Numerical Study on Shear Horizontal Electromagnetic Acoustic Transducers for Generation of Ultrasonic Guided Waves for Absorber Tubes used in Concentrated Solar Plants

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Abstract: Absorber tubes are one of the most critical components of parabolic trough Concentrated Solar Plants (CSPs). Due to the high temperatures where these tubes perform at with concentration of sunlight, it is very likely for them to get damaged such as crack and mass loss *etc.*, and lose functionality of power generation. Therefore, the monitoring of their structural health via Non-Destructive Testing (NDT) techniques is regarded as essential for preventing them from being significantly defective and thereby reducing maintenance cost. Non-contact ultrasonic guided wave (UGW) method is one of the best candidates, which is more reliable to the tubes at high temperature through a review. In this paper, reports simulated and modelling results for development of Electromagnetic Acoustic Transducers (EMATs) to performance non-contact UGW. A configuration and optimisation of EMAT transducers is carried out, which includes selection of wave mode, wave length, central frequency and phase velocity via dispersion curves. Design of coil and magnet for EMAT transducers along with numerical simulation results are investigated using COMSOL.

Keywords: Electromagnetic acoustic transducer (EMAT), ultrasonic guided wave (UGW), shear horizontal (SH) mode, absorber tubes, concentrated solar plant (CSP), COMSOL

1. Introduction

As the greenhouse effect on the climate across the world grows, there is an increasing need for more stable renewable sources of energy as alternative means for environmentally friendly power generation. Concentrated Solar Power (CSP) plants are a promising technology for renewable energy production. CSP plants consist of several km of solar absorber tubes and insulated pipes working at a high temperature up to 550°C. The inspection of CSP tubing and piping, absorber tubes in particular, is currently very challenging due to their complex design which offers poor access to the surfaces requiring inspection. Mahoney of Sandia National Laboratories reported a failure rate of 30-40% in solar absorbers at the Solar Energy Generating Systems within a decade of operation[1]. The price of replacement was expensive resulting in a significant extra maintenance cost on an annual basis[1]. Failures can also result in significant leaks and fires due to combustion of the oil commonly used as working fluid in the majority of CSP plants resulting in further significant infrastructure damage[2]. At the moment there is no reliable methodology for the inspection of in-service solar receivers and insulated pipes and therefore CSP plant maintenance procedures are corrective rather than preventive. Therefore there is an urgent need to increase the reliability of CSP infrastructure and optimise maintenance procedures by using efficient and cost-effective inspection methods.

To monitor the condition of absorber tubes, there are three major criteria used for assessing their performance including the way the specimen is accessed, the efficiency in accurately detecting, sizing and localizing a defect and up to what temperature the technology employed can perform reliably. The main potential NDT techniques are divided into contact methods such as acoustic emission (AE)[3], alternating or direct current potential drop measurement[4], and non-contact approaches including laser ultrasonic[5], ultrasonic guided wave (UGW)[6], eddy current, remote field testing[7], thermography[8] etc.

AE can be used for defect detection in operating structures especially for detecting the initiation and evolution of defects. It gives qualitative indications of the structural health of the specimen but is affected by mechanical noise[3]. Alternating or direct current potential drop measurement is widely used in petrochemical and power industries for flaw detection and defect sizing and it can be applied to both ferromagnetic and non-ferromagnetic materials which are conductive, however, it is not suitable for scanning and only defects which are already known can be accessed in terms of their depth[4]. The aforementioned techniques are contact methods, which are hard to be implemented under high temperature conditions.

Laser ultrasonics, eddy current, remote field testing, thermography *etc*. are all non-contact NDT techniques which do not require any couplant for accessing and inspecting the specimen. Laser ultrasonics is frequently employed when small defects are to be detected and the geometry of the specimen is complicated. The inspection setup is complicated and it is also expensive[5]. UWG is capable of inspecting large structures with fewer transducers and minimal insulation removal. Moreover inspection of structures while they are operating is also possibe[6]. Eddy current testing can be used to inspect coated structures and also requires little surface preparation. However, it can be used for surface and near-surface defect detection only on conductive materials due to skin effect and the sensing range is not efficient to cover the whole length of absorber tubes[7]. Remote field testing is relatively insensitive to lift-off, it can detect both surface and internal defects and is frequently used for pipe inspection in power plants and steam boilers, but only on non-ferromagnetic materials. Moreover, thermography can be applied to monitor structures while they are operating and can scans large areas with short time frames[8]. However, thermography gives poor resolution results for absorber tubes especially for interior defects.

Among the NDT techniques mentioned above, non-contact UGW can be seen as a good candidate for this application, because it is capable of non-contact ultrasound generation and reception with a large coverage of inspection range. EMAT transducers are highy appropriate for the generation of UGW without contact, because the ultrasound is directly generated within the material. Due to the couplant-free feature, EMATs are particularly useful for automated inspection, and hot, cold, clean, or dry environments. EMAT are ideal transducers for generating Shear Horizontal (SH) bulk wave mode[9], Surface Wave, Lamb waves**Error! Reference source not found.**[10] and all sorts of other guided-wave modes in metallic and/or ferromagnetic materials. Besides, some designs of EMAT transducers can sustain high temperature operation up to 500°C[10]**Error! Reference source not found.**. With respect to high temperature inspection relevant to absorber tubes and insulated pipes in CSP plants, several authors have reported on the use of EMATs at elevated temperature[11]. Dixon *et al.*[12] reported on water-cooling EMATs at temperatures up to 450°C, which meets temperature requirements for this application.

In this paper, a design of SH EMAT transducer will be introduced and the performance of EMAT will be simulated and investigated using COMSOL. Section 2 introduces the theoretical background of EMAT particularly for paramagnetic absorber tubes; Section 3 describes the physical coupling of EMAT using COMSOL as well as the developed EMAT model; Numerical results are reported in Section 4, followed by a conclusion in Section 5.

2. Theoretical background of EMAT

There are two mechanisms to generate waves through magnetic field interaction. One is Lorentz force, when the material is conductive, and the other is magnetostriction when the material is ferromagnetic. In this application, the materials used for absorber tubes are austenitic stainless steel grades which are paramagnetic. Therefore, Lorentz force is the dominant factor for the generation of ultrasound.

Lorentz force is generated by the alternating current (AC) in the electric coil inducing eddy currents on the thin skin of the material. Due to skin effect, the distribution of eddy current is only at a thin layer of the material. Eddy current in the magnetic field experiences Lorentz force. The Lorentz force is applied on the surface region of the material, governed by following equation:

$$\boldsymbol{f} = q\mathbf{E} + \mathbf{J} \times \mathbf{B}$$

where $\boldsymbol{f}$ is Lorentz force density (force per unit volume), q is the charge density (charge per unit volume), $\mathbf{E}$ is the electric field, $\mathbf{J}$ is the current density and $\mathbf{B}$ is the magnetic flux density. When there is no charge, the equation can be rewritten as:

$$\boldsymbol{f} = \mathbf{J} \times \mathbf{B}$$

Then the tensor of $\boldsymbol{f}$ can be written in x, y, z coordination as:

$$f_x = J_y B_z - J_z B_y$$
$$f_y = J_z B_x - J_x B_z$$
$$f_z = J_x B_y - J_y B_x$$

A ferromagnetic material undergoing a dimensional change due to an external magnetic field being applied is referred to as magnetostrictive. The phenomenon is called magnetostriction, and the change is affected by the magnitude and direction of the field[Error! Reference source not found.]. The AC in the electric coil induces an AC magnetic field and thus produces magnetostriction at ultrasonic frequency in the material. The disturbances caused by magnetostriction then propagate in the material as an ultrasound wave.

In this application, the major material for absorber tube and insulation pipe is paramagnetic austenitc stainless steel as mentioned earlier wit a relative magneticpermeability μ_R=1.008. Therefore, Lorentz force is the main consideration for ultrasound generation.

3. Model and design for EMAT

3.1 Physical coupling in COMSOL for EMAT

Finite Element Method (FEM) techniques, based on numerical solutions of Partial Differential Equations (PDEs), offer a method for finding approximate numerical solutions of the coupling of electromagnetics and ultrasonics for EMAT. The solution approach involves either eliminating the differential equations completely or rendering the PDEs into an approximating system of ordinary differential equations, which are then solved numerically by integration using standard techniques such as Euler's method[14]. By using COMSOL, models of the Lorentz force generated by coupled electromagnetic field excited by magnets and coils and the propagation of ultrasound is possible to be determined with a reasonable accuracy. This can be performed using time dependant analysis in the magnetic field, magnetic field without currents and structural mechanics modules.

- Magnetic field module is used to solve the induced currents $\boldsymbol{J}_e$ (or called eddy currents) in the test sample excited by coils.
- Magnetic field without currents module is implemented to calculate the static magnetic field $\boldsymbol{B}_s$ generated by magnets.
- Lorentz force can be calculated according to $\boldsymbol{J}_e$ and $\boldsymbol{B}_s$ governing equation $\boldsymbol{f} = \boldsymbol{J}_e \times \boldsymbol{B}_s$. Then, solid mechanics module is utilised to model the ultrasound generated in the test sample with respect to Lorentz force.

According to the convergence study completed[15], the minimum number of elements required for a wavelength to obtain the best approximation of results is 10. Therefore the maximum element size to be used to define the mesh can be calculated as follows:

$$\textit{Max element size} = \lambda_{min}/10$$

where λ_{min} is the minimum separation between mesh elements

For the maximum time step, it is governed following equation:

$$\textit{Max time step} = \lambda_{min}/(10c)$$

where c is speed of wave.

3.2 Design of EMAT

To inspect a defect in the range of 10 mm as it is required, EMAT with 12 mm wavelength is chosen. In order to calculate the working central frequency for a selected wave length, the crossover points of dispersion curve and a curve of Vph=λf will be found, as shown in Figure 1.

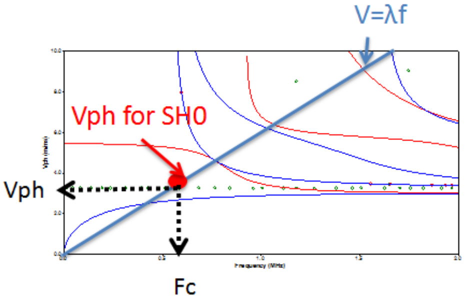
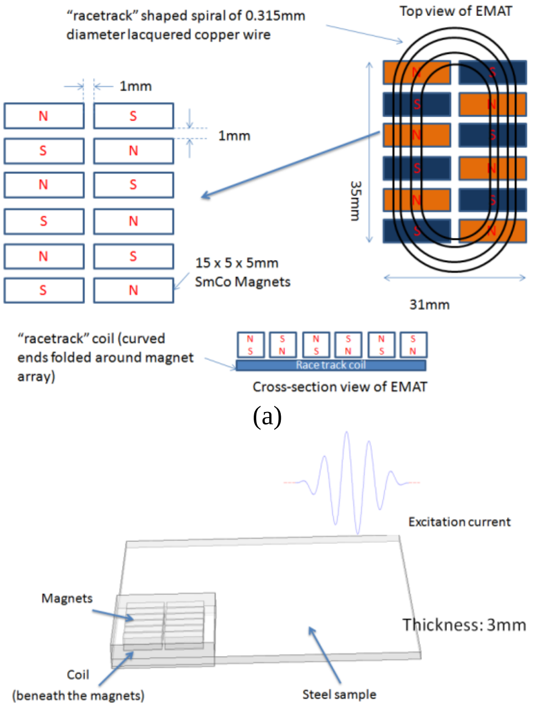


Figure 1. Demonstration of selecting central frequency and determining phase velocity using dispersion curve and line $v_{ph} = \lambda f$.

From the dispersion curve, the working frequency for SH0 mode with wavelength of 12mm is obtained as 256.7 kHz.

In order to focus the energy to cover the inspection of the whole sample up to several metres, Shear Horizontal (SH) mode SH0 is determined as the best option for this application. Through dispersion curves, SH EMAT working at 256.7kHz with a 12 mm wavelength is determined for 3mm-thick plate made of stainless steel 316L. Then a Periodic Permenat Magnet (PPM) and race-track coil are selected for the EMAT transducers. The design of the EMAT is shown in Figure 2a and this configuration of EMAT developed in COMSOL as shown in Figure 2b, where a Hanning window centred at 256.7 kHz with five cycles is used for excitation of the coil.



(a)

(b)

Figure 2. (a) Design of the EMAT transducer; (b) EMAT model developed in COMSOL for the design.

As illustrated in Figure 1, the dimension of each magnet is 15mm x 5mm x 5mm. The distance between magnets is 1mm. In addition, the magnetic strength of each magnet is 0.3T. The diameter of coil is 0.315mm and the width and length are 15mm and 35mm respectively with a lift-off distance 0.1mm to the sample. The excitation current density J(t) is defined as follow:

$$J(t) = \begin{cases} J_0 \sin(2\pi f t)[1-\cos(2\pi f t/N)], & \text{for } t \leq N/f \\ 0, & \text{for } t > N/f \end{cases}$$

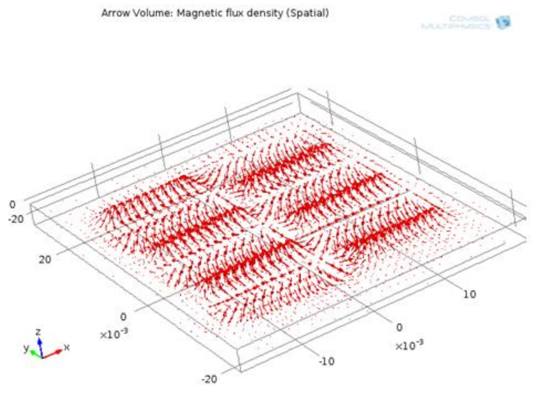
where J_0=1A/(0.315 mm)^2 (diameter of coil is 0.315 mm), f=256.7 kHz, N=5 cycles. The material properties is summarised in Table 1.

Table 1 Material properties of stainless steel 316L at room temperature

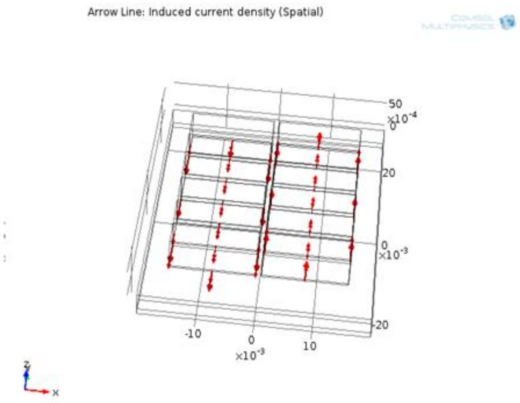
Young's Modulus (GPa)	195
Poisson Ratio	0.285
Density (kg/m^3)	8000
Electrical conductivity (S/m)	1.45e6
Permeability	1.008
Permisivity	1

4. Results

The direction of magnetic flux density and eddy current density in the steel plate generated from magnets and coils respectively at 9 µs, is shown in Figure 3.



(a)



(b)

Figure 3. (a0 Magnetic flux density and (b) eddy current density at 9 μs.

As it can be seen from Figure 3, the magnetic field is mainly in z direction whilst the eddy current field is dominant in y direction. As a result, the Lorentz force will be in x direction mainly. It satisfies the requirement of the generation of shear horizontal mode.

The ultrasonic waveform 75mm away from the EMAT transducer on the central line of the EMAT in y axis, is represented in Figure 4. And the displacement on the surface of the sample at 20, 80 and 100 μs is illustrated in Figure 5.

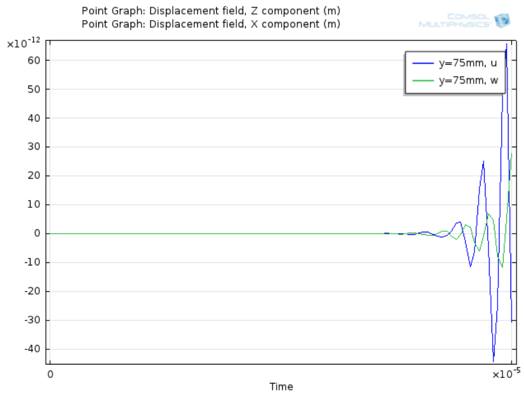
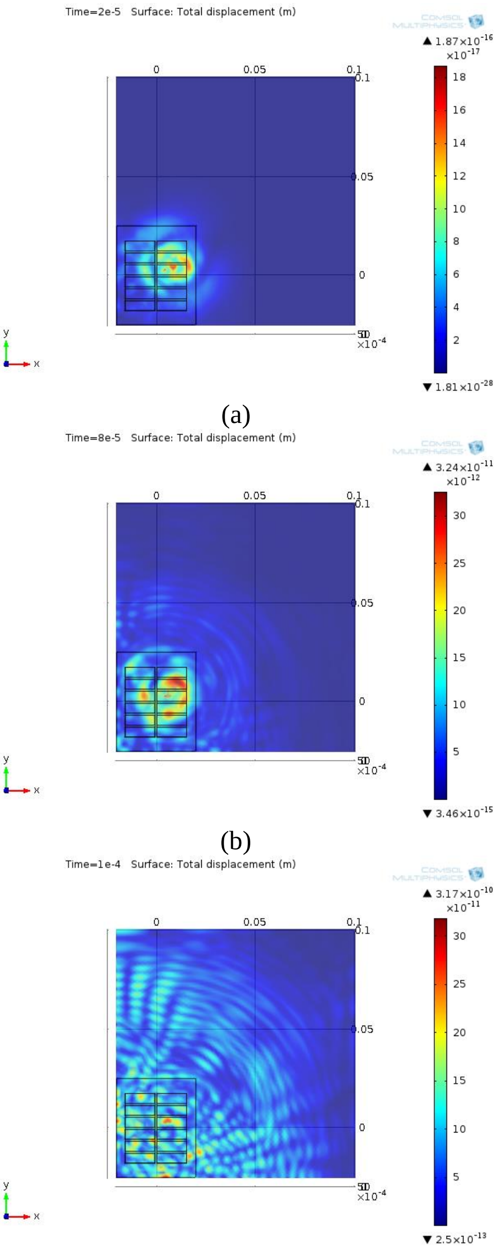


Figure 4. Displacement in x and z direction at a location 75mm away from the EMAT.



(a)

(b)

(c)

Figure 5. Total displacement at (a) 20 μs, (b) 80 μs, (c) 100 μs.

The results show that the ultrasound is focused to propagate along x and y directions, whilst the displacement in other directions is relatively small in a plate. The numerical model for plate can be extended for a tube. The EMAT transducers will be implemented on CSP absorber tubes to detect defects such as crack and mass loss.

5. Conclusions

In this paper, a design of EMAT transducer has been modelled numerically for the generation of UGW to monitor the absorber tubes used in CSPs.

To concentrate the energy, shear horizontal SH0 mode for plate and torsional mode T(0,1) are determined as the best options for this application. The dispersion curve is subsequently calculated at room temperature to select central frequency and calculate the phase velocity in 316L stainless steel which is used in manufacturing of CSP absorber tubes are derived.

Then, the periodic permanent magnet (PPM) and race track coil are selected for the first generation of EMAT transducers. A simulation for this design of EMAT is carried out to investigate excited electromagnetic fields and generated ultrasound, displacement distributions from EMAT transducer. The results show that the ultrasound is concentrated in x and y direction where the displacement in other directions is relatively small, which can be used for the monitoring on both the length and circuference of the tubes.

In future work, the numerical model will be updated with experimental studies on both plate and pipe specimens. In addition, the improved version of EMAT transducers will be designed for high temperature up to 550^{0}C.

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