A NOVEL LINEAR ARRAY SYSTEM FOR INSPECTION OF LARGE METAL SURFACES

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INTRODUCTION

Recently, much effort has been focused on the development of arrays for the non-destructive testing (NDT) of metal structures in offshore, nuclear and aerospace industry, eg: [1-2]. The main feature of these arrays is electronic scanning which reduces (or eliminates) mechanical noise and makes rapid scan of large areas possible. Some arrays can also provide opportunity for direct signal processing of data. This paper is concerned with a linear array using the non-uniform field ac field measurement (ACFM) technique which is also known as the surface magnetic field measurement (SMFM) method [3].

In the NDT of metal surfaces involving the SMFM technique, a high frequency current carrying structure is used to induce a thin skin eddy current in the work-piece and a probe to sample the field tangent to the metal surface [4]. The rhombic wire loop has a flat profile and a narrow shape and possesses a field region with odd symmetry [5]. These properties make the rhombic wire loop a suitable inducer for developing long linear flexible arrays for the SMFM inspection of large flat and curved surfaces of ferrous and non-ferrous metals. The probe used with the rhombic inducer is a linear wire-wound coil which is attached below the inducer along its major diagonal. It picks up the field tangential to the metal surface. Fig.1 shows the probe-inducer structure and the field pattern of the inducer near a metal surface.

ARRAY STRUCTURE

The structure in Fig.1.a is the building block of the linear array. The novel feature of this structure is the differential behavior of the single probe. The way that the structure operates to detect cracks and defects in metal surfaces has already been explained fully in a previous paper [5]. In brief, when the probe is symmetrically located with respect to the minor diagonal, it is subjected to opposite equal fields and hence is balanced in the absence of a crack. Under this ideal condition, the voltage induced in the probe is nil. Near a crack, the voltages induced in the two parts of the probe located on either sides of the minor diagonal, are not the same and hence a voltage appears at the probe output. Usually, the probe is made slightly off-balanced in order to be able to normalize the crack signal to the voltage in the absence of a crack. This reference voltage is essential if the crack signal is to be inverted to the crack size using mathematical modeling. A signal (including the phase, magnitude and the reference voltage, V_r) associated with the scan of a 4 mm deep uniform saw-cut notch in mild steel ($\mu_r \approx 100$ and $\sigma = 1.6 \times 10^6$ S/m) by a structure similar to that in Fig.1.a, is shown in Fig.2. This signal is typical of a crack signal [5]. The theoretical signal is also shown in the same figure for comparison. It was obtained using a computer program developed by the authors [6].

The schematic diagram of a linear array using the rhombic inducer and a prototype

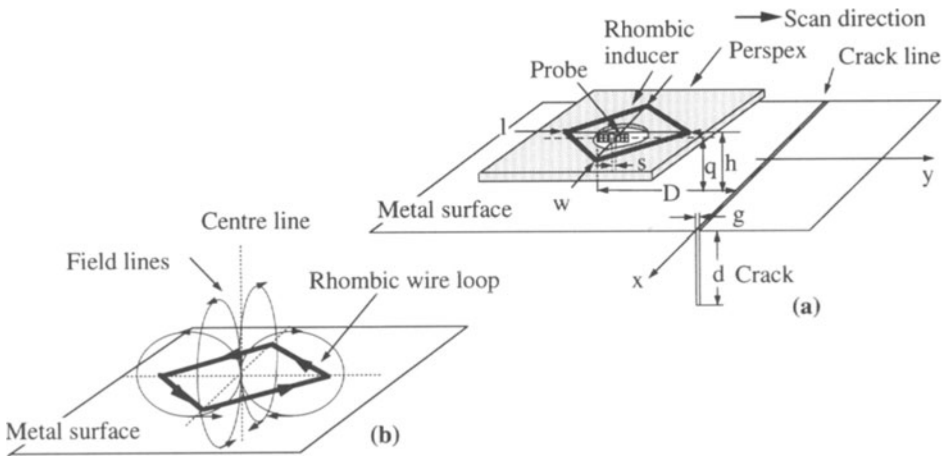

Fig. 1 (a) The schematic diagram of a rhombic wire loop and a linear probe attached below the long diagonal. The probe offset 's' is the distance between the short diagonal and the middle of the probe. (b) The field pattern of a high frequency current carrying rhombic inducer close to a metal surface.

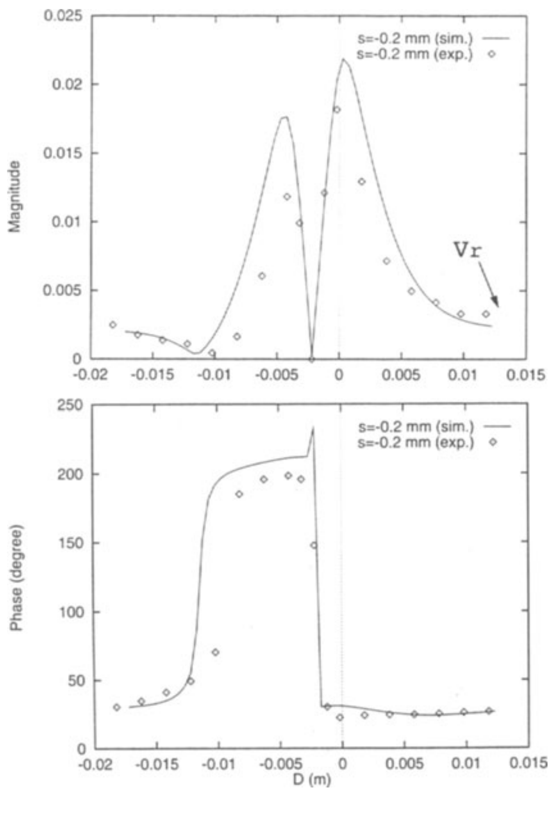

Fig.2 Magnitudes and phases of signals from the scan of a 4 mm deep saw-cut notch (with opening g = 150 μm) in mild steel by the probe-inducer structure shown in Fig.1; w = 11.5 mm, l = 21.5 mm, h = 3.16 mm, q = 0.76, s ≈ - 0.2 mm, probe length = 4 mm, no. of probe turns = 80, probe layers = 2, probe core diameter = 0.88 mm, probe wire gauge = 0.0032" and f = 20 kHz.

array with 28 elements, is shown in Fig.3. The currents in the consecutive inducers must be in opposite directions in order to have sensitivity to long cracks. When the currents are in the same direction, the resultant field is uniform close to the inducer and hence gives rise to a uniform eddy current. If such a current is parallel to the crack line, it was found that its perturbation by a long uniform crack is insignificant. To fabricate long arrays with opposite currents in neighboring cells, two-sided thin printed circuit boards can be used. On each side a zigzag narrow metal track is produced. These are connected together at one end and fed on the other. For experimental arrays (eg: Fig.3.b), thin insulated wires were used. They were glued to the required shape on a thin perspex substrate, crossing each other at joining rhombic loops.

A signal generator through a current source feeds the array, Fig.4. The switching mechanism to obtain data from the array is sequential and can be easily repeated for any

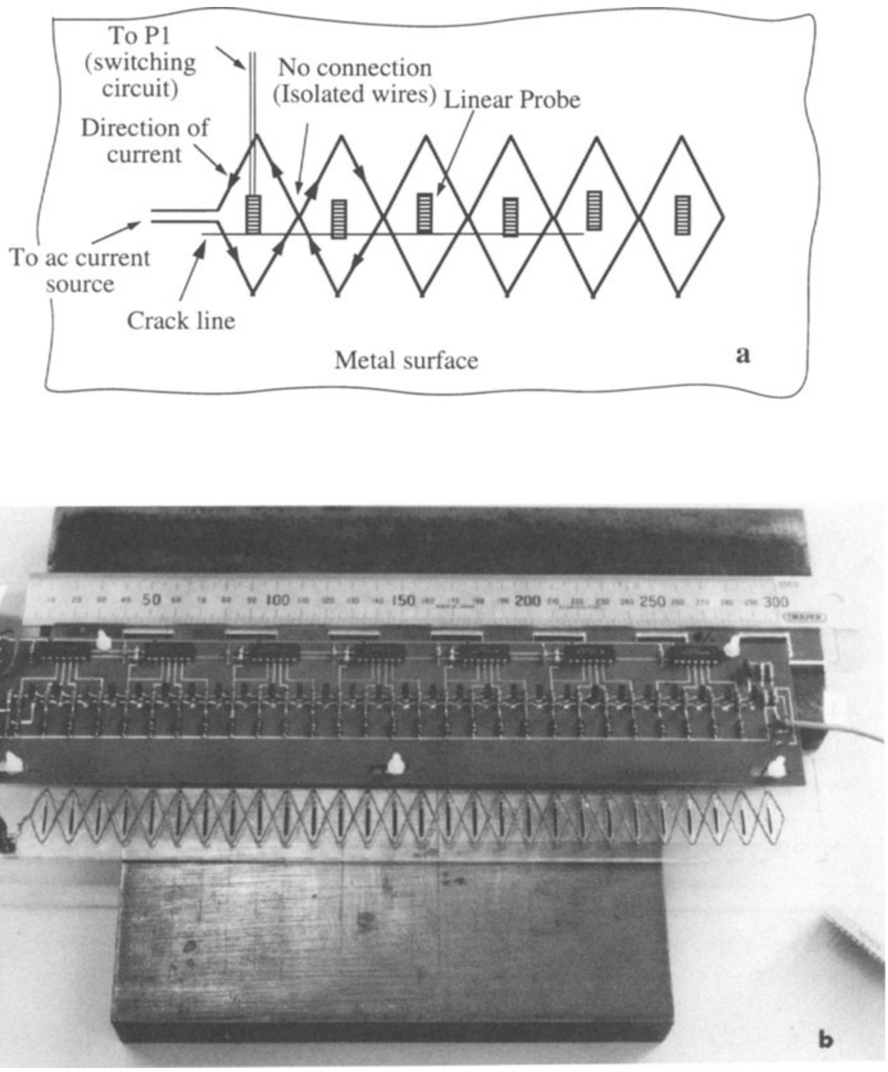

Fig.3 (a) The schematic diagram of a linear array using the rhombic inducer and the linear probe shown in Fig.1 and (b) the prototype 28 element array with the switching system.

length of array. It consists of sequentially connected shift registers and transistors. The input to the switching system is the clock and the start ('on') bit. In this switching circuit, a transistor receives a pulse and trips to an amplifying stage while other transistors are 'off'. One important feature of the circuit is the use of the same collector and emitter resistors for all the transistors. As a result, there are always two wires for the output for any number of array elements and no extra resistor is required at the collector and emitter of transistors. However, this advantage is achieved at the expense of a resistive loading between the collector and emitter of an 'on' transistor. This resistor is equivalent to the parallel sum of all the resistors between the collector and emitter of all 'off' transistors. As the length of the array increases, this resistor reduces in value and eventually short circuits the 'on' transistor. This effect imposes a limit on the length of the array. The limit depends on the type of the transistor.

In the system developed for crack detection, Fig.4, the array output which is a train of sinusoidal pulses from the probes, is sampled with an A/D and the data is stored in a computer. The computer is also responsible for controlling the start of sampling by sending the 'on' pulse to the array. The clock is externally supplied to the array. The computer is also used to process the data which is explained in the results section.

In an array, ideally, the inducers and the linear probes should be identical and probes should have the same location in all inducers. Although reaching close to the ideal condition is possible by resorting to automatic manufacturing, prototype arrays made by hand cannot enjoy a high degree of uniformity. In particular, achieving the same offset for all the probes is almost impossible. Also a small gain variation from transistor to transistor was observed, in spite of using a potential divider circuit for the transistors to achieve gain uniformity. As a result, the sinusoidal pulses received from the probes do not have the same amplitudes in general, even if the array is not over a crack. In order to detect a crack with the array, the signal received from each probe in the presence of the crack is subtracted from that obtained in the absence of the crack. This procedure is, however, acceptable as long as the phase of the signal does not change considerably from no crack to crack position. In view of Fig.2, showing typical phase and magnitude variations with the probe location, this condition is guaranteed if probes are applied just over the crack, Fig.3.

RESULTS

A prototype 28 element array with its switching electronics is shown in Fig.3. The width and length of the rhombic inducers are 11.5 mm and 21.5 mm respectively. The probes are double layer linear coils of 10 mm length, consisting of 200 turns of 0.0032" gauge wire on a core with a diameter of 1.18 mm. The rhombic inducers are on the top of a

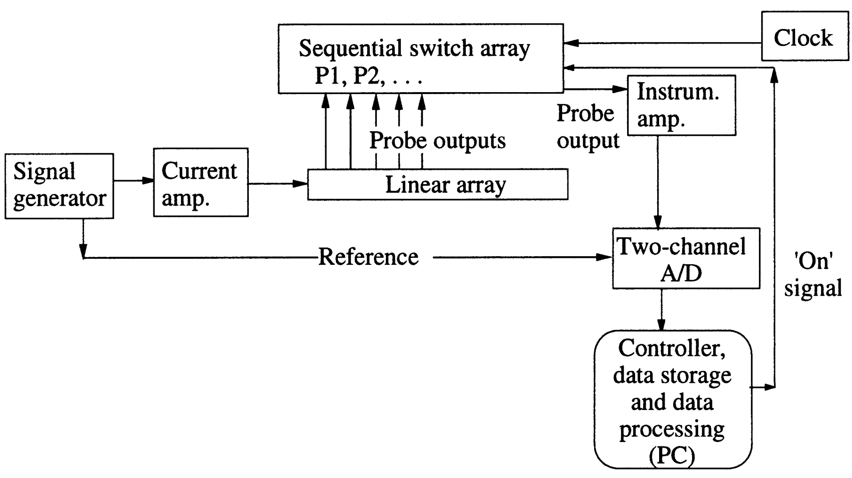

Fig.4 The block diagram of the detection system for the linear array.

sheet of 3 mm thick perspex and probes are located inside slots cut into the perspex along the major diagonal of the inducers. A plastic layer of 0.08 mm is applied to the bottom of the perspex to close the slots. The probes in the slots rest on this plastic layer. The operating frequency for the experiments whose results are shown here, was 20 kHz and the sampling rate for the A/D was 125 kHz. The clock was running at 100 Hz, corresponding to 0.01 s connection time between the A/D and each probe. Therefore, the area under the array, which is about 2 cm x 28 cm, is effectively scanned in 0.28 s.

Signals from this array when it was applied to a mild steel block containing an arc-circular saw-cut notch simulating a fatigue crack, is shown in Fig.5.a. One set of signals is for the case when the array was off the notch and one set is for the case when the probes 9,

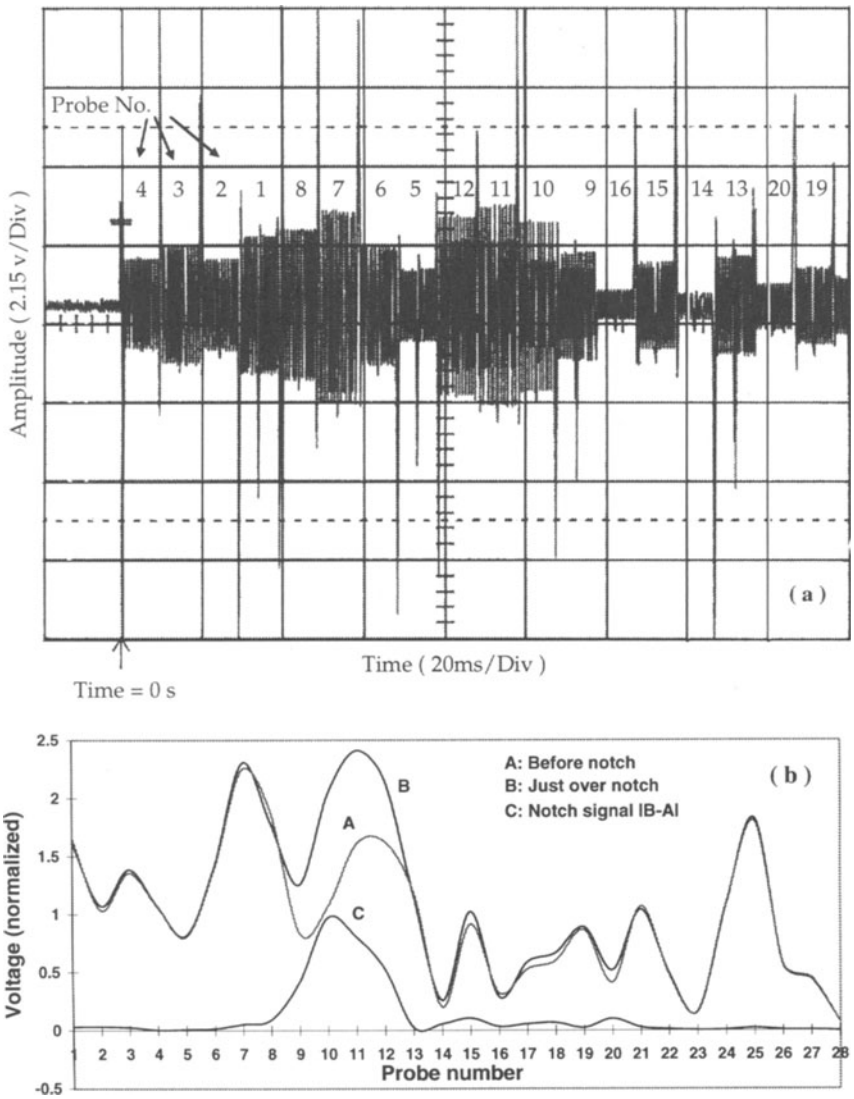

Fig.5 (a) The modulated signals (sinusoidal pulses) from the array in Fig.3.b when it was off and on the arc-circular notch and (b) the software demodulated signals (A and B) and the resultant (crack) signal (C). In this experiment, the probes liftoff q = 0.83 mm.

10, 11 and 12 were slightly over the notch. The length of the notch is 38 mm, its opening g=120 μm and its maximum depth (depth in the middle of the notch), is 5 mm. As Fig.5.a shows, the presence of the notch under the array has significantly changed the signals from the mentioned probes. Software has been developed to demodulate pulses after arriving at the computer. The software has two important features: it ignores the spikes from the switching circuits, Fig.5.a, and it averages over several periods of sinusoidal waveform within a pulse duration in order to reduce the effect of noise. After the demodulation of pulses, the software then subtracts the two sets of demodulated signals. The results for the set of signals in Fig.5.a is given in Fig.5.b, clearly showing the presence of the notch. Since the computer also samples the waveform from the current amplifier, if required, it is possible to detect the change of the phase of signals and produce a more accurate picture for the crack signal.

Further results are shown in Fig.6. The signals labeled A, B, C, D and E correspond to the application of the prototype array to 0.5 mm, 1 mm, 2 mm, 3 mm and 4 mm saw-cut notches of g=0.15 mm opening in a mild steel test block. Signal F is from a closed (invisible) fatigue crack in a mild steel block of the same width as the test block. Comparing F with signals from the notches, it is clear that the crack has not propagated to the whole width of the block and it has a maximum depth between 3 mm and 4 mm. In the experiments leading to results in Fig.6, the current to the inducer was maintained the same.

CONCLUSIONS

A novel linear array together with its electronics for the inspection of large metal surfaces is reported. The array uses the surface magnetic field measurement (SMFM) technique to detect defects in metals. It can also be used to size surface cracks. The array employs a sequential switching system for sampling the output from each probe. In the switching system, the number of outputs and inputs does not depend on the number of array elements. The array can be made in long lengths. The maximum length is dictated by the collector-emitter resistance of the transistor used in the switching circuit. Another factor limiting the array length is the amount of data which should be captured and processed by the software responsible for the signal processing, especially if the detection is to be carried out in real-time. The array can be made on flexible printed circuit boards when applications on curved metal surfaces like offshore structures and aircraft panels, are required. The performance of the array was found to be excellent for the detection and sizing of various types of surface cracks.

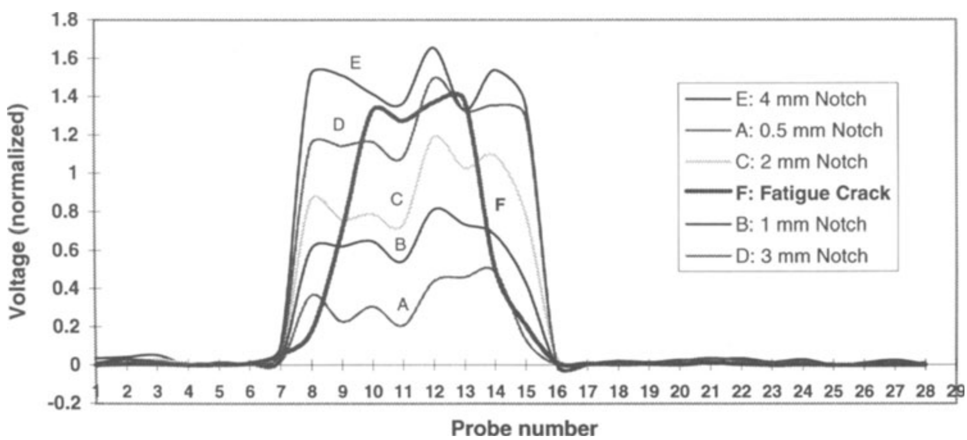

Fig.6 Results of the application of the array to a set of notches in a mild steel test-block and to a closed (invisible) fatigue crack in a mild steel block with the same width as the test block. In these experiments, the probes liftoff q = 0.83 mm.

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