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# Analytical model and experimental investigation of electromagnetic tube compression with axi-symmetric coil and field shaper

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ABSTRACT

In this study, a computationally cost effective, pure analytical model was developed for a multi-turn, axisymmetric coil with field shaper to predict the magnetic pressure and velocity during electromagnetic tube compression. This model is electro-magnetic-mechanically coupled with tube position affecting the magnetic field generated at each time increment. The mechanics-based analytical approach is different than past research and includes experimentally determined coupling coefficients between the coil, field shaper, and tube. To validate the analytical model, experimental tests with Photon Doppler Velocimetry (PDV) were conducted. The results show reasonably good agreement between the analytical and experimental results.



## 1. Introduction

Electromagnetic Forming (EMF) is advantageous in forming, joining, and welding of the lightweight structures ranging from aerospace and automotive industry to medical devices and household appliances. Improved strain distribution and formability; short cycle time; and reduced wrinkling are among the benefits. EMF is suitable for tubular compression and expansion, sheet metal forming, and powder compaction [1]. The EMF process is based on Faraday's law of electromagnetic induction. In this process, a capacitor bank is charged with a significant amount of electrical energy which is quickly dissipated into a specially designed coil. A magnetic field is generated that induces eddy currents in nearby conductive materials. These eddy currents produce a repulsive magnetic field, and Lorentz forces cause the workpiece to plastically deform away from the coil at a high velo`city. See schematic in Fig. 1. One of the key process parameters in EMF is workpiece velocity. If the relative workpiece velocity is sufficient (>300 m/s [3]), this technique can be used for welding of dissimilar metals, i.e., Magnetic Pulse Welding (MPW), where a shear instability creates the characteristic wavy morphology at the weld interface [4,5].

While some multiphysics finite element packages exist that are capable of modelling the process and estimating the critical process parameters (e.g., velocity), there is a lack of simplified and accurate analytical modelling tools available. Such analytical models help to eliminate empirical investigations to determine the necessary process parameters and velocities to produce successful EMF and MPW parts.

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In this research, a purely analytical model for determining the pressure distribution applied to the workpiece and the subsequent workpiece velocity for a multi-turn, axi-symmetric coil with field shaper was investigated. In the proposed model, at each time increment, the magnetic field is automatically updated in response to the tube deformation. Compared to previous analytical modelling efforts [6–9], a rigid body or a rigid-plastic material assumption was eliminated. Alternatively, plastic deformation of the workpiece during the forming process was taken into account at each time increment. In addition, the coupling factors between the coil, field shaper, and workpiece were experimentally measured and incorporated into the analytical model. The analytical model was then experimentally verified using Photon Doppler Velocimetry (PDV) to measure the workpiece velocity. Reasonably accurate velocity and radial location results were obtained.

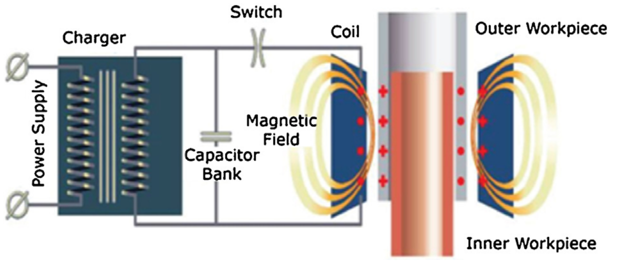


**Fig. 1.** Schematic of EMF/MPW process [2].

## 2. Analytical model

The basic EMF process consists of three fundamental parts: a capacitor bank to store energy, a coil to create the magnetic field, and a workpiece to be formed. Based on the multiphysics nature of the

EMF process, the analytical model was divided into three stages. First, electrical theory was used to determine primary current and voltage out of the capacitor bank and passing through the coil based on the charge energy. Second, the magnetic field distribution and the effective magnetic pressure that was developed on the workpieces were calculated from electromagnetic analyses. Lastly, classical mechanics theory was used to determine the radial position and velocity of the workpiece caused by the effective magnetic pressure. Since the magnetic field distribution strongly depends on the gap distance between the field shaper and workpiece, the magnetic and mechanical processes were coupled. To calculate the workpiece displacement, a simplified constitutive law for the material was incorporated into the model. At each time increment, the magnetics field geometry was updated with an incremental displacement of the workpiece and hence the model includes the new gap between the field shaper and workpiece.

In this study, a commercially purchased multi-turn, axi-symmetric coil (Poynting, model: SMU-K100-4/65) was used. The workpiece was an Al6061-T6 tube with a length of 100 mm, wall thickness of 0.88 mm and outer diameter of 25.36 mm. In tube compression processes, a "*field shaper*" is often positioned between the coil and workpiece to concentrate the magnetic field generated (see Fig. 2a and b).

A quick discharge of the capacitor bank causes a damped sinusoidal current flowing through the coil which induces a related electromagnetic field. In the field shaper, which acts as a short circuited second winding of a transformer, a secondary current is induced. Due to the skin effect and Lenz' law, this induced current flows opposite to the coil current at the outer surface of the field shaper [10]. At the axial slot, the current is directed to the inner surface of the field shaper where the current direction is the same as in the coil (see Fig. 2c). Compared to the outer surface of the field shaper, the inner area is much smaller, resulting in a higher current density and field strength. For this analysis, a series of elements were generated along the surface of the field shaper. The elements were equally spaced, $dz$, in the axial direction and the width of each element, $dr$, (see Fig. 2d) was equal to the skin depth, $\delta$, defined as:

$$\delta = \sqrt{\frac{2\rho_r}{\mu_0\mu_r\omega}} \tag{1}$$

where $\omega$ is the frequency of the current through a conductor of resistivity $\rho_r$, $\mu_r$ is the relative magnetic permeability of the conductor, and $\mu_0$ is the magnetic permeability of free space.

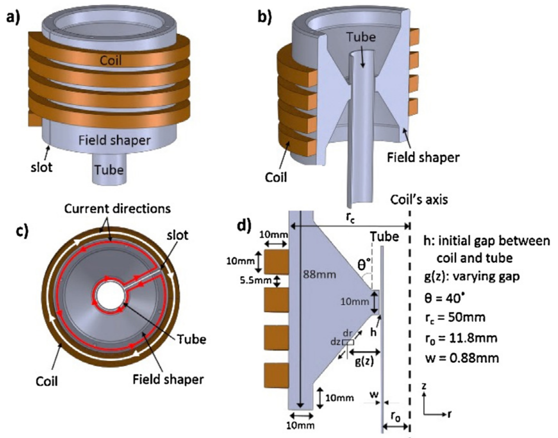


**Fig. 2.** Schematic of multi-turn, axi-symmetric coil with field shaper and tube: (a) full view, (b) half view, (c) current directions, (d) cross section.

### 2.1. Electrical theory

The electrical circuit consisting of the capacitor bank, coil, field shaper and workpiece can be represented by ideal electrical elements and circuits (see Fig. 3). As is clear from Fig. 3, both the primary and induced circuits are coupled with the secondary circuit through the mutual inductances (i.e., $M_1$ and $M_2$) which are a measure of induction between the two circuits. A "*coupling factor*" ($k$) represents the loss of magnetic flux with a value between $0 \le k \le 1$. In this study, the two coupling factors (i.e., $k_1$ and $k_2$ corresponding to $M_1$ and $M_2$ respectively) were experimentally measured by placing a Rogowski coil in two different locations in the experimental set-up and calculating the ratios of the secondary to primary current ($k_1 = 0.78$) and induced to secondary current ($k_2 = 0.91$). Applying Kirchhoff's voltage law and summing the voltages around the primary circuit, a differential equation is obtained with respect to time, $t$ [10]

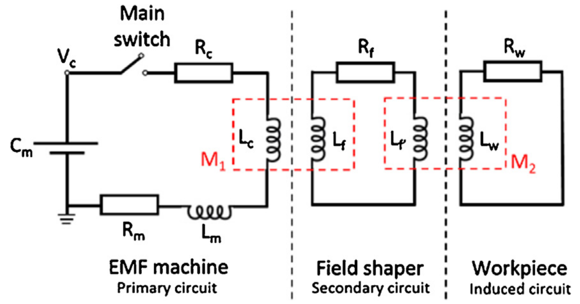


**Fig. 3.** Configuration of three circuits and two coupled systems.

$$\frac{1}{C_m}\int i_p(t)dt + i_p(t)R + L\frac{di_p(t)}{dt} = 0 \tag{2}$$

where $C_m$ is the capacitance of the machine, $i_p$ is the current in the primary circuit, $R = R_m + R_c$ is the total resistance, and $L = L_m + L_c$ is the total inductance. Note that the resistance and inductance of the machine, $R_m$ and $L_m$, can be determined experimentally with a known capacitance by calculating the damped natural frequency and damping ratio of the RLC circuit. Resistance and inductance of the coil, $R_c$ and $L_c$, are functions of the material properties (i.e., resistivity of the coil), the geometry of the coil, current condition (i.e., the angular frequency), and the cross-sectional area of the coil contained from the skin depth to the surface of the coil. For detailed information see Refs. [9,11].

### 2.2. Magnetic theory

The magnetic field produced from a given axi-symmetric coil can be determined with respect to the gap distance between the field shaper and tube along the axial direction. As is clear from Fig. 2d, because of the tapered geometry of the field shaper, the gap distance is varied along the axial length of the field shaper (i.e., $g(z)$). The magnetic flux density, $B$, produced by the coil induces eddy current in the workpiece with a current $J$ density. The current density, $J$, is related to the magnetic field, $H$, through a partial derivative in the radial direction. A Lorentz force based on $H$ is created which acts as a volume force, $F$, [10]

$$F = -\mu_m H\frac{\partial H}{\partial r} = -\frac{1}{2}\mu_m\frac{\partial(H2)}{\partial r} \tag{3}$$

The body force, $F$, is integrated through the thickness of the tube to determine the magnetic pressure acting on the tube surface

$$P_m = \int_0^w F dr = \frac{1}{2}\mu_m H_{gap}^2 \tag{4}$$

where the integration limit, $w$, is the tube thickness (see Fig. 2d) and $H_{gap}$ is the gap magnetic field strength. In this study, the penetrated magnetic field was neglected due to the skin effect [10]. The magnetic field strength, $H_{gap}$, is the resultant field of a superposition of magnetic field strength from many current carrying differential elements, $dH_{gap}$ (see Fig. 2d). For the axi-symmetric coil investigated in this study, only the magnetic field strength along the coil's axis is of interest (i.e., tangential to the workpiece) because this will create a force in the radial