1977

THE DEVELOPMENT OF A PORTABLE STEEL REINFORCING BAR DETECTION DEVICE FOR CONCRETE BRIDGE DECKS

Second Quarterly Report
State Study No. 77-04-2

W. T. Cronenwett
C. R. Haden

SCHOOL OF
ELECTRICAL ENGINEERING
THE UNIVERSITY OF OKLAHOMA

202 West Boyd, Room 219 Norman, Oklahoma 73069

The University

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Report No. OUEE-WTC-1977-02

I. INTRODUCTION

During the last quarter a variety of steel reinforcing bar (rebar) detection schemes were studied so that an optimum sensing device could be selected. It was found that magnetic techniques were superior to infrared, acoustical, and other alternative approaches. Work was begun on a magnetic sensor to meet the specifications of the study.

In the course of this quarter a particular magnetic sensor was selected, designed, constructed, tested, and calibrated. Sections II through VI report the theory, operation, and performance of the sensor.

Work is now ready to begin on the construction of a prototype instrument. Preliminary design considerations have been made and summarized in Section VI.

II. THE SINGLE COIL APPROACH

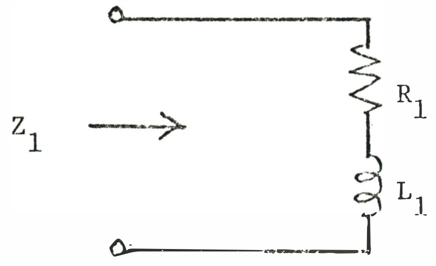
For magnetic detection either a single coil or a multiple coil approach could be used. A single coil sensor was selected for initial work with the possibility of other arrangements being used later. The use of a single coil offers the following advantages:

1. Simple to wind,
2. Noncritical mechanical positioning,
3. Symmetry about the solenoid axis,
4. Ease of fabrication and modification,
5. Simple theoretical analysis, and
6. Sturdy design.

A two coil approach allows the construction of a balanced magnetic bridge, with the increased sensitivity of bridge measurements. The additional sensitivity was not thought to be necessary in the present application.

III. THEORY OF THE SINGLE-COIL DETECTOR

Assume an inductor of inductance L_1 and resistance R_1, where the resistance includes not only the AC resistance of the winding but the effect of all other coil losses as well. Figure 1 lists the values appropriate to the sensor coil now in use:

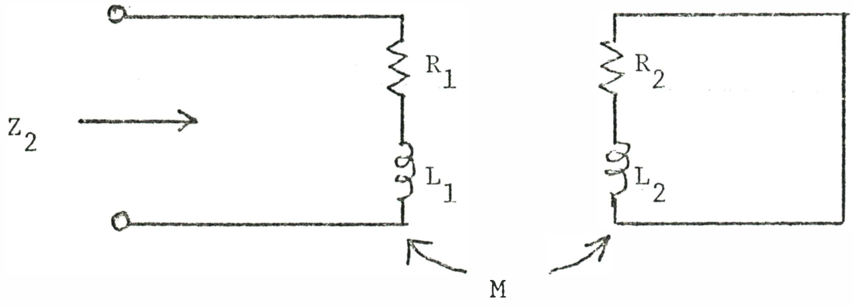


L_1 = 1.07 H
f = 4210 Hz
ω = 26450 s^{-1}
Q = 100
R_1 = 280 Ω

$$Z_1 = R_1 + j\,\omega\,L_1$$

FIGURE 1

If a second, short circuited coil be brought nearby so that a mutual impedance M exists, the circuit becomes as shown in Figure 2 with the input impedance Z_2 increased as shown:



$$Z_2 = Z_1 + \Delta Z = (R_1 + \Delta R) + j\omega\,(L_1 + \Delta L)$$

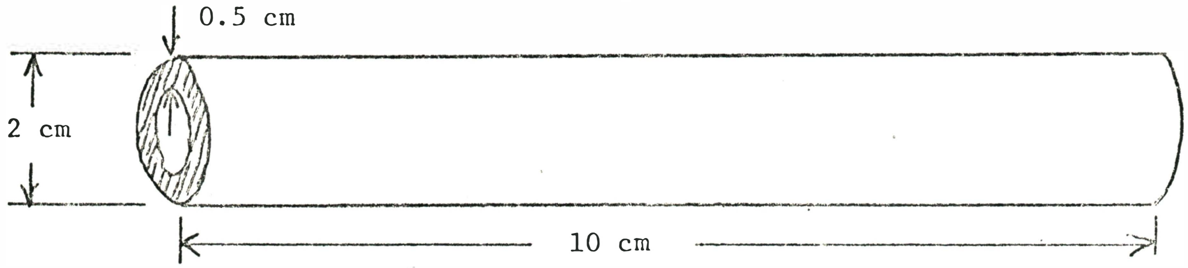
$$R = \frac{\omega^2 M^2 R_2}{R_2^2 = \omega^2 L_2^2} \qquad L = \frac{\omega^2 M^2 L_2}{R_2^2 + \omega^2 L_2^2}$$

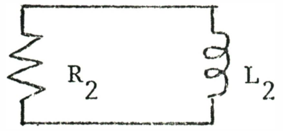
$$\%\ R\ \text{change} = 100\,\frac{\Delta R}{R_1}$$

$$\%\ L\ \text{change} = 100\,\frac{\Delta L}{L_1}$$

FIGURE 2

A typical rebar, considered as a shorted, one-turn coil is shown in Figure 3 where standard formulae have been applied to find R_2 and L_2 for the geometry shown and the electrical properties of steel.





$R_2 = 45.3 \times 10^{-6}\ \Omega$

$L_2 = 3.7 \times 10^{-9}$ H

FIGURE 3

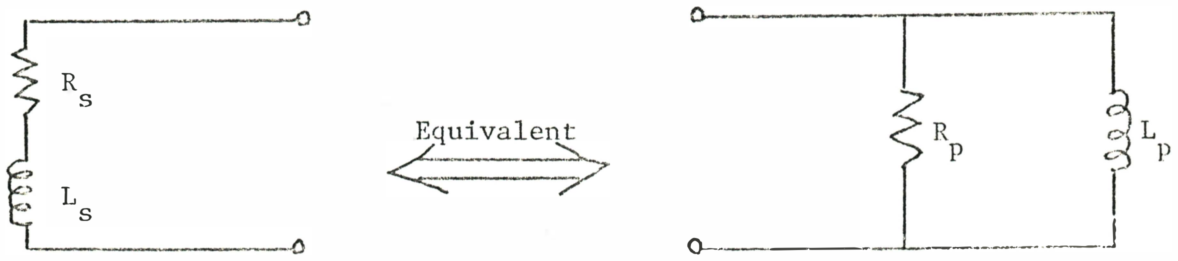
With these values and an assumed coupling coefficient of 0.01 ($M = 6.29 \times 10^{-7}$ H) the percentage changes in the real and reactive components of Z_2 are found to be:

% R change = 0.38%

% L change = 0.0083%.

Thus greater sensitivity would be obtained by measuring the change in resistance as contrasted to measurement of the change in inductance.

A series circuit containing resistance and inductance can be transformed into an equivalent parallel combination at a given frequency by the use of appropriate transformation algebra:



$$R_p = \frac{R_s}{R_s^2 + \omega^2 L_s^2} \qquad L_p = -\frac{L_s}{R_s^2 + \omega^2 L_s^2}$$

FIGURE 4

Therefore the sensor coil may be tuned with a parallel capacitor and operated at its resonant frequency in the feedback loop of an operational amplifier:

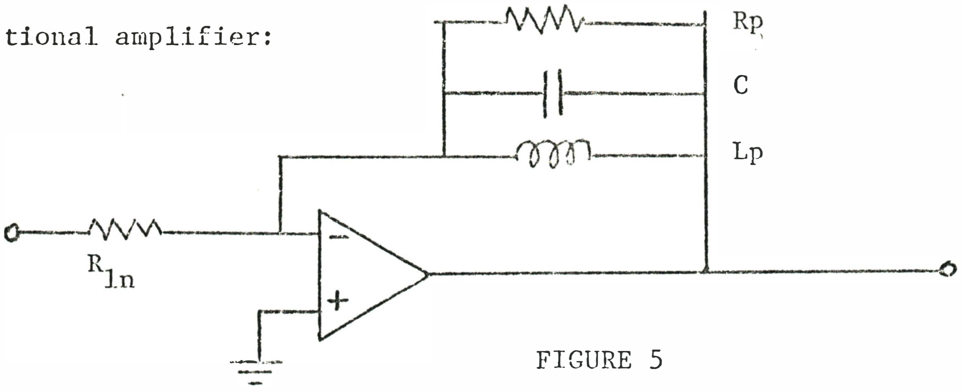


FIGURE 5

At its resonant frequency the sensor coil behaves as a resistor of value R_p so that the voltage gain of the amplifier circuit becomes:

$$A_v = - \frac{R_p}{R_{1n}}$$

and a measurement of the amplifier gain corresponds to a measurement of the effective parallel coil resistance R_p.

IV. ELECTRONIC CIRCUITRY

As was noted earlier, the reinforcement rod has a much more pronounced effect on the Q of the coil than on its inductance. For this reason the present circuit was designed to respond primarily to changes in Q. A block diagram of the circuit is shown in Figure 6 and the circuit diagram is given in Figure 7.

The heart of the circuit is the frequency-determining stage. A 1300 pf capacitor is connected in parallel with the coil to form a parallel resonant circuit. At resonance, the combination appears to be a pure resistance with the value of resistance directly related to Q. The L-C combination is used in the feedback loop of an operational amplifier. At resonance, the phase of the stage is exactly 180^{o} and the gain is some maximum value which is a function of Q. Thus, Q may be measured by applying resonant frequency to this stage and observing the gain.

The simplest way to match the applied frequency to the resonant frequency of the coil is to build the stage into an oscillator. This is the approach used in the present circuit. The oscillator loop consists of the frequency-determining stage and the voltage-controlled amplifier. An automatic gain control (AGC) circuit is used to maintain the loop gain at exactly unity for stable oscillations.

An output related to Q is conveniently available in the form of the AGC voltage. The gain around the oscillator loop must be exactly unity. Therefore when the gain of the frequency-determining stage varies with a change of Q, the voltage-controlled amplifier must make up the difference. Since its gain is a known function of the AGC voltage, the AGC voltage must be related to Q.

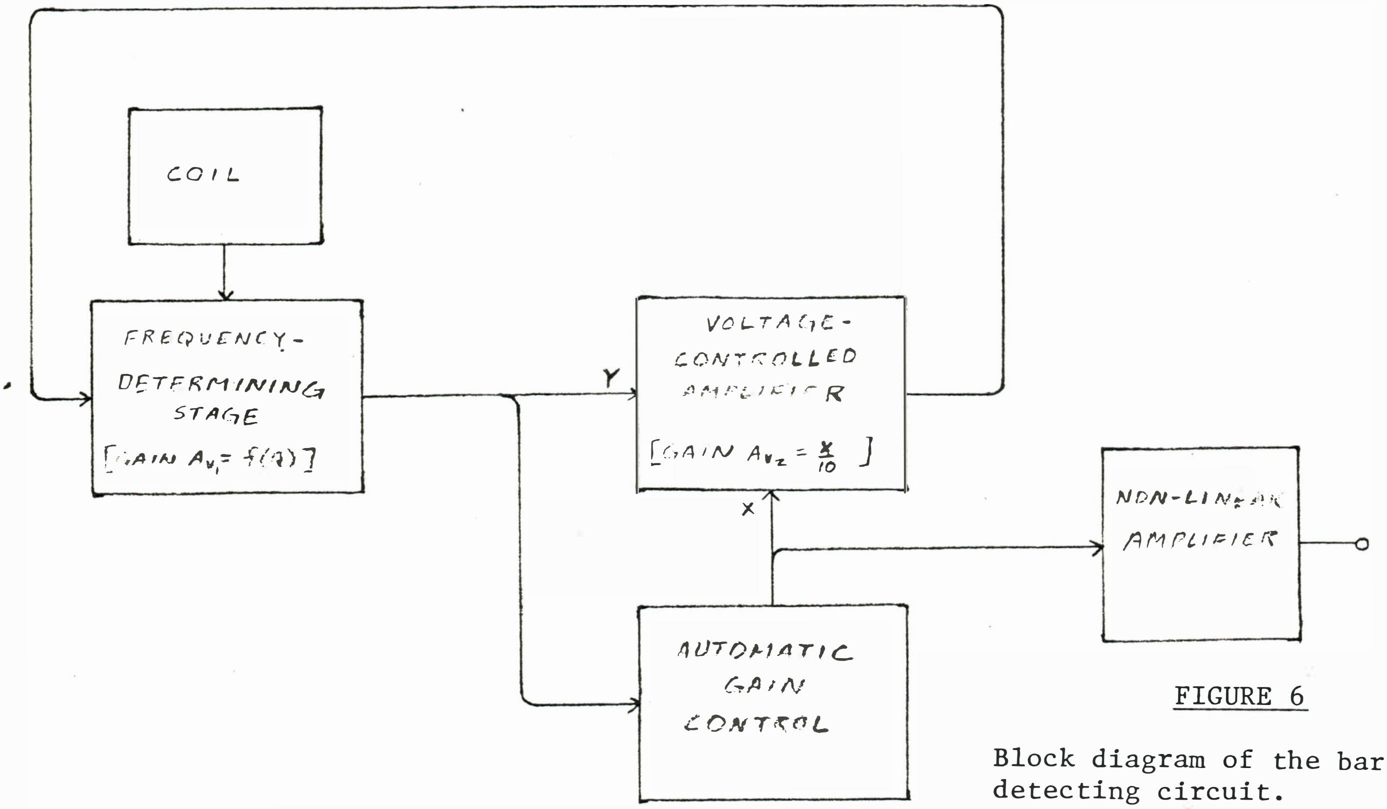


FIGURE 6

Block diagram of the bar detecting circuit.

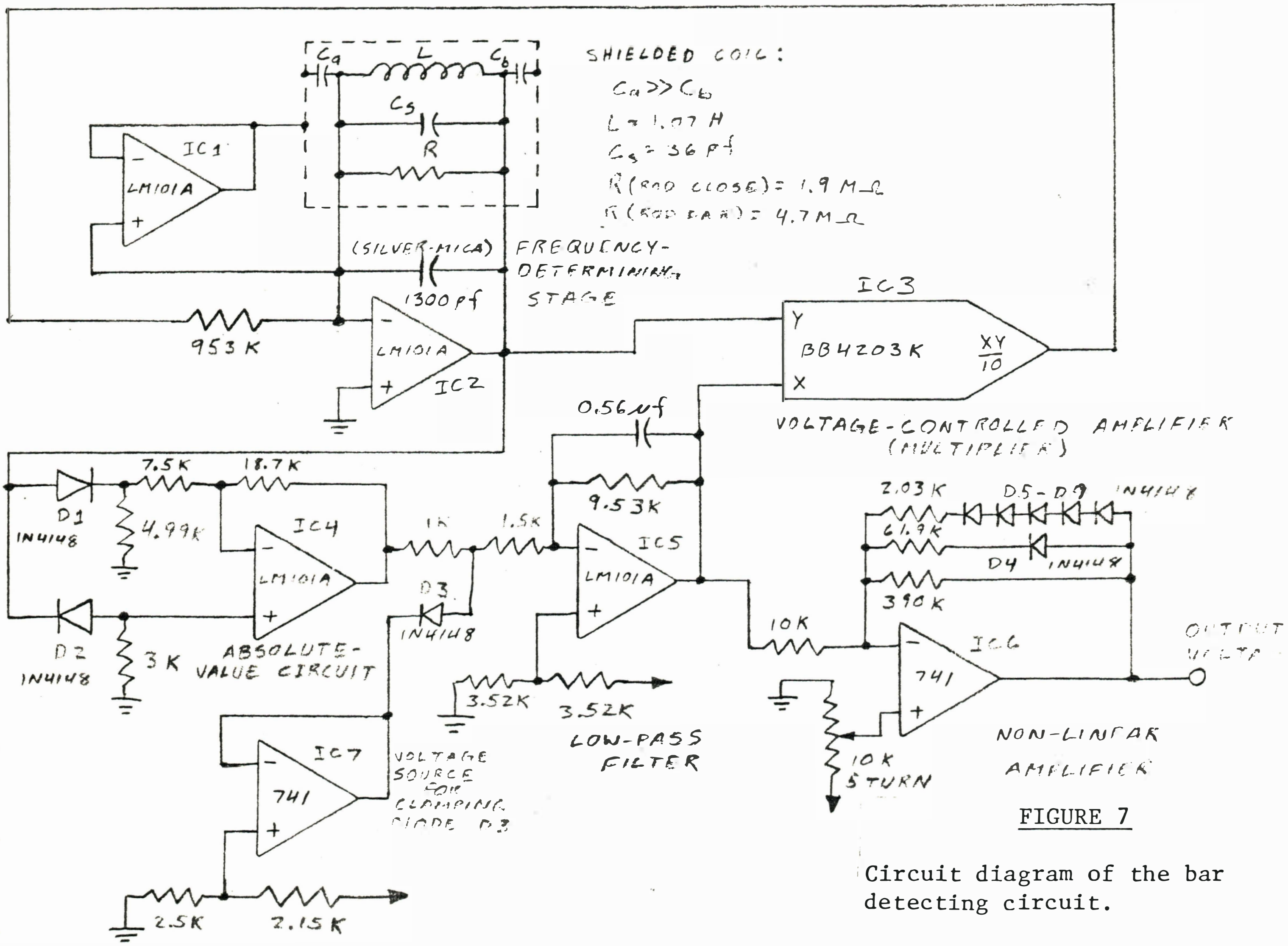


FIGURE 7

Circuit diagram of the bar detecting circuit.

A non-linear amplifier was added to provide an output voltage which is approximately linear in rod distance. It is likely that this stage will be eliminated in the final design, since the conversion could be done more accurately and repeatably in software.

One problem encountered initially was that of electrostatic effects. The tuned circuit responded to changes in capacitance as well as inductance, and this tended to mask the effect of the rod. The problem was solved by electrostatically shielding the coil. However, grounding this shield introduced intolerable capacitance into the tuned circuit. A bootstrap technique was used to eliminate the problem. IC_1 maintains the shield at the potential of the outer winding of the coil. This has virtually eliminated electrostatic coupling to the coil.

The AGC circuit provides a DC voltage which is a function of the oscillation amplitude. IC_4 is used in a simple absolute value circuit, and IC_5 is part of a low pass filter which passes only the 0 to 40 Hz component of the absolute value circuit output. Because the AGC circuit is part of a closed loop, the possibility of unwanted oscillations exists. For this reason, the low-pass filter may have no more than one pole. Thus there is a trade-off between ripple and response speed. This compromise was troublesome in the present circuit. However, it is possible to reduce the ripple with no loss in the speed of response by using a non-linear circuit to clamp the absolute value circuit output. IC_7 provides a stable low-impedance voltage source for clamping diode D_3. This modification has reduced the ripple to an acceptable level.

The present circuit is inherently quite stable. The Q of the tuned circuit is nominally around 100. The coil is not sensitive to vibration and seems to be mechanically stable. It is affected by deformations, but this should not be a problem when ultimately enclosed.

All operational amplifiers in the circuit are stabilized with feedback, so the characteristics of the circuit depend primarily on resistors rather than semiconductors. The multiplier tends to introduce noise, but that noise is filtered out veryeffectively by the frequency-determining stage. Some noise is present in the AGC loop, but the DC component of this noise is very low, so it doesn't disturb the operation of the circuit.

The stability of the circuit depends heavily on the stability of the multiplier. The present design responds to very small changes in Q and thus requires very high stability from the multiplier. In fact, the multiplier does show some temperature dependence, and this is reflected in the output. The output may vary 20 or 30 mV with normal variations in room temperature. This temperature dependence may be minimized in three ways: 1) temperature regulate the multiplier chip, 2) temperature compensate the multiplier, and 3) use a more effective coil which requires less sensitivity from the circuit.

V. PERFORMANCE

The completed sensor assembly of electronics package and sensing coil performs well for detection of steel reinforcing bars. The detection distance required by the specifications is to detect rebars at depths up to 4 inches while moving horizontally across a bridge deck. Figure 8 shows the sensor output vs. horizontal distance between a No. 3 rebar and the sensor coil for various fixed vertical separations from 1 to 6 inches. Maximum sensitivity is obtained at minimum rod-to sensor separation, as is expected, while adequate sensitivity is obtained at 4 inch separation, with usable sensitivity available out to 6 inches. With a U-shaped magnetic core these sensitivities should be improved by the equivalent of a 1 inch separation, since the U-shape allows the rebar to come that much closer to the magnetic path of the sensor coil.

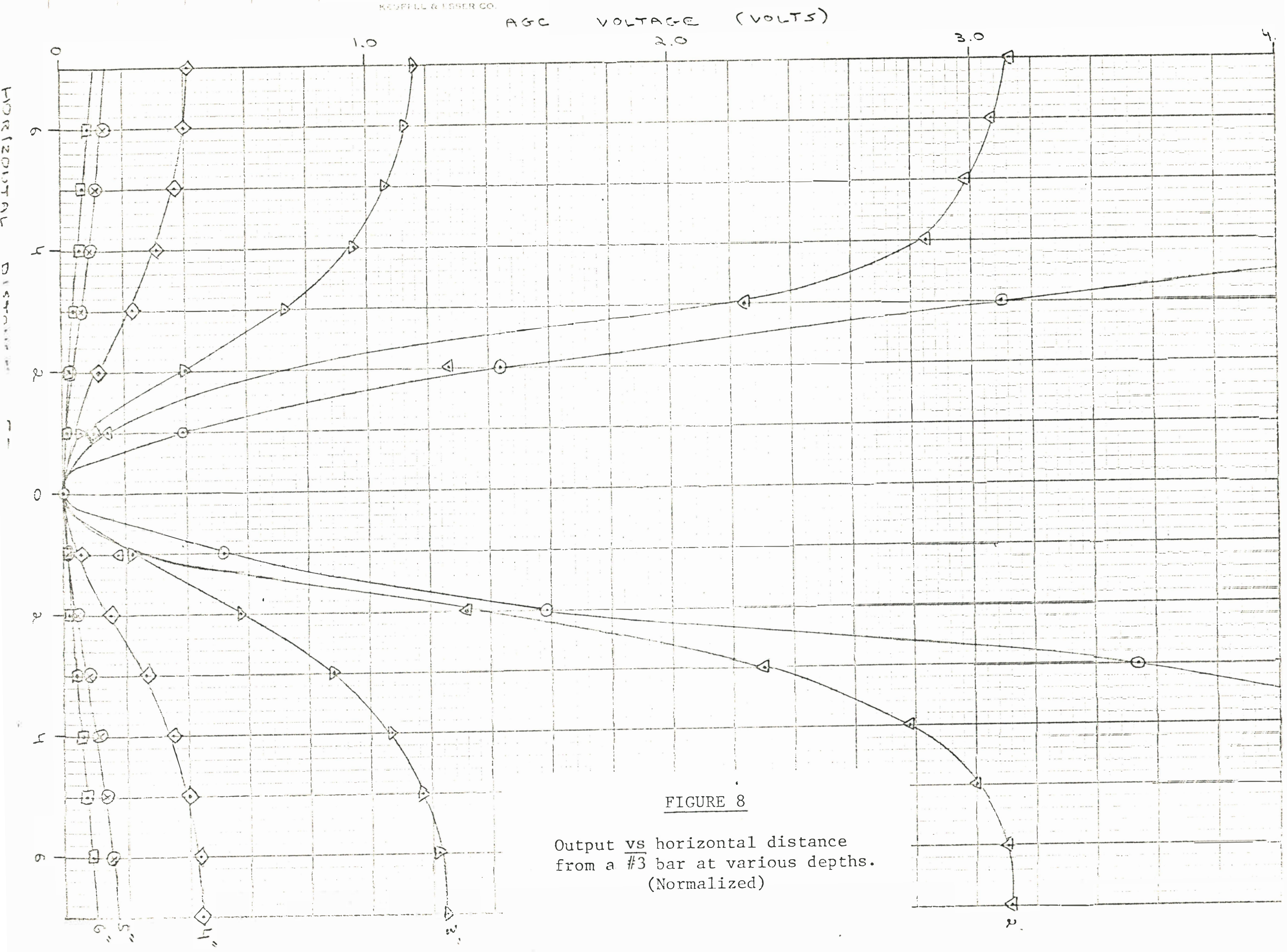


FIGURE 8

Output vs horizontal distance from a #3 bar at various depths. (Normalized)

Figure 9 shows the extent to which the sensor discriminates between rebar sizes for three selected rod-to-sensor spacings. The larger the rebar diameter, the less the apparent separation. Thus it will be necessary to know the rebar diameter in order to interpret depth measurements.

These measurements do not include the effect of longitudinal bars. Their effect is small, but will have to be included in final calibration.

In the current configuration there are two drift problems: first, the particular integrated circuit multiplier used is temperature sensitive and produces an error proportional to temperature and second, the sensor coil is mechanically unprotected and hence sensitive to squeezing or other deformation. Both problems arise from the prototype nature of the first model and can be refined out by more carefully selected circuitry and by more careful mechanical construction. Neither is significant except at maximum sensitivity (maximum distance to rebar).

It is planned to redesign the sensor coil using U-shaped silicon steel transformer laminations to improve the magnetic flux distribution, to improve mechanical stability, and to improve sensitivity.

VI. PLANNED WORK

Sensor. The sensor now in use will be improved through a better selection of multiplier to diminish temperature effects, through the redesign of the sensor coil to use a laminated steel magnetic circuit, and through the use of an off-the-shelf logarithmic amplifier for gain adjustment. The need for these modifications has been established earlier and the remedies planned.

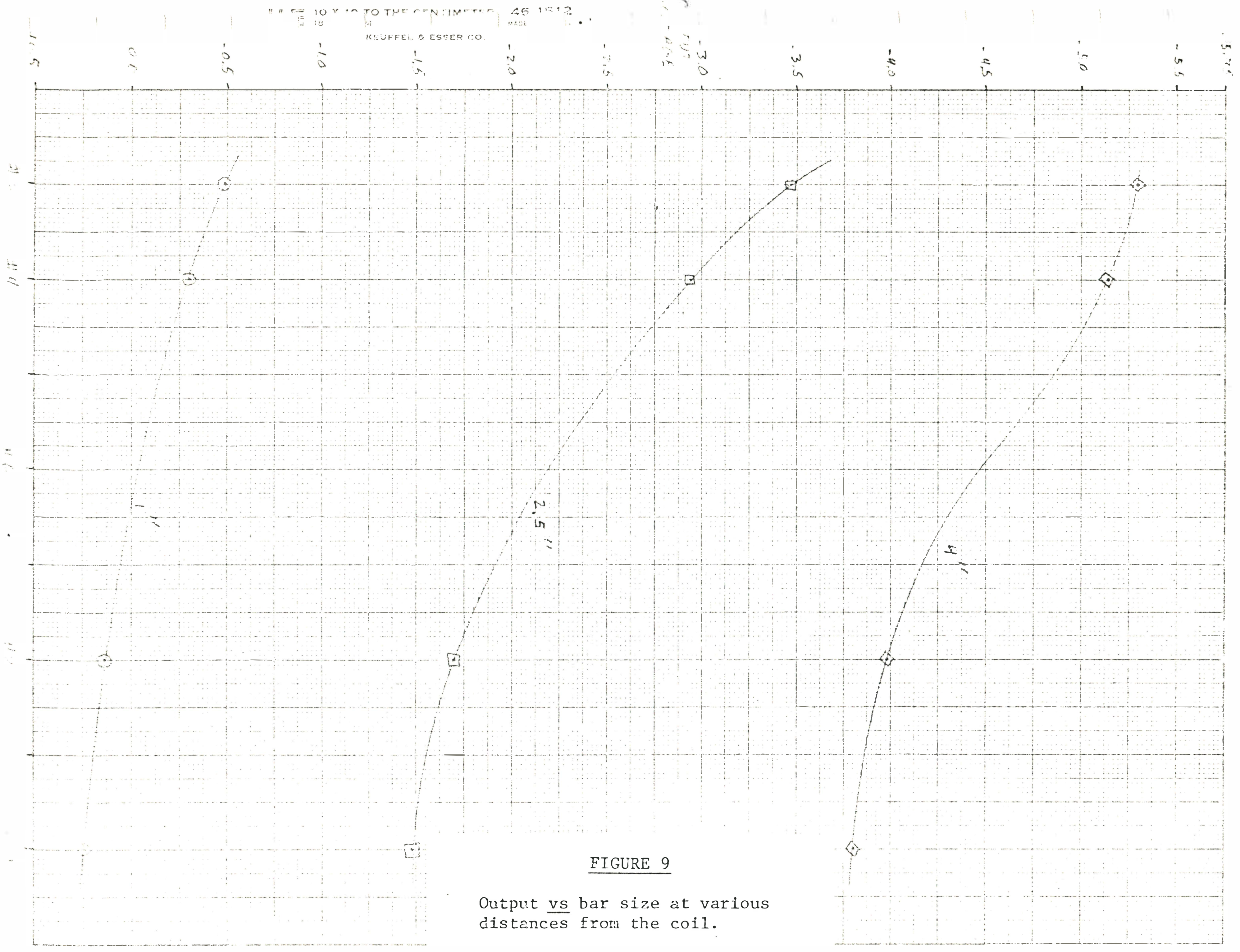


FIGURE 9

Output vs bar size at various distances from the coil.

Instrument. A chart recorder, power supply, data processor, and auxiliary components will be selected for the complete instrument. The instrument will be constructed and calibrated. A microprocessor approach to data processing has been selected. Sensor calibration curves will be reduced to polynomial expansions and written into microprocessor memory. Data reduction is planned to be carried out essentially in real time.

Calibration. Calibration will be carried out with a jig that reproduces bridge rebar spacings. The effect of longitudinal bars will be examined both for the case where the sensor lies between longitudinal bars and for that in which it straddles a bar.