A multiple wire magnetostrictive delay line for improved signal and reduced reflections

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Abstract. The amplitude of the output signal per unit of cross sectional area of a magnetostrictive delay line decreases for increasing wire diameter due to the skin effect. For a fixed area a large output signal can be obtained by using a number of thin wires. An additional advantage is the reduced influence of inhomogeneities along the wires. Reflections in this multiple wire delay line can be reduced firstly by means of interference by fixing half of the number of wires to a mass and leaving the other half ends free, and/or secondly through spreading out the reflections by shifting the ends of the wires with respect to each other. A simple magneto-acoustic position measurement system using a multiple wire delay line and one single transmitting/receiving coil is demonstrated.

1. Introduction

The amplitude of the output signal in a magnetostrictive delay line is determined by the construction of the coils and the magneto-elastic properties of the transmission medium (Epstein and Stram 1957). Two methods have been employed to increase the output signal for a given input power. A phase compensation network for the output signal of successive receiving coils (Makowiecki 1977), and autocorrelation of transmitting and receiving coils in a Barker sequence (Worthington and Thompson 1980, Thompson and Worthington 1980). A third method using a multiple wire delay line will be discussed below.

2. Generation and detection of acoustic pulses

The longitudinal stress pulses in a delay line are generated by a magnetic field pulse in a transmitting coil around a magnetostrictive medium, propagate with the velocity of sound v in both directions, and are detected in a receiving coil by means of the inverse magnetostrictive effect (see figure 1). The output signal can be deduced using the equivalent circuit for the magnetostrictive transducers (the coils) and the delay line and the Laplace transform of the transfer admittance of the delay line (Onoe 1962). Here the duration of the current input pulse t_p is chosen equal to time L/v , the time taken to propagate over the effective length L of the field of the coil, resulting in a maximum peak amplitude of the output signal. The wire is biased in a DC magnetic field along the wire.

Due to eddy currents the applied magnetic field pulse with the assumed constant amplitude H_0 over the effective length of the transmitting coil will diffuse only gradually into the wire.

For a plane conductor the field at depth x at time t after switching on the field, is given by the relation (Gray 1972):

$$H(x, t) = H_0 [1 - \operatorname{erf} 0.5(\mu\sigma t)^{1/2}]$$

where μ is the permeability, σ is the conductivity of the

Figure 1. Scheme of magnetostrictive delay line (a), the current pulse in the transmitting coil (b) and the amplified output signal in the receiving coil (c). The time delay is given by the ratio of the distance between the coils and the velocity of sound.

conductor and erf is the error function given by the relation

$$\operatorname{erf} u = 2/\sqrt{\pi} \int_0^u \exp -t^2 dt.$$

Now the penetration depth d will be defined as the value of x for which the field has decreased by a factor e at the end of the current pulse $t = t_p$. For a microsecond pulse the penetration depth is a few micrometers for nickel. It means that the field is restricted to the skin of the wire if the radius r of the wire is a factor ten larger than the penetration depth d .

The amplitude of the output signal is proportional to the area $2\pi r d$ where the acoustic pulse is generated by the magnetostrictive effect. Per unit area of the wire cross section this output signal is then proportional to the inverse radius.

This has been verified experimentally for Permenorm wires (see figure 2). Similar results have been obtained for nickel and

Figure 2. Amplitude of the output voltage per unit of cross sectional area of the wire as function of the inverse radius of the wire for Permenorm 5000H3.

are in agreement with other data (Thompson and Lyon 1956). In these experiments the transmitting and receiving coils, both having a length of 1.0 mm and an inner diameter of 2.0 mm, consisted of 100 windings of 0.025 mm diameter copper wire. A current pulse of 60 mA results in an axial field of $\sim 1200 \text{ A m}^{-1}$. A typical value of the DC bias field, generated by a pair of air coils coaxial with the transmitting and receiving coils, is 4000 A m^{-1} . The signal of the receiving coil is electronically amplified by a factor 400.

For a given cross sectional area of the transmission medium a large output signal can be obtained by using a number of thin wires, each having a larger output signal per area, instead of a single wire. The total amplitude of the output signal is proportional to the number of wires. No electromagnetic screening effect of the inner wires by the outer ones has been observed.

The gain of a multiple wire delay line consisting of n wires with radius r over a single wire with radius R is nr/R . A single wire with radius R can be replaced by approximately $\lambda R^2/r^2$ wires with radius r with a similar overall cross sectional area, where λ is the space factor (0.65–0.75). In this case the gain is $\lambda R/r$. The experimental gain of 3.5 for 19 nickel wires with radius 0.05 mm over a single wire with radius 0.25 mm is in good agreement with the theoretical value. An important advantage of a multiple wire delay line is that the influence on the amplitude of the output signal of local inhomogeneities along each wire are averaged out, whereas each transducer consists of a single coil (which is not the case for the previous mentioned methods).

3. Reduction of reflections

By using a multiple wire delay line two simple methods can be employed to reduce reflections. The first reflections can be eliminated almost completely by interference for each pair of wires by fixing one end to a mass (incident and reflected pulse have same phase) and leaving the other wire end free in the same position (reversed phase of reflected pulse). The resulting output signal of both reflected pulses with opposite phases is zero (for two wires shown in figure 3).

Secondly the reflections can be split up in the individual contributions of each wire by shifting the ends of the wire with respect to each other, as is shown for four wires in figure 4.

These two methods can be used simultaneously and in combination with an absorbing termination (e.g. neoprene (Thompson and Lyon 1956)). It is also possible to combine

Figure 4. Spreading out of output signal due to reflected acoustic pulses (a) for four wires with free ends (b).

these methods in conjunction with phase compensation and autocorrelation methods.

4. Discussion

For magneto-acoustic position measurement the accuracy is among others determined by the slope of the output signal. This slope can be increased by several methods as mentioned above. Some variants are feasible. Autocorrelation has been achieved by sending successive current pulses in a Barker sequence in a single transmitting coil whereas the receiving coils are wound in the corresponding order. The duration and separation of the current pulses can be adjusted to obtain an optimum output signal.

A very simple position measurement system has been realised using a multiple wire delay line and one and the same coil for the generation as well as the detection of the acoustic pulses (see figure 5). The time is determined between the current pulse and the reflected pulse at one end of the line where all wires are fixed to a mass; the other end has half of the number of wires fixed to a mass and the other half free, in combination with an absorbing pad, eliminating the reflections of this side.

Figure 3. Interference of output signals due to the reflected acoustic pulses in two wires (a) with one fixed and one free end in the same position (b); and separated reflections (c) by shifting free and fixed ends (d).

Figure 5. Magneto-acoustic position measurement using a multiple wire delay line with a single generating and receiving coil. The time delay is given by the ratio of two times the distance between the coil to the fixed ends and the velocity of sound.

5. Conclusion

It has been shown that a multiple wire delay line gives a large output signal for a given input and cross sectional area of the line. The influence of local inhomogeneities on the amplitude of the output signal is reduced. Two simple methods to reduce reflections are feasible. A simple magneto-acoustic position measurement system using a multiple wire delay line has been demonstrated.

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