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Design and Fabrication of the Spiral Coils for Guided Wave Magnetostrictive Transducers

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Abstract We propose rectangular type spiral coils with folded corners for the applications to low frequency guided wave magnetostrictive transducers and describe a method for making the proposed coils from insulated electrical wire such as enameled copper wire. Expressions for the electrical properties of the coils are also presented and compared with experimental measurements. An overlapped-2-channel folded-corner spiral-coil array is fabricated and applied to a magnetostrictive strip transducer generating and detecting fundamental torsional mode guided waves. From the results we conclude that the design and fabrication method make it possible to use the magnetostrictive transducers optimized for various guided wave applications and also will greatly help engineers gain easy access to the optimized transducers.

Keywords: Spiral Coil, Magnetostrictive Transducer, Guided Wave, Long Range Ultrasonic Testing

1. Introduction

Guided wave magnetostrictive transducers have been used for long range ultrasonic testing (LRUT) of large structure elements such as plates, shells, rods, ropes, tubes, and pipes (Kwun and Teller, 1994; Choi et al., 2005; Kim and Choi, 2008). Usually, each transducer consists of a magnet (either permanent or electromagnet) and an RF coil (i.e., coil of wire driven at a radio frequency) array being put near a magnetostrictive material so that a static bias field by the magnet overlaps with dynamic magnetic fields by the coil array which are limited in a region under the material surface by the skin effect. To generate elastic waves in the subsurface region, the transducer takes advantage of the interaction between the combined magnetic fields and the magnetostrictive material. Through reciprocal processes the same transducer can also be used to detect guided waves incoming to the subsurface region. The mode and polarization of generated and detected waves are controlled using the relative orientation between the static bias field and the dynamic magnetic fields which varies with the transduction mechanisms.

Two types of RF coils have been used for the magnetostrictive transducers: a coil encircling channel-shaped ferrite core (Kwun and Kim, 2005) and a solenoid (Choi et al., 2005). The former is used for plate waves, while the latter is used for the guided waves propagating along the axis of a cylindrical structure. Usually, the solenoids have been made from ribbon cables. Due to extremely limited specifications of commercial ribbon cables, use of the optimized solenoids is very difficult. In EMAT field, it has been well known that a spiral coil has more

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superior performance rather than these two coils (Hirao and Ogi, 2003). Nevertheless using the encircling coil or the solenoid for magnetostrictive transducers is attributed to the difficulty of making spiral coils with large size and large aspect ratio which can efficiently generate and detect low frequency (usually less than 200 kHz) guided waves required for LRUT. It has been recently reported that flexible flat cable (FFC) is useful for the fabrication of low frequency spiral coils (Heo and Choi, 2008). Due to limited specifications of commercial FFCs, however, making the spiral coils optimized for various LRUT applications is still not easy. Besides it is expected that the difficulty becomes more serious with increasing wave frequency.

In this paper, a flexible rectangular type spiral coil with folded-corners is proposed for LRUT applications. First of all, the coil design is described and expressions for electrical properties of the coil are derived. Then, described are methods for making such a coil from thin insulated electrical wire such as enameled copper wire and an overlapped-2-channel coil array from the identical two coils. A prototype of such a coil array is fabricated and its electrical properties are evaluated. Finally, the coil array is applied to a magnetostrictive strip transducer for fundamental torsional mode guided waves and then the transducer performance is evaluated.

2. Coil Design

A flexible rectangular type spiral coil with folded-corners, which is proposed in this paper, is made from a thin rectangular or circular electrical wire with an insulation layer, such as an enameled copper wire. Fig. 1 schematically shows a planar view and a cross-sectional view of such a coil made from a rectangular wire. In this figure, t_c and w_c denote the thickness and width of the wire conductor, w_{sc} indicates the width of the spiral coil, l and w_l are the length and width of each leg of the coil, and N means the number of turns of the coil. In order to efficiently generate and detect the guided waves that propagate along the direction perpendicular to the coil legs, the coil should be designed so that the center-to-center distance (b) between the two legs is equal to the half wavelength of the guided waves (thus, $w_{sc} = w_l + b = w_l + \lambda/2$) and the length of legs becomes much larger than the wavelength. In any consideration on the electrical property and the guided wave transduction performance of the coil, the contribution from the other parts of the coil except for its legs is thus negligible. In section 3, one will see that the folded corners of the coil appear in a process of making an easy fabrication of large size spiral coils possible without any degradation of the coil property or performance.

An expression for the DC resistance of the proposed spiral coil is easily obtained as follows:

$$R \approx 2\rho Nl/A \tag{1}$$

In this equation, ρ and A mean the resistivity and cross-sectional area of the wire.

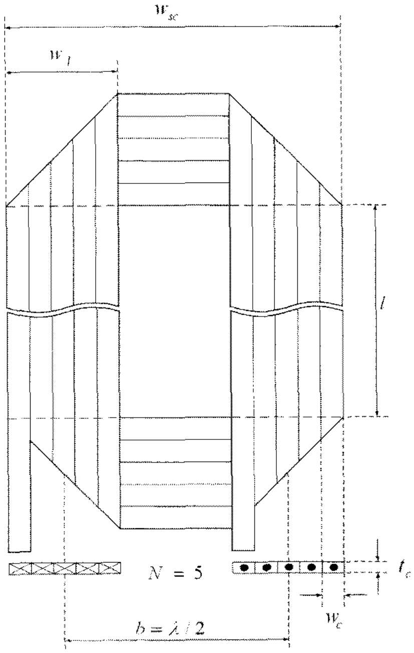

Fig. 1 Planar view and cross-sectional view of a folded-corner rectangular type spiral coil

According to the approach for the meanderline coils or grating coils that have been widely used in the field of EMAT (Frost, 1979), an expression for the inductance (L) of our coil will also be derived. The derivation process requires calculation of the magnetic fields ($\vec{H}$), which are generated by the coil current (I), in all space and use of the following relationship:

$$\int \mu_0 \omega \vec{H} \cdot \vec{H}\, dV = \omega L I^2 / 2 \qquad (2)$$

In this equation, μ_0 and ω are the magnetic permeability of free space and the angular frequency of AC current. The left side of the equation means the volume integral of the time-averaged rate at which magnetic field energy density is stored. The formal derivation process thus becomes very tedious. Here we report another way to the spiral coil inductance expression. It starts from the following expression for meanderline coil inductance (Frost and Szabo, 1976; Frost, 1979):

$$L_{mc} \approx \frac{2}{\pi} m \mu_0 l \sum_{n=1,3,5,\cdots}^{\infty} \frac{1}{n} \left(\frac{\sin n\pi s / 2b}{n\pi s / 2b} \right)^2 \qquad (3)$$

In this equation, s and l indicates the width and length of coil legs, m is the number of the leg pairs where the current flows are opposite to each other, and b means the center-to-center distance of each leg pair. Now, let's consider a meanderline coil and a spiral coil with an identical appearance of coil legs. When the meanderline coil current is N times larger than the spiral coil current, these two coils will produce almost the same magnetic fields in all space. Then, from the fact that magnetic field energy density is proportional to square of current amplitude, one can see that the spiral coil inductance is given as follows:

$$L \approx \frac{2}{\pi} N^2 \mu_0 l \sum_{n=1,3,5,\cdots}^{\infty} \frac{1}{n} \left(\frac{\sin n\pi w_l / 2b}{n\pi w_l / 2b} \right)^2 \qquad (4)$$

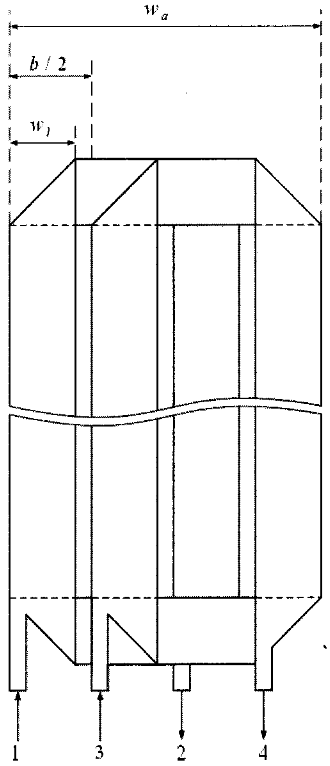

Fig. 2 Overlapped 2-channel spiral coils

Fig. 2 shows an overlapped-two-channel folded-corner spiral-coil array schematically. The two identical coils overlap so that one leg of each coil is placed at the center of the other coil. The offset distance between the two coils is thus given as $b/2$ and the width of the coil array is expressed as follows: $w_a = w_l + 3b/4$. In order to avoid any overlap among the coil legs, the width of the legs should be equal to or less than the offset distance: $w_l \leq b/2$. For example, if $w_l = b/2 = \lambda/4$, then $w_a = 2b = \lambda$. In the figure, the numbers 1 and 2 indicate the terminals of the left (first channel) coil, while the numbers 3 and 4 represent the terminals of the right (second channel) coil. When the coil array is operated according to the phased array principle (Silk, 1984; Heo and Choi, 2008), the direction control of wave propagation becomes possible. This allows us to get a simple echo structure which makes the necessarily following signal analysis easy.

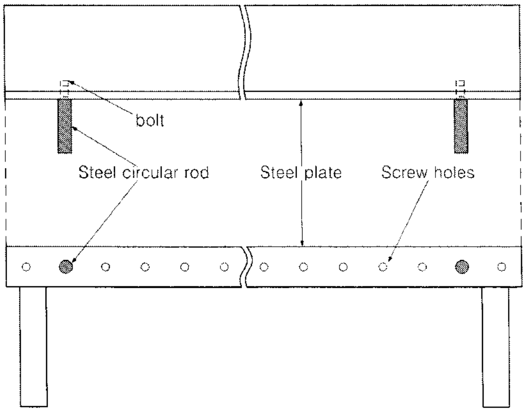

Fig. 3 Worktable used for fabricating flexible loop coils

3. Coil Fabrication and Electrical Properties

The folded-corner spiral coil shown in Fig. 1 is made by folding a flexible loop coil over (or down) so that both surfaces of the coil are switched at the four corners. Therefore an accurate fabrication of the loop coil is most important to get the spiral coil with uniform pattern. In this study, the worktable schematically shown in Fig. 3 was used to fabricate such loop coils. It includes a steel plate which is tightly attached on upper front side of the table. In the plate, there exist periodic several screw holes. Two circular rods are placed at two holes. Each rod, which is made of steel, has with a bolt on the end unseen. The procedure of making a loop coil is as follows: i) Prepare insulated wire of the dimensions determined in the design stage. ii) Place the two circular rods at two screw holes apart almost the same distance as the leg length of the spiral coil and then fasten the rods. iii) Wind the wire tightly so that a short solenoid encircling the two rods is made. The length of the solenoid must be the same as the width of the spiral coil legs. iv) Fix the wire elements in the space between the two rods by bonding single-side adhesive tape to both surfaces of the strip consisting of the elements. v) Loose the two rods slightly and then rotate the wire strip so that unfixed part of wire elements appears in the working space for tape bonding. vi) Fasten the rods again and then fix the remaining wire elements after making them parallel and closely packed. vii) Eliminate extra part of the fixing tape over both edges of the strip of the fixed wire elements by using a heated monofilament wire cutter. This finishes the fabrication procedure of a flexible loop coil. Fig. 4 shows a typical example of such a coil.

Fig. 4 Example of a flexible loop coil

Fabrication of a proposed spiral coil array proceeds as follows: i) Arrange identical two folded-corner spiral coils as shown in Fig. 2 on a flat platform and then fix the arrangement by using single-side adhesive tape. ii) Turn the coil array up and then remove the tapes carefully which were attached during the fabrication process of loop coils. iii) Fix the upper surface of the coil array by using single-side Polyimide tape of slightly wider width than that of the coil array so that the centerlines of the tape and the coil array fall in with a single line. iv) Detach the coil array together with the Polyimide tape from the flat platform. Turn it up again and then put it on the platform. Remove the tapes carefully which were attached during the fabrication process of loop coils and in the first step of this paragraph. v) Bond double-side Polyimide tape of narrow (about 10 mm) width to both edges of the coil array surface. vi) Fix center part of the coil array by using single-side Polyimide tape of the same width as the center-to-center distance of the two double-side

Polyimide tapes so that the centerlines of the tape and the coil array fall in with a single line. vii) Fold the opposite-side Polyimide tape up and then bond it to the two double-side Polyimide tapes. viii) Strengthen the bonds between the Polyimide tapes and make the coil array flat by a using heated roller type press. ix) Insert terminal part of the coil array into a case with a connector, which is used for protecting the terminals form damage and for facilitating its uses, and then fix it by using strong adhesive material, such as epoxy, after connecting the terminals to the connector. x) Closing the case lid finishes the fabrication procedure of the spiral coil array.

Rectangular wire is appropriate for the fabrication of a low impedance spiral coil with the small number of turns, while circular wire is appropriate for a high impedance spiral coil with the large number of turns. Circular wires of various sizes are easily available with low cost, but rectangular wires are not the case. The latter means the low impedance spiral coil fabrication is still not easy. In this paragraph, we describe a method for fabricating such a low impedance spiral coil from insulated circular wire. The description starts from a ribbon cable which is obtained by cutting such a flexible loop coil shown in Fig. 4. The fabrication procedure is continued to the following steps: i) Arrange two identical ribbon cables as shown in Fig. 5. Except for the lowest part of the arrangement, its appearance is the same as that of Fig. 2. ii) According to the procedure described in the above paragraph, fix all the wire elements, except terminal part of the coil array, by using Polyimide tapes. iii) Strengthen the bonds between Polyimide tapes and make the coil array flat by using a heated roller type press. iv) Remove the insulation layers on the wire elements near the terminal part. v) Divide the insulation-removed wire elements into several bundles consisting of almost the same number of elements and then connect the bundles using

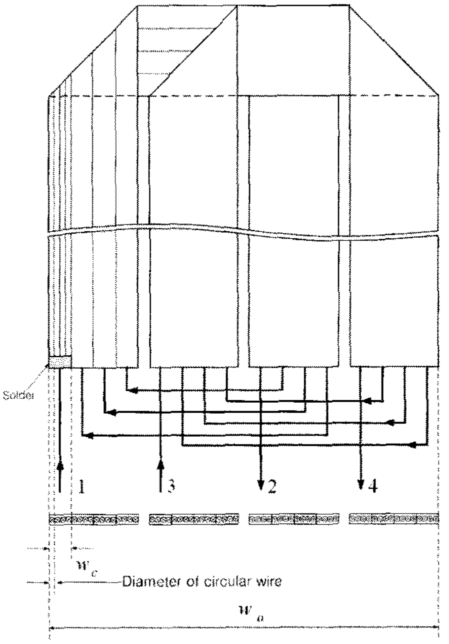

Fig. 5 Schematic diagram of a low impedance spiral coil array including pseudo rectangular wires made from circular wires

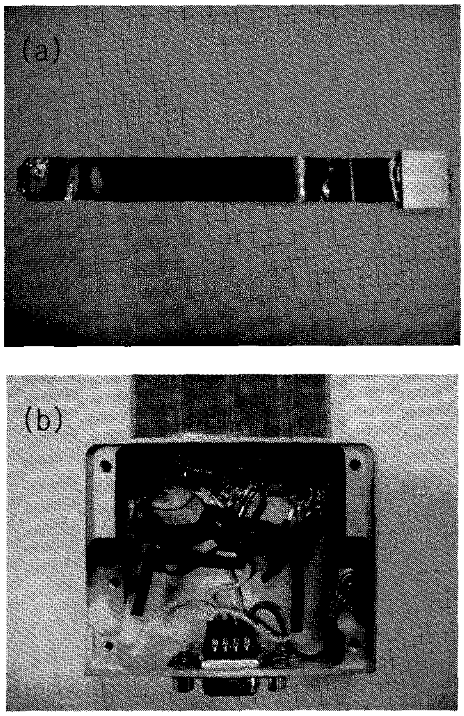

Fig. 6 (a) Prototype of an overlapped-2-channel folded-corner rectangular-type spiral-coil array and (b) a close view of the terminals of the pseudo rectangular wires in the case insulated thick wires of short length so that each ribbon cable is transformed to a spiral coil consisting of pseudo rectangular wire of nearly uniform width. vi) Follow the last two steps described in the above paragraph. This finishes the fabrication procedure for the low impedance spiral coil array.

Fig. 6(a) shows a prototype of the spiral coil array. The width of the array (w_a) was 56 mm. In each coil, the length (l) and width (w_l) of two legs were 500 mm and 13.7 mm, respectively, and the center-to-center distance (b) between two legs was 28 mm. In order to obtain low impedance coils, the procedure described in the above paragraph was applied to the fabrication of the prototype coil array. Each loop coil was made from enameled copper wire of 0.2 mm diameter, while each spiral coil was realized with pseudo rectangular wire including 10 circular wires. The cross-sectional area (A) of rectangular wire is thus given by 10 times $\pi(0.1mm)^2$. The resistivity of the copper (ρ) was $1.72\times10^{-8}\Omega$m, and the number of turns (N) of the spiral coil was 6. Fig. 6(b) illustrates the terminals of the rectangular wires in the protection case with the connector. Table 1 shows the electrical properties of the prototype spiral coil array. The theoretical values were obtained using eqns. (1) and (4). And the experimental values were measured using an LCR meter (Hioki 3235-50). One can see good agreement between theory and experiment. This indicates the proposed fabrication method allows us to get the spiral coil array as designed. On the other hand it implies that a break of any wire or an electrical short among wires was not arisen in the folded-corners.

Table 1 Electrical property of the spiral coil

	Theory	Experiment	
		Average	Deviation
$R(\Omega)$	0.33	0.46	±0.06
$L(\mu H)$	12.3	16.3	±0.07

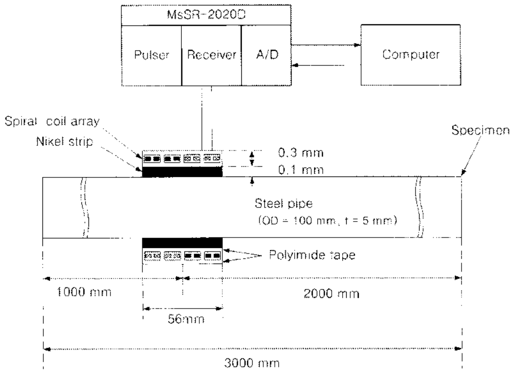

Fig. 7 Schematic diagram of pulse-echo experimental setup for generating and receiving T(0,1) mode guided waves

4. Application to a Magnetostrictive Strip Guided Wave Transducer

Fig. 7 schematically shows a pulse-echo experimental setup for generating and receiving T(0,1) mode guided waves. The specimen was a carbon steel pipe of 3 m length, 100 mm diameter, and 5 mm thickness. The magnetostrictive transducer, which was placed at about 1/3 length position on the pipe, consisted of a nickel strip (0.1 mm thickness, 56 mm width, and 314 mm length) and the prototype spiral coil array. The ferromagnetic strip was bonded to the pipe specimen along the circumference by using 5-minute epoxy. The coil array was set to encircle the strip bonded to the pipe. The electronics operating the transducer was MsSR-2020D system supplied from Southwest Research Institute, USA. In fact, the width of the strip and the coil array was designed with a consideration of shear wave velocity (about 3050 m/s) in the nickel strip so that the center frequency of the transducer becomes about 50 kHz. Although not shown in this figure, an U-shape permanent magnet was also used to form a residual magnetization in the strip that was required for the T(0,1) mode operation of such a magnetostrictive transducer (Kim and Choi, 2008). Its length and the center-to-center distance between two poles were 90 mm and

20 mm, respectively. The magnetic field strength near each pole was about 0.6 T.

Experimental procedure was as follows: i) The pulser was set to generate sinusoidal pulses of 50 kHz, 2 cycle and 30 V amplitude. ii) The receiver was set so that its overall gain becomes 40 dB and the wideband filter is used. iii) The sampling rate, the number of samples, and the number of data sets for averaging signals were set to be 1.5 MHz, 3600, and 500, respectively. iv) The direction control was set to generate the guided waves toward the both ends of the pipe and to detect reflections from the ends. v) The signal data were acquired and stored in the computer and then it was repeated after changing the direction control to generate the guided waves toward the right (or left) end of the pipe and to detect the end reflection.

Fig. 8 shows the experimental results. The top, middle, and bottom traces represent the guided wave signal data for the both-, left-, and right-side direction control, respectively. The data for the both-side direction control include three echoes. Echo 1 is the left end reflection signal of the guided wave generated toward the left end, while Echo 2 is the right end reflection signal of the guided wave generated toward the right end. Echo 3 is a result of superposition of two signals which are detected after the generated two waves experience reflections from both ends. The data for the one-side direction control show enhancement of the corresponding echo and descent of the other echoes. The S/N ratio was about 38 dB. And the direction control capability was 97 %, which was evaluated from a relative amplitude ratio between Echo 1 and Echo 2.

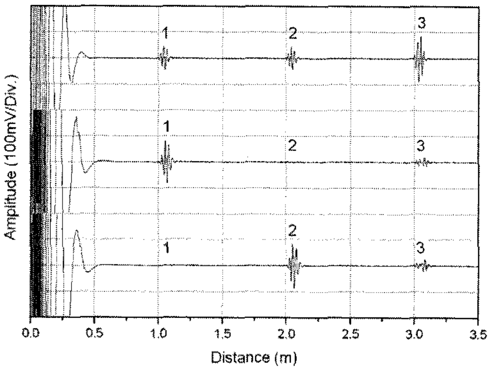

Fig. 8 Guided wave signals obtained using the spiral coil magnetostrictive strip transducer. Top, middle, and bottom traces show those generated toward and detected from both sides, left side, and right side of the transducer, respectively

5. Conclusions

According to the method presented in this paper, a rectangular type thin and large spiral coil with folded corners is easily made from insulated electrical wire such as enameled copper wire. The electrical properties of such a coil with large aspect ratio can be predicted analytically. Various wires are commercially available with low cost, which are so flexible that the insulation layers are not broken by folding. These will make it possible to use the magnetostrictive transducer RF coils optimized for various LRUT applications. It is also expected that these greatly help engineers gain easy access to the optimized transducers.

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