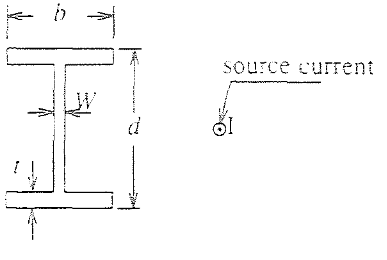

Fig. 1. A steel beam in the vicinity of a current-carrying conductor

The study is based on the finite element solution of the two-dimensional diffusion equation. The problem consists of a current carrying conductor in the vicinity of an I-shaped magnetic conductor (see *Fig. 1*). Since this problem is unbounded, the finite element method needs a special technique to overcome this. In this paper, we use the asymptotic boundary conditions to represent the outer boundary. The employment of the asymptotic boundary conditions preserves the sparsity and symmetry of the finite element matrix. This characteristic makes it possible to solve large unbounded engineering problems using the finite element method.

The asymptotic boundary conditions for two-dimensional quasistatic electromagnetic problems are derived for circular outer boundaries. While circular asymptotic boundary conditions are very effective, they are not efficient for problems with large aspect ratios. Since I-beams have aspect ratios higher than 1.0 and their physical dimensions are large compared to their skin depths, it is important to reduce matrix size as much as possible. Consequently, we formulated rectangular asymptotic boundary for filament current sources. The filament current sources represent the high current conductors (electrodes or bus bars).

2. Finite Element Formulation

The finite element formulation is based on the following assumptions:

(1) The magnetic field is quasistatic and time harmonic with an angular frequency ω;

(2) Steel I-beams and their shields are parallel to the current carrying conductors;

(3) All currents are in the z-direction and the field is two-dimensional;

(4) Permeabilities and conductivities for the beam and shield are piecewise constant.

In a time-harmonic field, the diffusion equation governing the eddy currents can be written as

$$\frac{1}{\mu}\nabla^2 A - j\omega\sigma A = J \ . \tag{1}$$

For two-dimensional problems with z-directed currents, A is the z-component of the magnetic vector potential. If the external circuit connections to the conductors are considered, the diffusion can be transformed into the integrodifferential equation for finite element implementation [9]. For an open circuit connection and conductors with inhomogeneous conductivities, the modified integrodifferential equation is [10]

$$\frac{1}{\mu}\nabla^2 A - j\omega\sigma A + j\omega\sigma\frac{\int \sigma A \, dS}{\int \sigma \, dS} = 0 \ . \tag{2}$$

The application of Galerkin criterion to (2) leads to

$$\nu[S][A] + j\omega\sigma[T][A] - j\omega\sigma[C][A] = [T][M_s] \ , \tag{3}$$

where S, T are the regular finite element matrices and C is the matrix involving the integral term of (2). The presence of C accounts for the open circuit connections. For a grounded circuit connection, the matrix C vanishes due to the presence of circulation currents. M_s represents the excitation terms due to external current sources. The source magnetic vector potential A_s can be derived using analytic methods in [10] and written as

$$A_s(r,\theta) = \frac{\mu_0 I}{2\pi} \sum_{n=1}^{\infty} \left(\frac{r^n}{n r_0^n} - \frac{a^{2n} r^{-n}}{n r_0^n} \right) \cos n\theta \ , \tag{4}$$

where a is the radius of the circular interface used for the derivation, r_0 is the distance between the source current and the coordinate origin.

3. Rectangular Asymptotic Boundary Conditions

The first order asymptotic boundary condition for two-dimensional Laplacian fields is given by [11]

$$\left(\frac{\partial}{\partial r} + \frac{1}{r} \right) A_\varepsilon = 0 \ , \tag{5}$$

where A_ε is the reaction magnetic vector potential because only the reaction magnetic vector potential is governed by the Laplace's equation. The total magnetic vector potential A is the sum of the source magnetic vector potential A_s and the reaction magnetic vector potential A_ε, i.e.

$$A = A_\varepsilon + A_s \ . \tag{6}$$

Since (5) is valid only for circular boundaries, asymptotic boundary conditions for rectangular boundaries are derived for eddy current problems excited by filamentary current sources in parallel to the conductors. The derived asymptotic boundary conditions were validated by the agreement of the simulated results with those of hybrid integro-differential finite element – Green's function method [10] and finite elements with circular asymptotic boundary conditions [11].

The first order rectangular asymptotic boundary conditions for the surface $\mathbf{a}_n = \mathbf{a}_x$ is

$$\frac{\partial A}{\partial x} = -\frac{x}{r^2} A \ . \tag{7}$$

Similarly, on the surface $\mathbf{a}_n = \mathbf{a}_y$, we have

$$\frac{\partial A}{\partial y} = -\frac{y}{r^2} A \ . \tag{8}$$

The M_s can be subsequently represented as

$$M_s = \frac{x}{r^2}\tilde{A}_s + \frac{x}{r^2}\frac{\partial \tilde{A}_s}{\partial r} + \frac{y}{r^2}\frac{\partial \tilde{A}_s}{\partial \theta} \tag{9}$$

for $\mathbf{a}_n = \mathbf{a}_x$ surface. Similarly, for $\mathbf{a}_n = \mathbf{a}_y$ surface, M_s is

$$M_s = \frac{y}{r^2}\tilde{A}_s + \frac{y}{r^2}\frac{\partial \tilde{A}_s}{\partial r} + \frac{x}{r^2}\frac{\partial \tilde{A}_s}{\partial \theta} , \tag{10}$$

where

$$\tilde{A}_s = \frac{A_s}{\mu_0} . \tag{11}$$

4. Power Efficiency of Shielded I-Beams

Two I-beams are studied and the simulation results are given in per unit values. The base value of power loss P_U for the beam is defined as follows [2]:

$$P_U = \frac{I^2}{\sigma \mu_r} . \tag{12}$$

In the following table and plots, P_t is the total power loss in the presence of shields; P_0 denotes the power loss in the absence of shields while P_s represents the shield loss, P_b is the beam loss; I_s is the shield circulation current, I_b is the beam circulation current, and I represents the excitation current.

The first I-beam has a dimension of depth $d = 203$ mm; width $b = 102$ mm; web thickness $W = 6$ mm and flange thickness $t = 6.5$ mm as shown in *Fig. 1*. The conductivity and relative permeability are 0.11×10^7 S/m and 400, respectively. The copper shield is a 'box' structure and covers the beam completely. The shield has a thickness of 9 mm. Its conductivity is 5.8×10^7 S/m. The ac current (60 Hz) carrying conductor is 2 m away from the centre of the beam. The base value of power loss is 145.45 watts.

The power losses and circulation currents are presented in *Table 1*.

The shielding in this case is not effective since the total power loss after shielding is marginally higher than the original loss without shields. It should be noted that I-beams smaller than this one should not be shielded.

The second I-beam has a dimension of depth $d = 289$ mm; width $b =$ 265 mm; web thickness $W = 19$ mm and flange thickness $t = 32$ mm. The material constants for the beam and the shield are the same as the first I-beam. Our simulations show that shielding is very effective in this case (see *Figs. 2* and *3*).

Table 1
Power losses, shielding efficiency and circulation currents of the first beam with a complete shield (spacing between the shield and the beam is 10 mm)

P_0/P_U	P_t/P_U	P_s/P_U	P_b/P_U	P_t/P_0	I_s/I	I_b/I
0.67	0.69	0.69	0.00	1.04	0.48e − 3	0.20e − 5

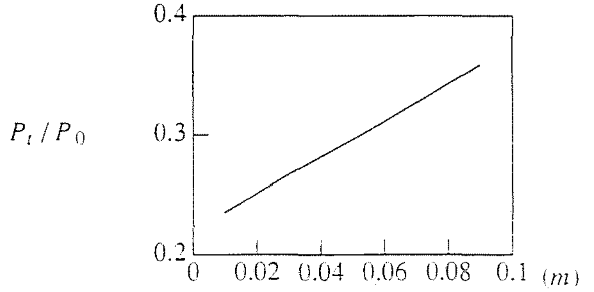

Fig. 2. Power (shielding) efficiency of the second beam as a function of the spacing between the beam and the shield (complete shield)

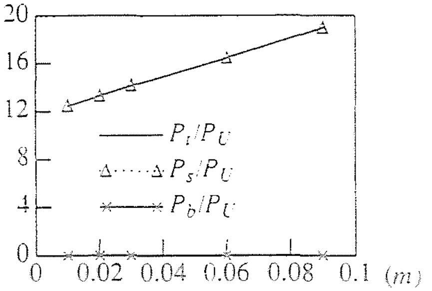

Fig. 3. Per unit power losses of the second beam as a function of the spacing between the beam and the shield (complete shield)

Although grounded shielding is more effective for the reduction of magnetic fields inside the shielded regions [8], it is not the case for power efficiencies. Power consumption is not reduced when the shields are grounded. Simulations show that for symmetrical structures, the grounded and ungrounded connections have little effects on the power losses. The circulation currents, if any, are very small compared to the excitation currents (see *Table 1* and *Fig. 4*). However, for unsymmetrical structures (with partial shield on front, top and bottom sides only), grounded shields have

Table 2
Power losses, shielding efficiency and circulation currents of the second beam with a partial shield (spacing between the shield and the beam is 30 mm)

P_0/P_U	P_t/P_U	P_s/P_U	P_b/P_U	P_t/P_0	I_s/I	I_b/I
52.81	29.12	14.13	14.98	0.55	$0.34e-1$	$0.79e-3$

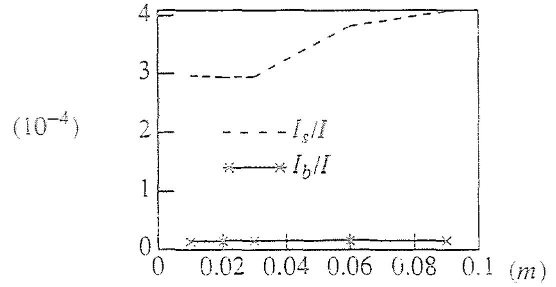

Fig. 4. Per unit circulation currents of the beam as a function of the spacing between the beam and the shield (complete shield)

higher power losses and the circulation currents are much larger as shown in *Table 2*.

The thickness of beam flange and web affects power efficiencies. For beams having the same depths and widths, the larger the flange and web thickness, the greater the unshielded power losses and the more likely shielding will be effective. This is because larger thickness produces higher ac resistance.

For the unshielded second beam, if its depth, width and flange thickness are unchanged, beam power losses and circulation currents without shielding are shown in *Figs. 5* and *6*, respectively. The abscissa in these two plots is the relative web thickness. δ is the skin depth of the beam. It is noted that beam power losses are almost constant when the web thickness is larger than 7 skin depths as shown in *Fig. 5*.

This is explained by the fact that when web thickness is several times larger than the beam skin depth. Any increase or decrease in web thickness will not affect the overall power losses since the eddy currents are primarily concentrated within first few skin depths from the surface. When web thickness is less than 3 skin depths, the power loss becomes smaller and the reduction in power loss is quite obvious. While a very small web thickness can reduce the stray power losses, practical web thickness could be larger due to mechanical constraints. The standard web thickness is 6.85 skin

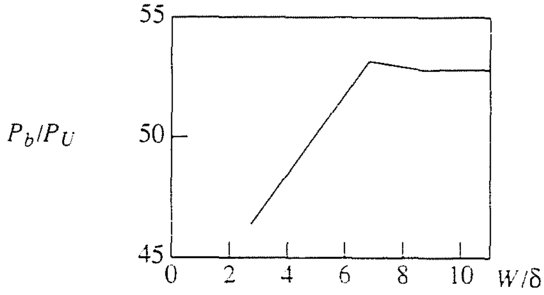

Fig. 5. Per unit beam power losses of the second beam as a function of the relative web thickness W/δ

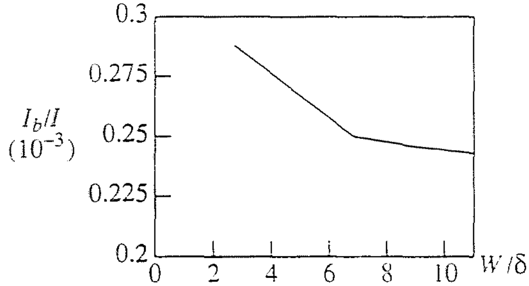

Fig. 6. Per unit beam circulation currents of the beam as a function of the relative web thickness W/δ

depths for this beam. The circulation currents decrease with the increase of the web thickness as illustrated in *Fig. 6*.

Another parameter determining the shielding efficiencies is the spacing between the shield and the beam. The smaller the spacing, the better the shielding efficiency. This is due to the fact that larger spacings between the shields and the beams lead to larger surface areas of shields which in turn cause an increase in power losses.

Our study demonstrates that for beams smaller than the first beam, shielding is not effective. The first beam can be regarded as a threshold of power efficiency shielding since power efficiency is marginally higher than 1.

5. Conclusions

This paper presents a study of power efficiencies of I-beams when shielded by grounded nonmagnetic shields. The aim of such shielding is to minimize power losses in the structural components. The study shows that grounding has little effect on power efficiencies for symmetrical structures. Shields should be placed as close to the beams as possible to maximize shielding efficiency. For shielding to be effective, the I-beam must be larger than a certain threshold size. For unsymmetrical shields, grounding should be avoided due to the large circulation of currents and higher power losses. A very small web thickness can reduce the power losses. However, the selection of web thickness should take mechanical constraints into account.

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