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Electromagnetic Force Predictions of a Stand Electromagnetic Stirring System Using an Analytical Model

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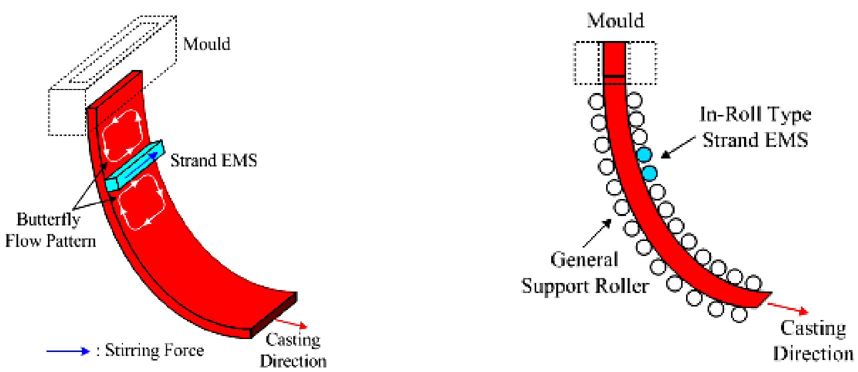
In the continuous casting process of a steel mill, methods of improving slab quality are always important and ongoing research issues. One type of electromagnetic technique is electromagnetic stirring (EMS), which is able to control fluid flow without contact between the liquid steel and a stirrer. In this paper, an analytical model is successfully developed to clarify the magnetic characteristics of strand electromagnetic stirring (S-EMS) in the slab continuous casting process. Several electromagnetic qualities, including vector potentials, magnetic flux densities, eddy current intensities within a solidified shell, and the driven forces in the liquid steel part all can be estimated or predicted by the developed analytical model. The solutions obtained are also confirmed by comparison with detailed 3-D finite element analyses (3D-FEA). With such a well-matching model, the relative variables of the operating conditions are also investigated, and the performances of S-EMS can be conveniently realized.

1. INTRODUCTION

In the continuous casting process of a steel mill, methods of improving slab quality are always important and ongoing research issues.[1] In addition to modifying the jet flow angle and remaking the submerged nozzle shape, an electromagnetic technique, which is able to control the fluid flow without contact between the liquid steel and a stirrer, has been used as a flow control technique. One type of electromagnetic technique is electromagnetic stirring (EMS), which generates a fluid flow by the Lorenz force provided by a linear induction motor. According to the setup position and metallurgical aspects, all electromagnetic stirring can be classified into several types, such as the mould type (M-EMS), the strand type (S-EMS), and the final type (F-EMS).

In this paper, one in-roll type of S-EMS system manufactured by *ROTELEC* Company will be described and investigated.[2] As illustrated in Fig. 1, the in-roll type S-EMS system can produce a stirring force that pushes the liquid steel horizontally along the slab width and generates a butterfly-type flow pattern in the liquid steel. Figure 2 shows the mechanical and electrical structures, in which the winding coils surround a



(a) 3D layouts (b) A side view

Fig. 1. S-EMS generates a butterfly-type flow pattern in the strand.

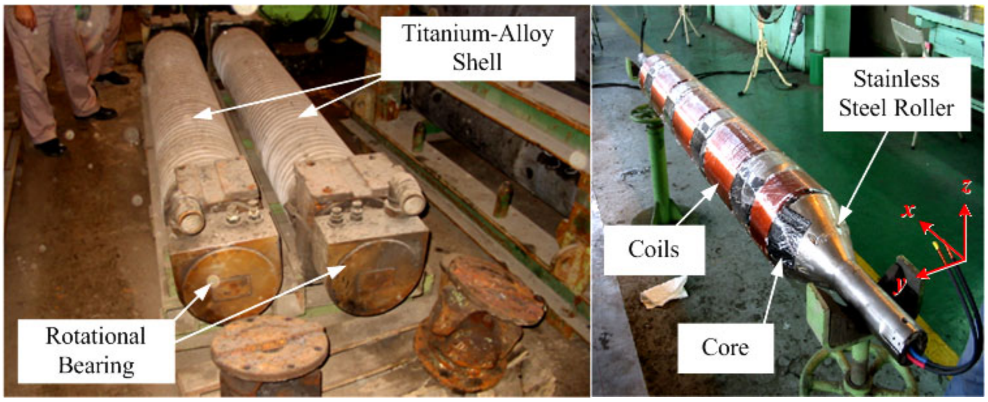


Fig. 2. Mechanical and electrical structures of the in-roll type S-EMS.

specially-designed magnetic core and are packaged by a rotational titanium-alloy shell. Table 1 and 2 list the relative mechanical structure and electrical parameters of the S-EMS system.

Table 1 Mechanical Structure Parameters of the S-EMS made by *ROTELEC*

Items	Values
Diameter of S-EMS	300 mm
S-EMS length (include bearing)	1.75 m
Thickness of Ti-alloy Shell	50 mm
Diameter of the induction motor	210 mm
Diameter of coil	4.5 mm
Thickness of slab	20-30 cm

Table 2 Electrical Parameters of the S-EMS made by *ROTELEC*

Items	Values
Power	128 KVA
Rated current of coils	400 A
Rated voltage of coils (RMS)	160V
Winding turn of coils	89
Normal operating frequency	2-5 Hz
Number of phases	2

To clarify the quasi-dynamic characteristics of the S-EMS, this paper aims to develop an analytical model systematically to estimate the magnetic performances of the system, such as vector potentials, magnetic flux densities, eddy current densities, and driven forces. By comparing the results with those obtained from 3-D finite element analyses (3-D FEA), it can be shown that the developed model not only provides adequate performance predictions, but also supplies the desired formulation scheme for other system applications.

2. SYSTEM ANALYTICAL MODELING

The working principle of an S-EMS system is very similar to that of a linear induction motor, except that the part to be driven is molten steel surrounding by thin solidification shell. The moving magnetic flux densities **B** are generated locally by the electromagnetic linear stirrer, and then the eddy currents **J** in the conductive parts in the vicinity will be induced. According to the Lorenz Force theory **F** = **J** × **B**, driving forces **F** are further generated which can push the liquid metal in the direction of the magnetic field movement. In order to produce a sufficient stirring force to the liquid, the generated eddy current must be able to penetrate the thin solid shell. In most cases of motor analyses the air-gap is substantially small; therefore the developed magnetic field is approximated to be sinusoidal distribution. However, in an EMS system the air-gap is quite large and the assumption for sinusoidal magnetic field may no longer be valid. To give a complete mathematical solution to such an EMS system, two-dimensional modeling is proposed and the vector potential is analytically solved. Subsequently, the eddy current distribution and stirring forces can be obtained.

2.1 Problem Description

Figure 3 shows the system arrangement for one pole pitch, in which the current of the coils are assigned to form a two-phase, two pole stator. To simplify the problem, an air-core is assumed for the coil and hence the medium in Regions I and II are air.[3] Furthermore, two coils are simply represented by four single conductors. Below the x-axis (Region III) is totally molten steel above Curie temperature.

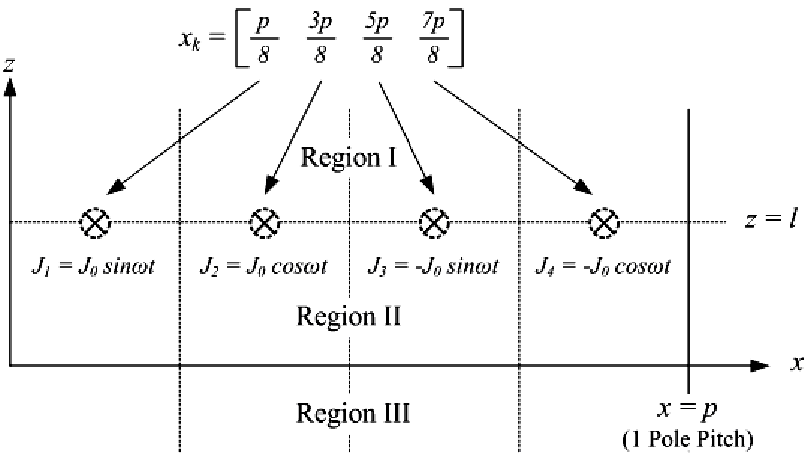


Fig. 3. System formulation for analytical modeling.

The governing equation in a quasi-static electromagnetic field is given as

$$\nabla^2 \bar{A} = -\mu \bar{J} + \mu\sigma \frac{\partial}{\partial t} \bar{A} \quad \text{...(1)}$$

where $\bar{A}$ is the vector potential and $\bar{J}$ is the current distribution in space. Suppose the position and current of the k^th^ conductors in space is (x_k, z_k) and $\bar{J}_k$, the current distribution is further expressed as

$$\bar{J} = \sum_{k=1}^{4} \bar{J}_k \delta(x - x_k)\delta(z - z_k) \quad \text{...(2)}$$

As Eqn. (1) is a linear ordinary differential equation, vector potential $\bar{A}$ can be decomposed into four components corresponding to the contribution from each current as

$$\bar{A} = \sum_{k=1}^{4} \bar{A}_k \quad \text{...(3)}$$

Considering the two-phase driving source and applying phasor expressions to each component of $\bar{A}$ and $\bar{J}$ gives

$$\bar{A}_k = A_k e^{j\omega t}\, \hat{y} \ \text{ and } \quad \text{...(4a)}$$

$$\bar{J}_k = J_0 e^{j\omega t + \phi_k}\, \hat{y} \quad \text{...(4b)}$$

where $\phi_k = \{-\pi/2 \quad 0 \quad \pi/2 \ \pi\}$. By substituting Eqns. (4a) and (4b) into Eqn. (1) and dropping the $e^{j\omega t}$ term, Eqn. (1) becomes a harmonic solution as

$$\nabla^2 A_k = -\mu J_0 e^{j\phi_k} \delta(x - x_k)\delta(z - z_k) + j\omega\mu\sigma A_k \quad \text{....(5)}$$

2.2 Analytical Solution

Considering the periodic arrangement for each pole pitch, a general solution for Eqn. (5) can be expressed explicitly as

$$A_k = \sum_{n=-1}^{\infty} \left(C_1 e^{\alpha_1 z} + C_2 e^{-\alpha_1 z}\right)\left(D_1 \sin \alpha x + D_2 \cos \alpha x\right) \quad \text{....(6)}$$

where $\alpha_1 = \sqrt{\alpha^2 + j\omega\mu\sigma}$, and C_1, C_2, D_1 and D_2 are the unknown coefficients to be solved. Without losing the generality, the arrangement shown in Fig. 3 can be extended along the x-axis infinitely. Therefore, A_k is a periodic function with its maxima at $x = x_k$ (where $\frac{\partial A(x,l)}{\partial x}\big|_{x=x_k} = 0$), resulting in

$$\alpha = \frac{2n\pi}{p} \ \text{ and } \quad \text{...(7a)}$$

$$\frac{D_1}{D_2} = \frac{\sin \alpha x_k}{\cos \alpha x_k} \quad \text{...(7b)}$$

By substituting Eqns. (6a) and (6b) into Eqn. (7), with additional rearrangement gives

$$A_k = \sum_{n=1}^{\infty} \left(C_1' e^{\alpha_1 z} + C_2' e^{-\alpha_1 z}\right) \cos \alpha(x - x_k) \quad \text{...(8)}$$

Using the property that A and its first derivative are continuous across the boundary, four equations are given to solve the unknown four coefficients. After tedious calculations, the vector potential for each region is given by

$$A_k^{(1)} = \sum_{n=1}^{\infty} \frac{1}{2}\left(e^{\alpha(l-z)} + \frac{\alpha - \alpha_1}{\alpha + \alpha_1} e^{-\alpha(l-z)}\right) \frac{\cos \alpha(x - x_k)}{\alpha} \mu e^{j\phi_k} J_0 \quad \text{...(9a)}$$

$$A_k^{(2)} = \sum_{n=1}^{\infty} \frac{1}{2}\left(e^{-\alpha(l-z)} + \frac{\alpha - \alpha_1}{\alpha + \alpha_1} e^{-\alpha(l-z)}\right) \frac{\cos \alpha(x - x_k)}{\alpha} \mu e^{j\phi_k} J_0 \quad \text{...(9b)}$$

and

$$A_k^{(3)} = \sum_{n=1}^{\infty} \frac{e^{-\alpha l + \alpha_1 z}}{\alpha + \alpha_1} \cos \alpha(x - x_k) \mu e^{j\phi_k} J_0 \quad \text{...(9c)}$$

Region III is of great interest where the eddy currents are generated to stir the molten steel. Superposition of the four components generates a complete solution for A in the region as

$$\overline{A}^{(3)} = \sum_{k=1}^{4}\sum_{n=1}^{\infty}\frac{e^{-\alpha l+\alpha_1 z}}{\alpha+\alpha_1}\cos\alpha\left(x-x_k\right)\mu e^{j\phi_k} J_0\, e^{j\omega t}\,\hat{y} \; \ldots(10)$$

2.3 Eddy Current and Stirring Force Calculation

When the vector potential is known by going through with the above exacting calculations, the y-directional eddy current in the molten steel can be derived as follows

$$\overline{J}_e = -\sigma\frac{\partial}{\partial t}\overline{A}$$

$$= \sum_{k=1}^{4}\sum_{n=1}^{\infty} -\mathrm{j}\omega\mu\sigma J_0\frac{e^{-\alpha l+\alpha_1 z}}{\alpha+\alpha_1}\cos\alpha\left(x-x_k\right)e^{j(\omega t+\phi_k)}\,\hat{y} \; \ldots(11)$$

Furthermore, the magnetic flux density also can be derived using the relation $\overline{B} = \nabla\times\overline{A}$. Finally, the force density distribution is obtained by $\overline{F} = real(\overline{J})\times real(\overline{B}) = F_x\hat{x} + F_z\hat{z}$, and the total driven force can be obtained by integrated force density over Region III.

3. COMPARISONS BETWEEN ANALYTICAL MODEL AND 3-D FEA

To verify the adequacies of the developed analytical model, some detailed 3-D FEA have been performed by using the commercial software *COMSOL Multiphysics.*[4] Figure 4 and Fig. 5 show the associated 3-D finite element geometry and meshes of the S-EMS system. With proper sub-domain and boundary settings, the time consumed for obtaining the solution is around several minutes, depending on the number of total meshes.

Figure 6 shows the induced eddy current density distributions in the liquid steel with 3 Hz, 400A input current sources. It can be observed that the induced eddy current densities in y-direction have a maximum value of about 5.8×10^5 (A/m^2). Considering the same input conditions and material parameters, the solutions from the analytical model are compared with those of the 3-D FEA.

Figure 7 shows the comparison curves of the eddy current densities obtained by both methods. The difference can be attributed to some factors such as flux leakage between the coils and to the assumption of a periodic pole pitch arrangement for the system. Figure 8 demonstrates the generated stirring force to the molten steel according to different current amplitude input. The developed analytical model can be used to evaluate a preliminary system design without complex, computational expensive FEA.

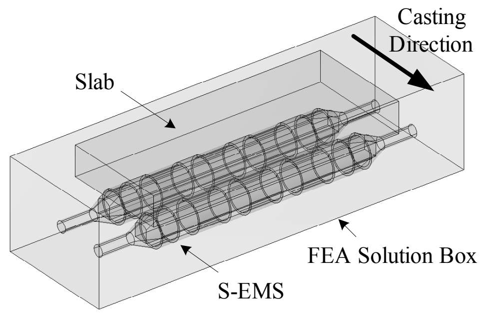


Fig. 4. 3-D finite element geometry of the S-EMS.

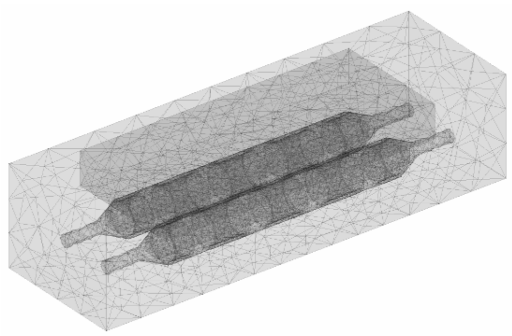


Fig. 5. 3-D finite element meshes of the S-EMS.

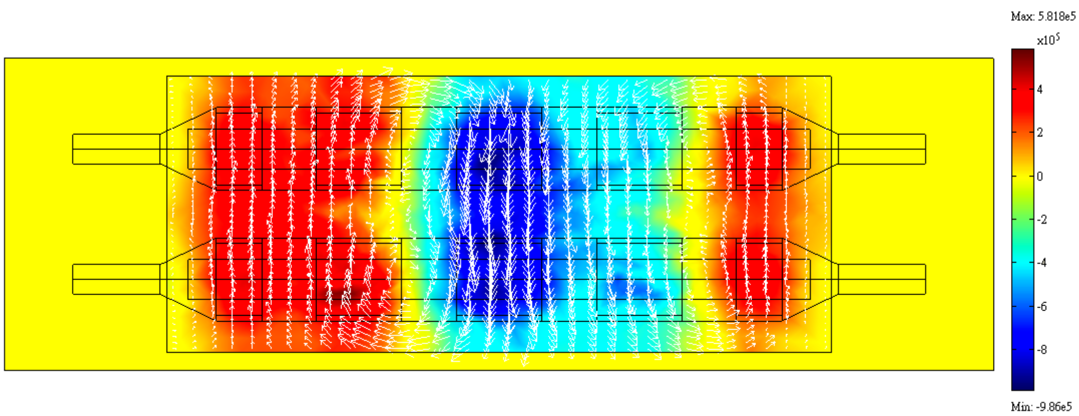


Fig. 6. 3-D finite element simulation result of eddy current distribution.

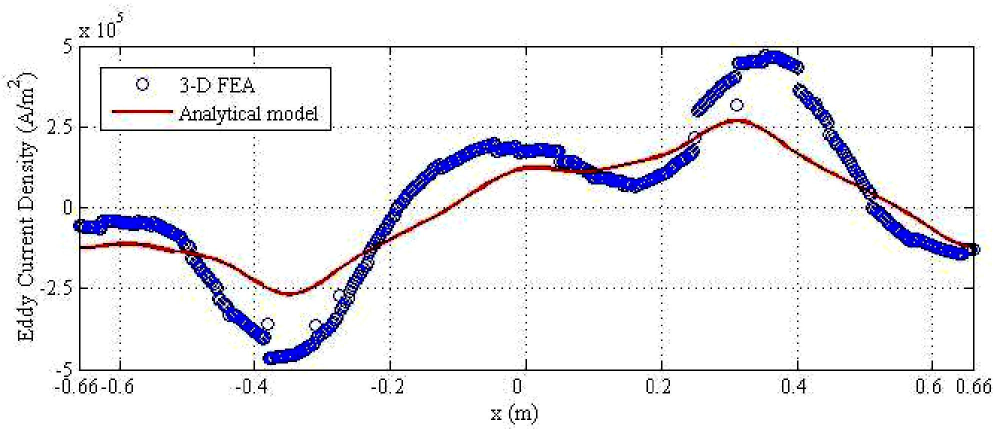


Fig. 7. Eddy current densities comparison between analytical model and 3-D FEA.

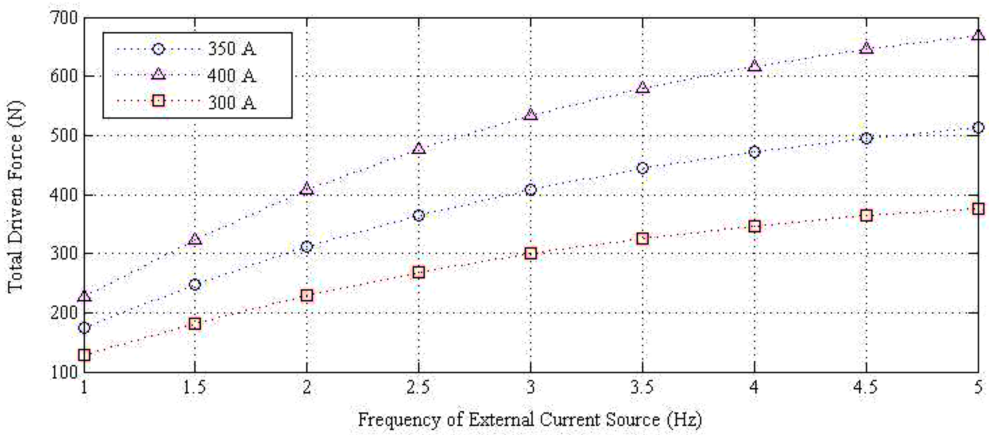


Fig. 8. Stirring force predictions with different external current amplitude input.

4. CONCLUSION

An applicable analytical model for an S-EMS in the continuous casting process was successfully developed. The particular analytical model can estimate the essential variables systematically, such as vector potentials, magnetic flux densities, and eddy current densities. Using the proposed method, the induced Lorenz forces can be predicted approximately. The mathematical results obtained were also compared with detailed 3-D FEA. It has been confirmed that the proposed method is able to give comprehensively qualitative analyses, which can help to evaluate the preliminary system design of other similar EMS facilities expeditiously.

REFERENCES

1. K. Fujisaki, etc.: IEEE Trans. On Magnetics, 1994, vol. 30 (6), pp. 4764-4766.
2. *Maintenance Instructions*, ROTELEC Corporation, 1987.
3. C. Dodd: "Solution to Electromagnetic Problems," Ph. D. Dissertation, Univ. of Tennessee, 1967.
4. *COMSOL Multiphysics User's Guide Version 3.4*, COMSOL AB., 2007. □