Detection of Bending Stresses in Buried Pipelines

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Detection of Bending Stresses in Buried Pipelines

Abstract
When gas or oil pipelines must be laid through sand or permafrost or other unstable soils, the pipe walls can be subjected to large bending loads if the soil shifts. In order to detect this condition and correct it, it would be useful to monitor the state of stress along the pipeline at regular time intervals using a vehicle that is moved through the line by the fluid or gas in it. The experiments described here demonstrate that such a vehicle, using EMATs to excite and detect ultrasonic waves in the pipe wall, would be feasible because the transduction efficiency of the EMATs and thus the insertion loss of such a system can be related quantitatively to the stress level in the pipe wall.

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DETECTION OF BENDING STRESSES IN BURIED PIPELINES

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ABSTRACT

When gas or oil pipelines must be laid through sand or permafrost or other unstable soils, the pipe walls can be subjected to large bending loads if the soil shifts. In order to detect this condition and correct it, it would be useful to monitor the state of stress along the pipeline at regular time intervals using a vehicle that is moved through the line by the fluid or gas in it. The experiments described here demonstrate that such a vehicle, using EMATs to excite and detect ultrasonic waves in the pipe wall, would be feasible because the transduction efficiency of the EMATs and thus the insertion loss of such a system can be related quantitatively to the stress level in the pipe wall.

INTRODUCTION

Whenever a gas or oil pipeline must be laid in unstable soil (such as in permafrost or on a sandy ocean floor), it may be subjected to earth movements which can bend an entire section of the line. The bending stresses thus induced in the pipe wall when added to the stress arising from the high pressure contents of the pipeline may lead to critical stress levels and possible rupture of the line. To avoid such a catastrophe, the designer must consider the worst case and must specify additional wall thickness along the entire route that is in unstable soil. If a reliable inspection method could be devised to monitor the stress level in the pipe walls, less steel would have to be used because the development of dangerous amounts of bending could be detected and corrective actions taken before the safety of the line becomes questionable.

Several years ago, it was shown that an instrumented vehicle could be sent through a pipeline to inspect it for wall thinning flaws by an ultrasonic Lamb wave technique. The transducers used to excite and detect the Lamb waves were of a noncontacting, electromagnetic type that utilized the magnetostrictive properties of the steel for interconversion of electrical currents and ultrasonic waves. It was later demonstrated in the ARPA/AFML program that this magnetostrictive mechanism of transduction was very sensitive to the presence of stresses in the metal under the transducer coils. In fact, a measurement of the efficiency of transduction as a function of applied magnetic field could be used to make a quantitative determination of both the direction and magnitude of this stress level. An example of these previous results is shown in Fig. 1 which plots the amplitude of acoustic wave generated by an Electromagnetic Acoustic Transducer (EMAT) as a function of applied, tangential magnetic field for different states of stress in a bar of iron under the transducer. Clearly, by characterizing the shape of each curve with a single parameter, the value of that parameter could be used to infer the magnitude and sign of the stress level acting on the metal.

The objective of the experiments described in this paper was to demonstrate that by combining the ultrasonic technique for detecting flaws in a buried pipeline with the phenomena of stress dependent transducer efficiency, it would be feasible to monitor bending stresses along a gas or oil pipeline traversing a region of unstable soil. The approach used was to assemble a mechanical device for bending a 36 inch
diameter, 40 foot long piece of gas linepipe at the Science Center and then to measure the magnetic field dependence of the transduction efficiency of a EMAT placed in the region of maximum wall stress. By placing the EMAT at different locations around the circumference of the bent pipe, it should be easily possible to observe the effects of both the compressive and tensile stresses that occur on opposite sides of such a bent structural element.

**EXPERIMENTAL APPARATUS**

Since an EMAT system for detecting flaws in large diameter pipes was already available at the Science Center, the most serious problem was the construction of a device to subject a large diameter pipe to a bending stress. Figure 2 displays a drawing of the apparatus designed to convert the force of a 200,000 pound capacity hydraulic jack into a bending moment. If the pipe could be considered as a rigid beam, simple mechanical formulae show that 200,000 pounds of force at the jack should deflect the two ends of the pipe by 1.7 inches and subject the 0.4 inch thick pipe wall directly under the jack to a tensile or compressive stress of 47,000 psi (assuming a 22 degree angle for the pull rods). Figure 3 shows a photograph of the completed mechanical structure which used four, 2 inch diameter aluminum alloy pull rods to transfer the load from the jack to the ends of the pipe.

Electrical resistance strain gages were distributed around the interior circumference of the pipe to make measurements of the actual state of stress in the pipe wall so that the pressure in the hydraulic jack or the end deflection values could be used to deduce the values of stress existing in any given experiment. Figure 4 shows the values of the strain observed at two key locations around the ID of the pipe as a function of deflection of the end of the pipe and the hydrostatic pressure in the 20:1 intensifier that supplied the jack.

The acoustic measurement apparatus consisted of an electromagnet in the center of the pipe under the jack support with a flexure wave generating EMAT between its pole pieces. This transducer acted as a generator of 130 KHz ultrasonic waves which propagated along the length of the pipe to a receiver EMAT mounted between the pole pieces of a large permanent magnet positioned about five feet away. In this way, the relative signal amplitude generated by the transmitter EMAT could be measured as a function of current in the electromagnet coils. It was very important that this electromagnet be powerful enough to generate a magnetic field sufficient to achieve the maximum in transducer efficiency that characterizes the magnetostrictive mechanism of acoustic wave generation.

**EXPERIMENTAL RESULTS**

The experiment consisted of recording measurements of the received signal amplitude at many different values of electromagnet current (both positive and negative) for a series of fixed settings for the bending load on the pipe. Figure 5 displays an example of these data for three different stress levels in the pipe.
Fig. 5. Experimental results showing the variation of EMAT signal generated by a transmitter EMAT in the gap of an electromagnet whose current was varied from -8 to +8 amperes. (a) Data for the EMATs on the bottom ID of the pipe. (b) Data for the EMATs on the top ID of the pipe.

Pipe wall under the transmitter EMAT. Compression was achieved by mounting the electromagnet and EMAT on the top of the ID of the pipe while tension was obtained for the EMAT on the bottom of the ID of the pipe. Obviously, the presence of a stress dramatically changes the shape and magnitude of the signal versus electromagnet current curves. The maxima in transduction efficiency are increased and moved to lower electromagnet currents by a tension while the opposite occurs under compression. In fact, the presence of a compressive load almost eliminates the magnetostrictive enhancement of the transduction process and spoils the response of the entire EMAT system.

In order to use this relationship between stress and EMAT efficiency as a quantitative tool to measure the stress levels in bent pipelines, it is necessary to extract a single parameter from an observed signal versus electromagnet current curve and to establish a calibration curve for this parameter as a function of stress. Because the signal voltage received in a particular experiment depends upon such uncontrollable variables as the spacing between the transducer coil and the pipe wall as well as on the gain and bandwidth of the particular electronic system used, the measured signal voltages must be normalized to eliminate sensitivity to these variables. Likewise the current in the electromagnet does not fully define the magnetic field at the transducer because variations in the pole-piece to pipe wall gap have a strong influence on the magnetic field distribution. Thus, the electromagnet current must also be normalized. The existence of a maximum in the experimental curves (Fig. 5) provides an excellent normalization opportunity because each curve can be replotted with the signal voltages normalized to the maximum signal voltage and the currents normalized to the electromagnet current needed to achieve the maximum in efficiency. This yields curves with unitless coordinates that are independent of the values of transducer lift-off, receiver gain and electromagnet pole gaps that are characteristic of a particular measurement situation.

The most obvious characteristic of these curves that changes with the stress level is the sharpest or width of the dip in efficiency around zero current. An easily determined parameter that measures this dip width is the difference in current between points at which the signal amplitude has fallen to half its maximum value. For normalization purposes, this difference in current can be divided by the difference in electromagnet current between points at which the maximum in transducer efficiency is observed. Thus a unitless, normalized parameter that qualitatively varies with stress level can be deduced from data such as that shown in Fig. 5 by using the formula

$$ P = \frac{I^+(v_1) - I^-(v_1)}{I^+(v_0) - I^-(v_0)} $$

(1)

where $I^+(v_1)$ is the current at which the signal voltage is half its maximum value for a positive current, $I^-(v_1)$ is the current at which the signal voltage is half of its maximum value for a negative current, $I^+(v_0)$ is the current at the maximum signal for positive currents and $I^-(v_0)$ is the negative current at which a maximum signal occurs.

Figure 6 plots this parameter value as a function of the stress in the pipe under the transducer. It can be seen that a reasonably linear relationship exists so that a measurement of the parameter under unknown stress conditions could be used to deduce the stress level present. The accuracy of this procedure can be assessed by performing a statistical analysis of the data. Such an analysis yielded the result that the line shown in Fig. 6 has a correlation coefficient with the data of 0.96 and that a measurement of the parameter could predict the highest stress level of 50 KSI to an accuracy of ±15 KSI.
CONCLUSION

Figure 5 shows that the presence of a bending stress in a pipe makes an easily recognized change in the magnetic field dependence of an EMAT's efficiency. By extracting a unitless parameter from the curve of signal voltage versus electromagnet current, a value of the stress and its sign can be deduced from a calibration curve such as shown in Fig. 6. In these initial experiments, an accuracy of ± 15 KSI was achieved. This translates into being able to monitor the bending stress levels in a pipeline to an accuracy of 25% of the yield stress since most line pipe has a yield strength of 60 to 70 KSI.

A measurement device for monitoring stress in a pipeline would consist of an electromagnet powered EMAT on a carriage that is pushed through the pipe by the fluid it carries. At regular intervals the current in the electromagnet could be driven through a programmed cycle while the ultrasonic signals generated by the EMAT were monitored. An on-board microprocessor could then extract the parameter from the electrical measurements and record its value along with the carriage location information on a tape recorder for subsequent analysis. By using four such electromagnet-EMAT systems around the circumference of the pipe, the maximum bending stress could be deduced at any given location.

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